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AFRPL-TR-67-144

# HYDROGEN PEROXIDE HANDBOOK

By

Chemical and Material Sciences Department
Research Division
Rocketdyne, a Division of North American Aviation, Inc.
Canoga Park, California

Technical Report AFRPL-TR-67-144

July 1967

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Air Force Rocket Propulsion Laboratory
Research and Technology Division
Edwards Air Force Base, California
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# FOREWORD

This handbook is submitted as the final report under Rocketdyne G.O. 7108 in compliance with Contract AF04(611)-11397, Part I, Para. B.1, and line items 2 and 3 of DD 1423. The effort under this contract was sponsored by the Air Force Rocket Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, USAF, Edwards, California, with 1/Lt. Ralph Fargnoli acting as the Air Force Project Officer.

This program was conducted by the Propellant Technology function of the Rocketdyne Research Division, with Dr. E. F. C. Cain serving as Program Manager and Mr. M. T. Constantine serving as Responsible Project Scientist. Technical personnel who contributed to the compilation and analysis of the data and information in this handbook include M. M. Williams and K. J. Youel.

This handbook has been assigned the Rocketdyne identification number R-6931.

This report has been reviewed and is approved.

W. H. EBELKE, Colonel, USAF
Chief, Propellant Division

# ABSTRACT

This handbook is a compilation of the engineering properties and handling characteristics of propellant-grade hydrogen peroxide. The handbook includes data and information on hydrogen peroxide physicochemical properties, production, storability, materials compatibility, materials treatment and passivation, facilities and equipment, disposal, transportation, safety, and decomposition.

# ACKNOWLEDGMENT

This handbook includes data and information generated through experimental and analytical studies conducted at many different organizations. Although every effort has been made to reference these studies, a great number of individuals responsible for these data have been neglected. These individual contributions as well as the contributions of the industry and government organizations are gratefully acknowledged.

Appreciation is also gratefully extended to the various organizations who responded to a request for data and information during an industry survey. These organizations (with the responding individual noted) are as follows:

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D. Couch

CONTENTS

## ILLUSTRATIONS

## TABLES

# SECTION 1: INTRODUCTION

## 1.1 GENERAL

The discovery of hydrogen peroxide was reported to the Paris Academy of Sciences in July 1818 by Louis-Jacques Thenard and was initially described as oxidized water. The discovery was a result of government-subsidized research on the preparation of voltaic cells. Thenard, in working with alkaline earth oxides, discovered that the reaction of barium peroxide with cold nitric acid resulted in the formation of "oxygenated water." Thenard then conducted a fairly extensive study of hydrogen peroxide, which included catalytic decomposition studies, density determinations, measurements of the volume of oxygen released, etc. He noted extensive supercooling and the inability to achieve appreciable concentration increases with crystallization techniques. Thenard also reported that vacuum distillation could continue to complete dryness in the reservoir without appreciable decomposition, although the determination of normal boiling points was impossible because of decomposition of the hydrogen peroxide. His work led to the publication of several papers, which are extensively summarized in Ref. 1.1.

In his work, Thenard cites reactions with some 130 elements, oxides, salts, acids, and bases with frequent notations of decomposition of the hydrogen peroxide. These decomposition reactions were sometimes accompanied with the note that "in these decompositions, chemical action is evidently missing; it is necessary then, to attribute these actions to a physical cause; but the actions are dependent on neither heat nor light, whence it follows that they are probably due to electricity" (Ref. 1.1). These "unexplained" reactions were later recognized by Berzelius (Ref. 1.2) in 1836 in the first notation of catalysts and catalytic activity.

Although Thenard's only noted uses for hydrogen peroxide were in removing sulfide deposits on oil paintings and as a skin irritant for medicinal purposes, hydrogen peroxide and its aqueous solutions have found a number of commercial applications since its discovery. The primary bulk of this commercial use is limited to hydrogen peroxide grades of less than 52 percent $H_2O_2$ by weight; these "industrial grades" have been used for many years in textile and pulp bleaching, synthesis of chemical derivatives, the manufacture of foam rubber, the oxidation of dyes, the purification of metal salt solutions, the treatment of metal surfaces, etc. The requirement for higher concentrations and their subsequent commercial development was based primarily on the establishment of hydrogen peroxide as a source of energy.

Hydrogen peroxide (in a 60 w/o aqueous solution) was first utilized as an energy source for underwater propulsion in Germany in 1934; this work led to its subsequent application (in higher concentrations) during World War II for auxiliary propulsion and gas generation concepts in aircraft and rockets. Its use in these areas resulted from its thermally or catalytically initiated exothermic decomposition (with substantial heat release) to yield a gaseous mixture of oxygen and superheated steam. Although its advantages as a monopropellant include a 47 w/o available oxygen content, high density, high boiling point, unlimited availability, and nontoxic exhaust gases, the initial areas of application for hydrogen peroxide were limited because of its questionable storage stability.

The use of hydrogen peroxide has been expanded with improvements in its stability, through stabilization additives and increased purification. Currently, hydrogen peroxide is the primary monopropellant used for underwater propulsion, aerospace propulsion, and auxiliary power concepts. Hydrogen peroxide/water solutions can now be stored for extended periods without significant decomposition (i.e., decomposition rates of $<$ 0.1 percent/year are readily attainable). Reaction control systems using hydrogen peroxide have already demonstrated space storability in excess of 2 years (with an estimated storability of 5 years).

The use of hydrogen peroxide as a monopropellant in the aerospace industry has been widespread in the areas of station maintenance, space maneuvering, thrust vector control, power generation, etc. Some examples of systems which have used or are presently utilizing hydrogen peroxide include the V-2 (gas generator), Redstone (gas generator), Mercury Spacecraft (reaction control system), Scout (reaction control system--2nd and 3rd stages), Little Joe II (reaction control system), Burner II (reaction control system), SATAR (reaction control system), ASSET (reaction control system), 122Y (attitude control system), Lunar Landing Simulator (main propulsion and attitude control systems), Astronaut Maneuvering Unit (main propulsion), SYNCOM (reaction control system), COMSAT (reaction control system), HS-303A "Blue Bird" (reaction control system), ATS (reaction control system), Personnel Rocket Belt, and X-15 (gas generator, reaction control, and auxiliary power systems). Although the use of hydrogen peroxide in operational bipropellant systems has been limited thus far to extremely high-performance aircraft rockets, hydrogen peroxide is potentially applicable to a variety of liquid bipropellant and hybrid propellant systems.

This widespread application potential of hydrogen peroxide has led to the requirement for a comprehensive and definitive compilation of physical, chemical, and handling properties of this important oxidizer. As a result of this interest, this handbook represents a current summary of the engineering properties of propellant-grade hydrogen peroxide. Propellant-grade hydrogen peroxide is defined in this report as high-purity hydrogen peroxide/water solutions in which the hydrogen peroxide concentration is ≥ 70 percent by weight. Within this concentration range of interest, solutions containing 70, 75, 90, 95, 98, and 100 percent by weight hydrogen peroxide have been designated as concentrations of special interest.

## 1.2 HANDBOOK FORMAT

The material contained in this handbook has been organized into sections. These are:

Section 1: Introduction
Section 2: Physico-Chemical Properties
Section 3: Production
Section 4: Storage and Handling
Section 5: Transportation
Section 6: Safety
Section 7: Decomposition, Stabilization, and Catalysts
Section 8: Bibliography

Each section is subdivided further to permit the user of this handbook to obtain specific information expeditiously. The material is arranged in such a manner as to permit convenient updating of various sections as data are generated from additional studies in these areas.

The interest of each individual user may be limited to specific aspects of the subject material; however, it is recommended that personnel involved in $H_2O_2$ handling be thoroughly familiar with all of the engineering properties contained in this report. Although every effort has been made to provide presently available information on $H_2O_2$ in sufficient detail for most of the potential users of the handbook, size limitations of the handbook obviously preclude inclusion of every conceivable detail.

Thus, for those users who desire additional details on specific items, consultation of the many referenced publications is recommended.

Wherever a series of reports or papers has been utilized to report the progress in a particular study, the data and information referenced are from final reports, whenever applicable. This was done to eliminate confusion in efforts where progress reports included incomplete experimentation and/or analysis of the data. In those efforts where a final report has not been issued or does not contain sufficient detail of the item, the data were taken from the latest progress report containing the pertinent results.

The tables figures, and references noted in each section are contained in that section for convenience. Each table, figure, and reference number is preceded by the section number (i.e., Table 1.3 is the third table in Section 1, etc.).

Because the major portion of this handbook is related to areas of engineering interest, all of the data ar presented in engineering terminology (i.e., English units). However, as a convenience to all of the users, data in certain sections (notably, the physical properties section) of the handbook are presented in both metric and English units. Where data are presented in both units, the attendant discussion indicates the units of the referenced work.

As a further convenience to the user, physical constants and conversion factors are presented in Tables 1.1 through 1.3 to enable the user to convert the values to his particular needs. Also, because these constants are presented to the known degree of significance, they can be rounded to fit particular needs.

## 1.3 REFERENCES

1.1 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, Hydrogen Peroxide, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

1.2 Berzelius, J. J., Jahresber. Chem., 15, 237 (1836), as presented in Ref. 1.1.

## TABLE 1.1

## PHYSICAL CONSTANTS

| Unit | Remarks | Value |
|---|---|---|
| $g_c$ | Standard gravitational acceleration | 32.1740 ft/sec$^2$<br>980.665 cm/sec$^2$ |
| 1 atm | Standard atmosphere | 1,013,250 dynes/sq cm |
| 1 mm Hg | Standard millimeter Hg | 1333.2237 dynes/sq cm |
| 1 cal | Thermochemical calorie | 4.1840 abs joules<br>41.2929 ±0.0020 cu cm-atm |
| 1 cal (I. T.) | International Stream Tables calorie | 1.000654 thermochemical calories |
| $T_0$ C | Ice Point | 491.6880 ±0.018 R<br>273.160 ±0.010 K |
| $(PV)_{0\,C}^{P=0} = (RT)_{0\,C}$ | Pressure-Volume product for ideal gas at 0 C | 22,414.6 ±0.4 cu cm-atm/g mole<br>2271.16 ±0.04 abs joules/g mole |
| R | Molar gas constant | 8.31439 ±0.00034 abs joules/K-g mole<br>1.98719 ±0.00013 cal/K-g mole<br>82.0567 ±0.0034 cu cm-atm/K-g mole<br>59.47 cu ft-atm/R-lb mole<br>10.73 cu ft-psia/R-lb mole |
| 1 Btu |  | 1055.040 abs joules<br>252.161 thermochemical calories<br>251.996 I. T. calories |
| 1 in. | United States unit | 2.54000508 cm |
| 1 ft | United States unit | 30.4800610 cm |
| 1 lb | Avoirdupois | 453.5924277 g |
| 1 gal | United States unit | 0.133680555 cu ft<br>3785.43449 cu cm |

Note: Compiled by Rossini, F. D. *et al*, *American Petroleum Institute Research Project 44*, U.S. Department of Commerce, Natl. Bur. Standards, Circular 461, U.S. Government Printing Office, Washington, D. C., 1947.

## CONVERSION FACTORS

### Temperature

C + 273.16 = K

F + 459.69 = R

(C x 1.8) + 32 = F

(F - 32)/1.8 = C

K(1.8) = R

### Pressure

atm x 14.69618 = psi

mm Hg x 0.00131579 = atm

mm Hg x 0.019337 = psi

g/sq cm x 0.00096784 = atm

g/sq cm x 0.0142234 = psi

bars x 0.98692 = atm

bars x 14.504 = psi

megabaryes x 1 = bars

### Mass

grams (mass) x 0.002204622 = pounds (mass)

### Length

centimeters x 0.393700 = inches

centimeters x 0.032808 = feet

### Area

square centimeters x 0.15500 = square inches

square centimeters x 0.0010764 = square feet

square feet x 144 = square inches

# TABLE 1.2

## (Concluded)

### Viscosity

centipoises x $0.672 \times 10^{-3}$ = $lb_f$/ft-sec

centistokes x $1.076 \times 10^{-5}$ = sq ft/sec

(kinematic viscosity) x (density) = (absolute) viscosity

### Thermal Conductivity

(cal/cm-sec-C) x 241.8588 = Btu/ft-hr-F

### Velocity of Sound

(m/sec) x 3.28083 = ft/sec

### Compressibility

(sq cm/dyne) x $1.01325 \times 10^{6}$ = $atm^{-1}$

(sq cm/dyne) x $6.8947 \times 10^{4}$ = $psi^{-1}$

## TABLE 1.2
(Continued)

### Volume

cubic centimeters x 0.061023 = cubic inches
cubic centimeters x $3.531445 \times 10^{-5}$ = cubic feet
cubic inches (U.S.) x $5.78704 \times 10^{-4}$ = cubic feet

### Time

seconds/60 = minutes
seconds/3600 = hours
seconds/86,400 = days

### Force

dynes x 0.00101972 = grams (force)
grams (force) x 0.00220462 = pounds (force)

### Density and Specific Volume

(g/cu cm) x 62.43 = lb/cu ft
(cu cm/g) x 0.016018 = cu ft/lb

### Surface Tension

(dynes/cm) x $6.8523 \times 10^{-5}$ = $\mathrm{lb_f}$/ft

### Thermodynamic Properties

(cal/g mole) x 1.8 = Btu/lb mole
(cal/g mole- K) x 1 = Btu/lb mole - R
(Btu/lb mole)/mol. wt = Btu/lb
(Btu/lb mole- R)/mol. wt = Btu/lb - R
(Cal/g) x 1.8 = Btu/lb

# TABLE 1.3

## TEMPERATURE CONVERSION

Interpolation Factors

| C | T | F |
|---|---|---|
| 0.56 | 1 | 1.8 |
| 1.11 | 2 | 3.6 |
| 1.67 | 3 | 5.4 |
| 2.22 | 4 | 7.2 |
| 2.78 | 5 | 9.0 |
| 3.33 | 6 | 10.8 |
| 3.89 | 7 | 12.6 |
| 4.44 | 8 | 14.4 |
| 5.00 | 9 | 16.2 |
| 5.56 | 10 | 18.0 |

Temperature Range

| -459 to 0 | | | 0 to 50 | | | 50 to 100 | | | 100 to 490 | | | 500 to 1000 | | | 1000 to 1490 | | | 1500 to 2000 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | T | F | C | T | F | C | T | F | C | T | F | C | T | F | C | T | F | C | T | F |
| -273 | -459 | | -17.8 | 0 | 32.0 | 10.0 | 50 | 122.0 | 38 | 100 | 212 | 260 | 500 | 932 | 538 | 1000 | 1832 | 816 | 1500 | 2732 |
| -268 | -450 | | -17.2 | 1 | 33.8 | 10.6 | 51 | 123.8 | 43 | 110 | 230 | 266 | 510 | 950 | 543 | 1010 | 1850 | 821 | 1510 | 2750 |
| -262 | -440 | | -16.7 | 2 | 35.6 | 11.1 | 52 | 125.6 | 49 | 120 | 248 | 271 | 520 | 968 | 549 | 1020 | 1868 | 827 | 1520 | 2768 |
| -257 | -430 | | -16.1 | 3 | 37.4 | 11.7 | 53 | 127.4 | 54 | 130 | 266 | 277 | 530 | 986 | 554 | 1030 | 1886 | 832 | 1530 | 2786 |
| -251 | -420 | | -15.6 | 4 | 39.2 | 12.2 | 54 | 129.2 | 60 | 140 | 284 | 282 | 540 | 1004 | 560 | 1040 | 1904 | 838 | 1540 | 2804 |
| -246 | -410 | | -15.0 | 5 | 41.0 | 12.8 | 55 | 131.0 | 66 | 150 | 302 | 288 | 550 | 1022 | 566 | 1050 | 1922 | 843 | 1550 | 2822 |
| -240 | -400 | | -14.4 | 6 | 42.8 | 13.3 | 56 | 132.8 | 71 | 160 | 320 | 293 | 560 | 1040 | 571 | 1060 | 1940 | 849 | 1560 | 2840 |
| -234 | -390 | | -13.9 | 7 | 44.6 | 13.9 | 57 | 134.6 | 77 | 170 | 338 | 299 | 570 | 1058 | 577 | 1070 | 1958 | 854 | 1570 | 2858 |
| -229 | -380 | | -13.3 | 8 | 46.4 | 14.4 | 58 | 136.4 | 82 | 180 | 356 | 304 | 580 | 1076 | 582 | 1080 | 1976 | 860 | 1580 | 2876 |
| -223 | -370 | | -12.8 | 9 | 48.2 | 15.0 | 59 | 138.2 | 88 | 190 | 374 | 310 | 590 | 1094 | 588 | 1090 | 1994 | 866 | 1590 | 2894 |
| -218 | -360 | | -12.2 | 10 | 50.0 | 15.6 | 60 | 140.0 | 93 | 200 | 392 | 316 | 600 | 1112 | 593 | 1100 | 2012 | 871 | 1600 | 2912 |
| -212 | -350 | | -11.7 | 11 | 51.8 | 16.1 | 61 | 141.8 | 99 | 210 | 410 | 321 | 610 | 1130 | 599 | 1110 | 2030 | 877 | 1610 | 2930 |
| -207 | -340 | | -11.1 | 12 | 53.6 | 16.7 | 62 | 143.6 | 100 | 212 | 414 | 327 | 620 | 1148 | 604 | 1120 | 2048 | 882 | 1620 | 2948 |
| -201 | -330 | | -10.6 | 13 | 55.4 | 17.2 | 63 | 145.4 | 104 | 220 | 428 | 332 | 630 | 1166 | 610 | 1130 | 2066 | 888 | 1630 | 2966 |
| -196 | -320 | | -10.0 | 14 | 57.2 | 17.8 | 64 | 147.2 | 110 | 230 | 446 | 338 | 640 | 1184 | 616 | 1140 | 2084 | 893 | 1640 | 2984 |
| -190 | -310 | | -9.44 | 15 | 59.0 | 18.3 | 65 | 149.0 | 116 | 240 | 464 | 343 | 650 | 1202 | 621 | 1150 | 2102 | 899 | 1650 | 3002 |
| -184 | -300 | | -8.89 | 16 | 60.8 | 18.9 | 66 | 150.8 | 121 | 250 | 482 | 349 | 660 | 1220 | 627 | 1160 | 2120 | 904 | 1660 | 3020 |
| -179 | -290 | | -8.33 | 17 | 62.6 | 19.4 | 67 | 152.6 | 127 | 260 | 500 | 354 | 670 | 1238 | 632 | 1170 | 2138 | 910 | 1670 | 3038 |
| -173 | -280 | | -7.78 | 18 | 64.4 | 20.0 | 68 | 154.4 | 132 | 270 | 518 | 360 | 680 | 1256 | 638 | 1180 | 2156 | 916 | 1680 | 3056 |
| -169 | -273 | -459 | -7.22 | 19 | 66.2 | 20.6 | 69 | 156.2 | 138 | 280 | 536 | 366 | 690 | 1274 | 643 | 1190 | 2174 | 921 | 1690 | 3074 |
| -168 | -270 | -454 | -6.67 | 20 | 68.0 | 21.1 | 70 | 158.0 | 143 | 290 | 554 | 371 | 700 | 1292 | 649 | 1200 | 2192 | 927 | 1700 | 3092 |
| -162 | -260 | -436 | -6.11 | 21 | 69.8 | 21.7 | 71 | 159.8 | 149 | 300 | 572 | 377 | 710 | 1310 | 654 | 1210 | 2210 | 932 | 1710 | 3110 |
| -157 | -250 | -418 | -5.56 | 22 | 71.6 | 22.2 | 72 | 161.6 | 154 | 310 | 590 | 382 | 720 | 1328 | 660 | 1220 | 2228 | 938 | 1720 | 3128 |
| -151 | -240 | -400 | -5.00 | 23 | 73.4 | 22.8 | 73 | 163.4 | 160 | 320 | 608 | 388 | 730 | 1346 | 666 | 1230 | 2246 | 943 | 1730 | 3146 |
| -146 | -230 | -382 | -4.44 | 24 | 75.2 | 23.3 | 74 | 165.2 | 166 | 330 | 626 | 393 | 740 | 1364 | 671 | 1240 | 2264 | 949 | 1740 | 3164 |
| -140 | -220 | -364 | -3.89 | 25 | 77.0 | 23.9 | 75 | 167.0 | 171 | 340 | 644 | 399 | 750 | 1382 | 677 | 1250 | 2282 | 954 | 1750 | 3182 |
| -134 | -210 | -346 | -3.33 | 26 | 78.8 | 24.4 | 76 | 168.8 | 177 | 350 | 662 | 404 | 760 | 1400 | 682 | 1260 | 2300 | 960 | 1760 | 3200 |
| -129 | -200 | -328 | -2.78 | 27 | 80.6 | 25.0 | 77 | 170.6 | 182 | 360 | 680 | 410 | 770 | 1418 | 688 | 1270 | 2318 | 966 | 1770 | 3218 |
| -123 | -190 | -310 | -2.22 | 28 | 82.4 | 25.6 | 78 | 172.4 | 188 | 370 | 698 | 416 | 780 | 1436 | 693 | 1280 | 2336 | 971 | 1780 | 3236 |
| -118 | -180 | -292 | -1.67 | 29 | 84.2 | 26.1 | 79 | 174.2 | 193 | 380 | 716 | 421 | 790 | 1454 | 699 | 1290 | 2354 | 977 | 1790 | 3254 |
| -112 | -170 | -274 | -1.11 | 30 | 86.0 | 26.7 | 80 | 176.0 | 199 | 390 | 734 | 427 | 800 | 1472 | 704 | 1300 | 2372 | 982 | 1800 | 3272 |
| -107 | -160 | -256 | -0.56 | 31 | 87.8 | 27.2 | 81 | 177.8 | 204 | 400 | 752 | 432 | 810 | 1490 | 710 | 1310 | 2390 | 988 | 1810 | 3290 |
| -101 | -150 | -238 | 0 | 32 | 89.6 | 27.8 | 82 | 179.6 | 210 | 410 | 770 | 438 | 820 | 1508 | 716 | 1320 | 2408 | 993 | 1820 | 3308 |
| -95.6 | -140 | -220 | 0.56 | 33 | 91.4 | 28.3 | 83 | 181.4 | 216 | 420 | 788 | 443 | 830 | 1526 | 721 | 1330 | 2426 | 999 | 1830 | 3326 |
| -90.0 | -130 | -202 | 1.11 | 34 | 93.2 | 28.9 | 84 | 183.2 | 221 | 430 | 806 | 449 | 840 | 1544 | 727 | 1340 | 2444 | 1004 | 1840 | 3344 |
| -84.4 | -120 | -184 | 1.67 | 35 | 95.0 | 29.4 | 85 | 185.0 | 227 | 440 | 824 | 454 | 850 | 1562 | 732 | 1350 | 2462 | 1010 | 1850 | 3362 |
| -78.9 | -110 | -166 | 2.22 | 36 | 96.8 | 30.0 | 86 | 186.8 | 232 | 450 | 842 | 460 | 860 | 1580 | 738 | 1360 | 2480 | 1016 | 1860 | 3380 |
| -73.3 | -100 | -148 | 2.78 | 37 | 98.6 | 30.6 | 87 | 188.6 | 238 | 460 | 860 | 466 | 870 | 1598 | 743 | 1370 | 2498 | 1021 | 1870 | 3398 |
| -67.8 | -90 | -130 | 3.33 | 38 | 100.4 | 31.1 | 88 | 190.4 | 243 | 470 | 878 | 471 | 880 | 1616 | 749 | 1380 | 2516 | 1027 | 1880 | 3416 |
| -62.2 | -80 | -112 | 3.89 | 39 | 102.2 | 31.7 | 89 | 192.2 | 249 | 480 | 896 | 477 | 890 | 1634 | 754 | 1390 | 2534 | 1032 | 1890 | 3434 |
| -56.7 | -70 | -94 | 4.44 | 40 | 104.0 | 32.2 | 90 | 194.0 | 254 | 490 | 914 | 482 | 900 | 1652 | 760 | 1400 | 2552 | 1038 | 1900 | 3452 |
| -51.1 | -60 | -76 | 5.00 | 41 | 105.8 | 32.8 | 91 | 195.8 | | | | 488 | 910 | 1670 | 766 | 1410 | 2570 | 1043 | 1910 | 3470 |
| -45.6 | -50 | -58 | 5.56 | 42 | 107.6 | 33.3 | 92 | 197.6 | | | | 493 | 920 | 1688 | 771 | 1420 | 2588 | 1049 | 1920 | 3488 |
| -40.0 | -40 | -40 | 6.11 | 43 | 109.4 | 33.9 | 93 | 199.4 | | | | 499 | 930 | 1706 | 777 | 1430 | 2606 | 1054 | 1930 | 3506 |
| -34.4 | -30 | -22 | 6.67 | 44 | 111.2 | 34.4 | 94 | 201.2 | | | | 504 | 940 | 1724 | 782 | 1440 | 2624 | 1060 | 1940 | 3524 |
| -28.9 | -20 | -4 | 7.22 | 45 | 113.0 | 35.0 | 95 | 203.0 | | | | 510 | 950 | 1742 | 788 | 1450 | 2642 | 1066 | 1950 | 3542 |
| -23.3 | -10 | 14 | 7.78 | 46 | 114.8 | 35.6 | 96 | 204.8 | | | | 516 | 960 | 1760 | 793 | 1460 | 2660 | 1071 | 1960 | 3560 |
| -17.8 | 0 | 32 | 8.33 | 47 | 116.6 | 36.1 | 97 | 206.6 | | | | 521 | 970 | 1778 | 799 | 1470 | 2678 | 1077 | 1970 | 3578 |
| | | | 8.89 | 48 | 118.4 | 36.7 | 98 | 208.4 | | | | 527 | 980 | 1796 | 804 | 1480 | 2696 | 1082 | 1980 | 3596 |
| | | | 9.44 | 49 | 120.2 | 37.2 | 99 | 210.2 | | | | 532 | 990 | 1814 | 810 | 1490 | 2714 | 1088 | 1990 | 3614 |
| | | | 10.00 | 50 | 122.0 | 37.8 | 100 | 212.0 | | | | 538 | 1000 | 1832 | | | | 1093 | 2000 | 3632 |

# SECTION 2: PHYSICO-CHEMICAL PROPERTIES

## 2.1 GENERAL DESCRIPTION

Hydrogen peroxide is a chemical compound with the empirical formula $H_2O_2$. Because of the compound's complete miscibility with water above 32 F, hydrogen peroxide is commercially available in aqueous solutions at concentrations to ~98 percent by weight $H_2O_2$. Propellant-grade hydrogen peroxide has generally been limited to aqueous solutions $\geq 70$ w/o $H_2O_2$ with regulation of the concentrations and impurity levels of the more frequently applied propellant grades by government procurement specifications.

Hydrogen peroxide and its aqueous solutions are water-like in appearance in both the liquid and solid states. Although hydrogen peroxide is generally considered odorless, the odor of high vapor concentrations has been described as sweet and comparable to the odor of weak concentrations of ozone and the halogens. Aqueous hydrogen peroxide solutions are more dense, slightly more viscous, and have higher boiling and lower freezing points than water.

Although hydrogen peroxide solutions are normally insensitive to shock and impact and are nonflammable, they are active oxidizing materials and can decompose exothermally to yield water and oxygen. Because of their strong oxidizing nature and the liberation of oxygen and heat during their decomposition, propellant-grade solutions can initiate the vigorous combustion of many common organic materials such as clothing, wood, wastes, etc. In the absence of contamination, propellant-grade hydrogen peroxide solutions are relatively stable (nominal decomposition rates are 0.1 percent per year) over ambient temperature ranges. However, in the presence of higher temperatures and/or various contaminants (including many inorganic materials), the decomposition rate is drastically increased. Rapid decomposition can occur in situations where extreme temperature levels and/or mass contamination are present. As the decomposition rate increases, the attendant heat release causes additional decomposition; this bootstrap effect can lead to a runaway reaction.

Hydrogen peroxide is normally stored, shipped, and handled as a liquid under its own vapor pressure with provisions for relief of pressure buildup. When stored and/or transferred in clean, passivated, compatible systems by properly educated and trained personnel, hydrogen peroxide does not present a serious storage or handling problem.

## 2.2 PHYSICAL PROPERTIES

A majority of the physical properties of propellant-grade solutions of hydrogen peroxide have been experimentally characterized (or analytically extrapolated) with a reasonable degree of accuracy over ambient temperature ranges. However, because of the increasing decomposition rates of these propellant solutions with increase in temperature, very few measurements have been conducted above 200 F. In addition, the accuracy of data is questionable in temperature ranges where decomposition rates are relatively high. This is evident in the discontinuity of some of the data at the higher temperature ranges.

It should also be noted that the data reported for "pure" (or 100 w/o) $H_2O_2$ is questionable since there is some doubt as to the existence of $H_2O_2$ concentrations above 99.7 to 99.8 w/o. Some of the data reported for 100 w/o $H_2O_2$ were obtained by extrapolation of property data of $H_2O_2$ solutions of lower concentration, while other experimental measurements reported on "100 w/o" $H_2O_2$ indicated propellant assays of "99+ percent," "99 ±0.5 percent," etc. Even for most of those studies which report the $H_2O_2$ concentrations, the methods of determining these concentrations are not reported or are based on an assumption of purity related to the purification technique.

Although it is suspected (because of discontinuities in the data) that many of the measurements on the "100 w/o" $H_2O_2$ represent, in reality, measurements on $H_2O_2$ of lower concentrations, properties are reported for 100 w/o $H_2O_2$ wherever an extrapolation (from lower concentrations) seems reasonable. This characterization is of academic interest only because ~ 98 w/o $H_2O_2$ is the highest concentration presently available commercially. Future aerospace industry utilization of higher concentrations appears unlikely because of practical and economical considerations.

Nominal values for physical property data that are recommended as the most representative of the existing data are summarized for the "100", 98, 95, 90, 75, and 70 w/o hydrogen peroxide grades in Table 2.1. All of the data presented are direct experimental determinations or are derived from curve-fits of the experimental data, except for those data referenced with an asterisk; the data referenced with an asterisk were a result of calculations made during the referenced work and based on standard analytical correlations and physical relationships. The absence of data on a particular property is denoted by blank spaces in the tables.

Properties for which property-temperature relationships have been established are noted in Table 2.1 with a figure or another table number; the corresponding property-temperature relationships are shown in Fig. 2.1 through 2.23a and Tables 2.2 through 2.17. The graphical illustrations represent either curve-fits of the best available experimental data or analytical estimations of the property; curve-fits of experimental data are noted with a solid line, while a dashed line designates calculated data. Equations resulting from computer curve-fits of some of the data are presented in attendant discussions.

The origin of the selected data is referenced in each table and figure. A brief discussion of the available data for each property is presented in the following paragraphs.

## 2.2.1 General Identification

The physical classifications under general identification are those properties that are used to identify hydrogen peroxide and its physical state.

2.2.1.1 **Molecular Weight.** The molecular weight of hydrogen peroxide was experimentally determined by freezing point depression (Ref. 2.1 and 2.2) and vapor density (Ref. 2.3) measurements. The results of these studies are comparable to the value of 34.016 calculated from the International Atomic Weights. The mole percent and apparent molecular weight as a function of weight percent $H_2O_2$ for various aqueous solutions of $H_2O_2$, as shown in Fig. 2.1, were calculated from the molecular weights of $H_2O$ and $H_2O_2$ based on the International Atomic Weights.

2.2.1.2 **Freezing Point.** The determination of freezing and melting points of $H_2O_2$-$H_2O$ solutions is relatively difficult because of the large degree of supercooling possible with these solutions. In addition, phase equilibrium measurements (Ref. 2.2) have indicated that solid solutions are not formed in the solidification of concentrated (greater than 65 w/o $H_2O_2$) aqueous solutions of $H_2O_2$; instead, the solid consists of crystals of $H_2O_2$ with occluded mother liquid. Thus, the range of temperatures over which the material melts or freezes is a function of the crystallization pattern of the $H_2O_2$.

The freezing point of "100 percent" $H_2O_2$ has been reported as -0.461 C (31.17 F), -0.43 C (31.23 F), and -0.41 C (31.26 F) in Ref. 2.2, 2.4, and 2.5, respectively. Based on a reported sample purity of 99.97 m/o $H_2O_2$, the freezing point determination of Ref. 2.4 was selected as representative of 100 percent $H_2O_2$. Measurements of the freezing points of aqueous solutions of $H_2O_2$ (Ref. 2.2) indicate eutectics at 45.2 w/o $H_2O_2$ and -52.4 C (-62.3 F), and at 61.2 w/o $H_2O_2$ and -56.5 C (-69.7 F). The results of these measurements, which are graphically illustrated in Fig. 2.2 and 2.2a, represent the temperatures at which 20 to 30 percent of the liquid had solidified. Experimental melting point studies (Ref. 2.6), based on observation of the temperature at which melting was complete, resulted in slightly higher melting temperatures for concentrations above 60 w/o $H_2O_2$.

A variety of experimental studies have produced no significantly effective freezing point depressants for propellant-grade $H_2O_2$ solutions. These studies, described in detail in Ref. 2.3 and 2.6 through 2.9, have shown that many additives will form unstable or shock-sensitive mixtures with $H_2O_2$.

2.2.1.3 Triple Point. The triple point of 99.97 m/o $H_2O_2$ was estimated as 272.74 K (-0.42 C or 31.24 F) from experimental heat of fusion studies (Ref. 2.5). Although no vapor pressure measurements have been made on solid $H_2O_2$, the vapor pressure at the triple point has been calculated (Ref. 2.10) as 0.26 mm Hg (0.005 psia).

2.2.1.4 Normal Boiling Point. The normal boiling points of propellant-grade $H_2O_2$ solutions have not been experimentally determined by conventional means since these points are in a temperature region where thermal decomposition of the $H_2O_2$ is significant. The normal boiling points listed in Table 2.1 and Fig. 2.3

for propellant-grade $H_2O_2$-$H_2O$ solutions represent extrapolations of the vapor pressure data of Section 2.2.2.4 to 1 atmosphere of pressure. Other references (i.e., Ref. 2.11 and 2.12) give very similar boiling points even though these temperatures were calculated from extrapolations of different individual sets of vapor pressure data. The correlation of these individual sets of data, which results in the newly calculated normal boiling points, is discussed in Section 2.2.2.4.

2.2.1.5 Critical Properties. There has been no experimental determinations of critical properties of $H_2O_2$ since the compound undergoes extensive decomposition before the critical temperature is achieved. However, because this property is of academic interest, the critical temperature has been estimated by assuming that the critical temperature/boiling point ratio of $H_2O_2$ is equal to that of water. Based on this technique, a critical temperature ($T_c$) of 458.8 C (857.8 F) has been reported for 100 w/o $H_2O_2$ (Ref. 2.11); another $T_c$ value of 457 C (855 F) for 100 w/o $H_2O_2$, which was alluded to in Ref. 2.12, was reported in Ref. 2.10. Using a vapor pressure equation established in Ref. 2.12, the critical pressure, $P_c$, was calculated (Ref. 2.10) as 214 atmospheres (3140 psia) at the latter $T_c$.

Using the estimated boiling point given in Table 2.1 and correlation technique described above, a $T_c$ of 733 K (460 C, 860 F) is recommended for 100 w/o $H_2O_2$. An estimation technique suggested in Ref. 2.12 ($P_c/T_c$ is equivalent for both $H_2O_2$ and $H_2O$) resulted in a calculated and recommended $P_c$ of 247 atmospheres (3630 psia) for 100 w/o $H_2O_2$ using the $T_c$ value of 733 K. Pseudocritical constants were calculated for the propellant-grade $H_2O_2$-$H_2O$ solutions through the use of Kay's method (Ref. 2.13); the results of these calculations are shown in Table 2.1 and in Fig. 2.3.

## 2.2.2 Phase Properties

Those properties of hydrogen peroxide, which are associated with one particular phase (either solid, liquid, or gas) have been grouped as phase properties.

2.2.2.1 Density. A density of 1.70 gm/cc (106.76 lb/cu ft) was computed for solid 100-percent $H_2O_2$ from X-ray diffraction measurements (Ref. 2.14) at -20 C (-4 F). Density measurements on $H_2O_2$-$H_2O$ solutions during cooling and freezing (Ref. 2.15) indicated that true solid solutions of $H_2O_2$ and $H_2O$ were not formed; this was later verified in Ref. 2.2. Since the occlusion of the mother liquor occurred in freezing, the measured densities were a function of the freezing technique. However, it was noted (Ref. 2.15) that solutions containing $<$ 45 w/o $H_2O_2$ expand during freezing and solutions $>$ 65 w/o $H_2O_2$ contract during freezing.

Experimental determinations of the liquid densities of various $H_2O_2$-$H_2O$ solutions were reported as a function of composition in Ref. 2.6 (at 0 and 18 C), Ref. 2.15 (at 0 C), Ref. 2.16 (at 20 C), and Ref. 2.17 (at 0, 10, 25, 50, and 96 C). In addition, experimental studies have determined the density of 90 w/o $H_2O_2$ from 76 to 193 C (Ref. 2.18), and the density of 98 w/o $H_2O_2$ from 27 to 105 C (Ref. 2.19). The data from these six studies were simultaneously curve fitted by a least-squares computer program, and the following equation was found to adequately (actual deviation for each experimental point was $<$ 0.002 gm/cc) describe the data from 0 to 193 C (32 to 379 F) over a concentration range of 60 to 100 w/o $H_2O_2$.

$$\rho_{(gm/cc)} = 1.0479 + 2.455 \times 10^{-3} W + 1.781 \times 10^{-5} W^2 - 6.76 \times 10^{-4} T_{(C)} - 2.4 \times 10^{-7} T_{(C)}^2 - 3.98 \times 10^{-6} W T_{(C)}$$

where W is weight percent $H_2O_2$.

Converting to English units, this equation becomes:

$$\rho_{(lb/cu\ ft)} = 66.166 + 1.577 \times 10^{-1} W + 1.112 \times 10^{-3} W^2 - 2.31 \times 10^{-2} T_{(F)} - 4.7 \times 10^{-6} T_{(F)}^2 - 1.38 \times 10^{-4} W T_{(F)}$$

The curves described by these equations are graphically illustrated for propellant-grade $H_2O_2$ solutions in Fig. 2.4 and 2.4a, respectively.

Experimental vapor density measurements (Ref. 2.3) at 92 C (165.6 F) show that $H_2O_2$ is not associated in the vapor state. If it is assumed that no decomposition occurs, the vapor density may be calculated through use of the perfect gas law.

2.2.2.2 Coefficient of Thermal Expansion. Using the curve fits of the density data, the coefficients (cubical) of thermal expansion were calculated for propellant-grade $H_2O_2$-$H_2O$ solutions from 0 to 100 C (32 to 212 F) through the following relationship:

$$\alpha = \frac{1}{V} \left(\frac{\partial V}{\partial t}\right)_P$$

Curve fits of these calculations are presented in Fig. 2.5 and 2.5a.

2.2.2.3 Compressibility. The adiabatic compressibilities of $H_2O_2$ solutions were calculated (Ref. 2.16) from experimental density and sonic velocity data covering a temperature range of 3.5 to 33.5 C (38.3 to 92.3 F) and a concentration range of 0 to 93.4 m/o (0 to 96.5 w/o). These data were used to plot the adiabatic compressibilities of propellant-grade $H_2O_2$ solutions shown in Fig. 2.6 and 2.6a.

Although no experimental data have been reported on the isothermal compressibility of $H_2O_2$, the adiabatic compressibility, density, and heat capacity data were used to calculate (Ref. 2.16) an isothermal compressibility of $26.514 \times 10^{-12}$ $cm^2$/dyne ($26.865 \times 10^{-6}$ $atm^{-1}$, $18.281 \times 10^{-5}$ $psia^{-1}$) for 100 w/o $H_2O_2$ at 20 C (68 F).

2.2.2.4 Vapor Pressure. The vapor pressure data resulting from four different experimental measurements (Ref. 2.11, 2.12, 2.20, and 2.21) on various aqueous solutions of $H_2O_2$ over temperature ranges of 0 to 90 C (32 to 194 F) have been correlated. Using a least squares curve-fit computer program, these data were curve-fitted with the following equations (in the metric system):

$$\underline{100\ w/o\ H_2O_2} \quad \log P_{(mm\ Hg)} = 8.92536 - \frac{2482.60}{T_{(K)}} - \frac{24675}{T_{(K)}^{2}}$$

$$\underline{98\ w/o\ H_2O_2} \quad \log P_{(mm\ Hg)} = 7.89728 - \frac{1797.84}{T_{(K)}} - \frac{134089}{T_{(K)}^{2}}$$

$$\underline{95\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{mm Hg})} = 7.68235 - \frac{1647.17}{T_{(K)}} - \frac{154665}{T_{(K)}^{2}}$$

$$\underline{90\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{mm Hg})} = 7.67297 - \frac{1606.47}{T_{(K)}} - \frac{157563}{T_{(K)}^{2}}$$

$$\underline{75\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{mm Hg})} = 7.39108 - \frac{1351.86}{T_{(K)}} - \frac{185863}{T_{(K)}^{2}}$$

$$\underline{70\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{mm Hg})} = 7.42560 - \frac{1354.10}{T_{(K)}} - \frac{181798}{T_{(K)}^{2}}$$

Converting these equations to English units resulted in the following:

$$\underline{100\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{psia})} = 7.21175 - \frac{4468.68}{T_{(R)}} - \frac{79947}{T_{(R)}^{2}}$$

$$\underline{98\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{psia})} = 6.18367 - \frac{3236.11}{T_{(R)}} - \frac{434448}{T_{(R)}^{2}}$$

$$\underline{95\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{psia})} = 5.96874 - \frac{2964.91}{T_{(R)}} - \frac{501115}{T_{(R)}^{2}}$$

$$\underline{90\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{psia})} = 5.95936 - \frac{2891.65}{T_{(R)}} - \frac{510504}{T_{(R)}^{2}}$$

$$75\ \text{w/o}\ H_2O_2\quad \log P_{(\text{psia})} = 5.67747 - \frac{2433.35}{T_{(R)}} - \frac{602196}{T_{(R)}^{2}}$$

$$\underline{70\ \text{w/o}\ H_2O_2}\quad \log P_{(\text{psia})} = 5.71199 - \frac{2437.38}{T_{(R)}} - \frac{589026}{T_{(R)}^{2}}$$

The equations are illustrated graphically in Fig. 2.7 and 2.7a, where the data are extrapolated to temperatures above 90 C (194 F) by assuming a linear relationship between the temperatures for which $H_2O_2$ solutions and water have the same vapor pressures. These extrapolations were used to determine the pseudo-boiling points (the temperatures where the pressures are equivalent to 760 mm Hg) of the propellant-grade $H_2O_2$ mixtures.

2.2.2.5 **Vapor-Liquid Equilibrium**. Vapor-liquid equilibrium compositions of $H_2O_2$-$H_2O$ solutions were determined experimentally in two different studies (Ref. 2.12 and 2.21). Although comparable, there are slight differences in the data at some of the temperatures. The data of Ref. 2.12 were used in Ref. 2.22 to plot vapor composition and vapor-liquid equilibrium, and to calculate and plot activity coefficients for the system. These plots are shown in Fig. 2.8 through 2.10.

Calculations (Ref. 2.23) of saturation pressure, activity coefficients, and vapor compositions have been made for three different $H_2O_2$-$H_2O$ solutions (90, 81.5, and 65.4 w/o) at high temperatures and pressures. The computation of these data, which are shown in Table 2.2, are described in detail in Ref. 2.23. Although these computations were based on assumptions of $H_2O_2$ critical constants that are different (critical temperature = 457 C, critical pressure = 215 atmospheres) from the values recommended in this handbook, corrections to Table 2.2 are slight.

2.2.2.6 **Surface Tension**. The surface tensions of $H_2O_2$-$H_2O$ solutions have been experimentally determined (Ref. 2.24) as a function of composition at 0 C (32 F) and 20 C (68 F). Graphical representations of the data are shown in Fig. 2.11 and 2.11a.

## 2.2.3 Thermodynamic Properties

The $H_2O_2$ properties which define energy changes in the physical transitions through the various solid, liquid, and gas states, as well as in chemical changes, have been listed under thermodynamic properties.

2.2.3.1 Heat of Formation. The heats of formation ($\Delta H_F$) of propellant-grade $H_2O_2$ solutions were calculated in this study from heat of dissociation data given in Ref. 2.25. Heat of fusion, heat of vaporization, heat of mixing, and heat capacity data used to characterize the heat of formation over a range of temperatures, phases, and concentrations are given in subsequent sections. Data for the aqueous solutions are presented as heats of formation of the solution (which includes the heat of formation contributions of both $H_2O$ and $H_2O_2$, and the heat of mixing).

The $\Delta H_F$ data for the liquid and solid phases of propellant-grade $H_2O_2$ solutions are given in Tables 2.3 through 2.8 and Fig. 2.12 and 2.12a. Figures 2.13 and 2.13a illustrate the $\Delta H_F$ of the liquid at 25 C (77 F) as a function of composition. The heats of formation of the vapor of propellant-grade $H_2O_2$-$H_2O$ solutions are given in Tables 2.9 through 2.14.

2.2.3.2 Heat of Fusion. The heats of fusion of propellant-grade $H_2O_2$ solutions were taken from the experimental studies of Ref. 2.2; these data are shown in Tables 2.3 through 2.8 as the change in enthalpy at the freezing point.

2.2.3.3 Heat of Vaporization. The experimental data of Ref. 2.26 were used to plot the heats of vaporization of $H_2O_2$-$H_2O$ solutions as a function of temperature; curve-fits of the data at 0, 25, 45, and 60 C (32, 77, 113, and 140 F) are shown in Fig. 2.14

and 2.14a. Heats of vaporization of propellant-grade $H_2O_2$ solutions at other temperatures can be obtained by computing the difference in the heats of formation of the liquid (Tables 2.3 through 2.8) and vapor (Tables 2.9 through 2.14) phases of the $H_2O_2$-$H_2O$ solutions at the corresponding temperatures and $H_2O_2$ concentrations.

2.2.3.4. Heat of Sublimation. The heat of sublimation of 100 w/o $H_2O_2$ has been calculated (Ref. 2.10) from the heats of fusion and vaporization as 457.8 cal/gm (824 Btu/lb).

2.2.3.5 Heat of Mixing. Graphical representations of the heats of mixing of propellant-grade $H_2O_2$-$H_2O$ solutions, shown in Fig. 2.15 and 2.15a, were plotted from smoothed data given in Ref. 2.26. These data represent experimental data of the referenced work, previous experimental studies (Ref. 2.25), and their extrapolation to higher temperatures for comparison with the experimental data of Ref. 2.12. Excellent agreement is noted between the data of Ref. 2.26 and Ref. 2.12 except in the 20 to 30 w/o $H_2O_2$ concentration range.

2.2.3.6 Heat of Decomposition. The heats of decomposition, graphically represented in Fig. 2.16 and 2.16a, were converted from smoothed data from the experimental studies of Ref. 2.25. The figures illustrate the heats of decomposition of propellant-grade $H_2O_2$-$H_2O$ solutions with decomposition to either liquid water or water vapor.

2.2.3.7 Heat Capacity. The heat capacities of solid and liquid propellant-grade $H_2O_2$-$H_2O$ solutions are shown in Tables 2.8 through 2.13 and in Fig. 2.17 and 2.17a from 0 to 400 K (0 to 720 R). The heat capacities of solid $H_2O_2$ were taken from the data of Ref. 2.5. Since solid solutions of $H_2O_2$ and $H_2O$ are not formed in the concentration region of interest, the heat capacities of the solid phases of propellant-grade $H_2O_2$-$H_2O$ solutions were assumed to be the sum of the individual heat capacity contributions of solid $H_2O$ and solid $H_2O_2$.

The liquid heat capacities were curve-fitted from the experimental data of Ref. 2.25 and 2.26; these studies indicated that the change in heat capacity of an $H_2O_2$-$H_2O$ solution of constant composition over the indicated temperature range was of the order of the accuracy of the experimental data. Experimental measurements of liquid heat capacity were not conducted below 0 C (32 F); therefore, the heat capacity was estimated in this region using the heat capacity of supercooled $H_2O$ and the extrapolated heat capacity contribution of the $H_2O_2$.

During experimental heat transfer studies at relatively high temperatures (Ref. 2.18), the heat capacities of 90 w/o $H_2O_2$ were indirectly determined from heat transfer data over a temperature range of 240 to 380 F. An equation was developed for the data which indicated an increasing deviation of the experimental data from the curve fit of the data with increasing temperature. The differences in these data from extrapolations of the data presented in Fig. 2.17 and 2.17a, which are $\leq$0.01 Btu/lb-F (cal/gm-C), are assumed to be the result of $H_2O_2$ decomposition in the experimental study.

The heat capacities of the vapor phase of propellant-grade $H_2O_2$ solutions are given in Tables 2.9 through 2.14. The origin of these data is discussed in Section 2.2.3.9.

2.2.3.8 Enthropy and Enthalpy. The entropy and enthalpy of the solid and liquid phases of propellant-grade $H_2O_2$ solutions were calculated from the other thermodynamic functions given in Tables 2.3

through 2.8. The basis for the vapor-phase entropy and enthalpy data on propellant-grade $H_2O_2$ solutions, given in Tables 2.9 through 2.14 is discussed in Section 2.2.3.9.

2.2.3.9 **Vapor-Phase Thermodynamic Properties.** The thermodynamic properties of hydrogen peroxide vapor were calculated (Ref. 2.27) from structural data. These data, which replaced earlier reported data (Ref. 2.28), were based on new spectroscopic measurements (Ref. 2.29) and new calorimetric data (Ref. 2.5 and 2.25). The primary difference in the presently accepted values and those reported earlier are in the internal rotation values.

The structural values used by Ref. 2.27 in the computation of the vapor-phase thermodynamic properties, given in Tables 2.9 through 2.14, are:

$r$ O-H = 0.965 Å

$r$ O-O = 1.49 Å

$\alpha$ OOH = 100 degrees

$\varphi$ = 95 degrees

$I_A = 2.785 \times 10^{-40}$ gm-cm$^2$

$I_B = 34.0 \times 10^{-40}$ gm-cm$^2$

$I_C = 33.8 \times 10^{-40}$ gm-cm$^2$

$I_{Red} = 0.696 \times 10^{-40}$ gm-cm$^2$

$\nu_1 = 3610$ cm$^{-1}$

$\nu_2 = 1350$ cm$^{-1}$

$\nu_3 = 880$ cm$^{-1}$

$\nu_4 = 520$ cm$^{-1}$

$\nu_5 = 3610$ cm$^{-1}$

$\nu_6 = 1266$ cm$^{-1}$

$\sigma = 2$

### 2.2.4 Transport Properties

All properties of propellant-grade solutions of $H_2O_2$ that involve the transfer of mass or energy at the molecular level are presented in the following paragraphs.

2.2.4.1 Viscosity. Experimental determinations of the viscosity of liquid $H_2O_2$-$H_2O$ solutions ranging in composition from 0 to 100 w/o $H_2O_2$, have been reported in Ref. 2.6 (0 and 18 C), Ref. 2.24 (0 and 20 C), and Ref. 2.22 (0, 25, and 50 C). Curve-fits of these data at 0, 20, 25, and 50 C (32, 68, 77, and 122 F) are graphically illustrated as a function of w/o $H_2O_2$ (from 50 to 100 w/o) in Fig. 2.18 and 2.18a. In addition, viscosity measurements have been conducted on 98 w/o $H_2O_2$ (Ref. 2.19) from 20 to 85 C (68 to 185 F) and on 90 w/o $H_2O_2$ (Ref. 2.18) from 77 to 325 F (25 to 162.8 C). The data for 98 and 70 w/o $H_2O_2$ from the various sources has been plotted as a function of temperature and compared to the viscosity of water in Fig. 2.19 and 2.19a.

The viscosity of the vapor phase of $H_2O_2$-$H_2O$ solutions at 1 atmosphere has been calculated (from experimentally determined data) as reported in Ref. 2.30. An equation (Ref. 2.30) representing these data from 100 to 300 C (212 to 540 F) with an estimated precision of ±2 percent is given as:

$$\mu \text{ (micropoises)} = 134 + 0.35 [T_{(C)} - 100] - 14 Y$$

where

$Y$ = mole fraction $H_2O_2$ in vapor

This equation, comparing the vapor viscosity of water with 100 w/o $H_2O_2$, is graphically represented in Fig. 2.20.

2.2.4.2 Thermal Conductivity. Experimental measurements of the thermal conductivity of $H_2O_2$-$H_2O$ solutions have been limited to determinations (Ref. 2.22) on 98.2 w/o $H_2O_2$ at 0 C (32 F) and 25 C (77 F) and on 50 w/o $H_2O_2$ at 25 C; resulting thermal conductivities were 0.321, 0.339, and 0.347 Btu/hr-ft-F, respectively.

Using the two experimental data points, the thermal conductivity of 98.2 w/o $H_2O_2$ was extrapolated to the critical point (Ref. 2.31). This extrapolation, shown in Fig. 2.21, used $H_2O$ as a reference substance and assumed no decomposition and a thermal conductivity of 0.100 Btu/hr-ft-F at the critical point.

Experimental heat transfer studies (Ref. 2.19) indicated that the estimated thermal conductivities reported in Ref. 2.31 agree reasonably well with those calculated from the experimental heat transfer data.

### 2.2.4.3 Coefficient of Diffusion

**Coefficient of Diffusion**. The experimental determination of the diffusion coefficient of liquid $H_2O_2$ into water has been reported (Ref. 2.32) for 0.17 w/o $H_2O_2$ from 0 to 40 C (32 to 104 F) and for 0.019, 1.44, and 7.92 w/o $H_2O_2$ at 20 C (68 F). At 20 C (68 F), the diffusion coefficients were $<1.2$ $cm^2$/day for the concentrations studied.

The diffusion coefficient of $H_2O_2$ vapor into air was experimentally determined (Ref. 2.33) in a vertical tube as 0.188 $cm^2$/sec at 60 C (140 F) and 1-atmosphere pressure. This can be compared to a diffusion coefficient of 0.320 $cm^2$/sec reported (Ref. 2.34) for water vapor under identical conditions.

### 2.2.4.4 Sonic Velocity

**Sonic Velocity**. The velocity of sound was experimentally measured (Ref. 2.16) in $H_2O_2$-$H_2O$ solutions from 3.5 to 33.5 C (38.3 to 92.3 F). These data are plotted for propellant-grade $H_2O_2$ solutions in Fig. 2.22 and 2.22a.

## 2.2.5 Electromagnetic Properties

The electrical, magnetic, and electromagnetic (optical) properties of $H_2O_2$ have been grouped as electromagnetic properties.

These properties generally are related to the electronic structure of the atoms in contrast to the transport properties which involve only molecular movement.

2.2.5.1 Index of Refraction. The refractive indexes of $H_2O_2$-$H_2O$ solutions were experimentally determined (Ref. 2.15) using the sodium D line. The data for propellant-grade $H_2O_2$-$H_2O$ solutions are presented in Table 2.15 at 25 C (77 F) with a temperature correction guide.

2.2.5.2 Dipole Moment. Calculated dipole moments of $H_2O_2$ were reported as 2.22 Debye (or $2.22 \times 10^{-18}$ esu-cm) and 2.05 Debye in Ref. 2.35 and 2.36, respectively. In addition, a value of 2.26 Debye was estimated (Ref. 2.37) from the Stark effect, and a value of 2.13 Debye was determined (Ref. 2.38) for $H_2O_2$ in dioxane. The latter value was selected as the representative dipole moment for $H_2O_2$.

2.2.5.3 Dielectric Constant. Figures 2.23 and 2.23a show the dielectric constants of propellant-grade $H_2O_2$-$H_2O$ solutions as a function of temperature. These data were interpolated from the experimental studies reported in Ref. 2.39, in which the dielectric constants were determined as a function of composition at constant temperatures from -40 to 30 C (-40 to 86 F). Because of the supercooling of the $H_2O_2$-$H_2O$ solutions, measurements were obtained on the liquid below the freezing point. The data from the measurements on 100 w/o $H_2O_2$ were curve-fitted from -60 to 30 C (-76 to 86 F) to the following equation (Ref. 2.40):

$$\epsilon = 84.2 - 0.62\,T_{(C)} + 0.0032\,T_{(C)}^2$$

2.2.5.4 Electrical Conductivity. The conductivity of "pure" $H_2O_2$ has been reported by several investigators with values ranging from 2 to 0.39 micromhos (microohms$^{-1}$). Experimental studies (Ref. 2.41) of the conductivity of unstabilized $H_2O_2$ were conducted as a possible means of determining its purity. The results of this study are summarized as follows:

1. Fractional crystallization reduced the conductivity of commercial 90 w/o $H_2O_2$ (11.5 microohms$^{-1}$ at 25 C) to approximately one-half (5.0 microohms$^{-1}$ at 25 C) of its initial value, while increasing its concentration to 98+ w/o $H_2O_2$.
2. Distillation of the crystallized $H_2O_2$ reduced its specific conductance to ~2 micromhos. This value compared with that reported in earlier studies (Ref. 2.42).
3. A second distillation of the crystallized and once-distilled $H_2O_2$ reduced its specific conductance to 1.2 micromhos; this value was still greater than that reported in Ref. 2.43 and 2.44.
4. The specific conductance of both 98 w/o $H_2O_2$ and deionized water increased on storage in contact with Pyrex glass. A conclusion of these studies indicated that only a rough correlation between low electrical conductivity and high stability was found (or that electrical conductivity per se is not a reliable indicator of stability).

The electrical conductivity of both water and hydrogen peroxide is increased by the addition of one to the other.

2.2.5.5 Magnetic-Optic Rotation (Verdet Constant). Although not optically active, $H_2O_2$, when placed in a magnetic field, will [illegible] rotate the plane of polarized light. This is expressed as:

$$\alpha = k_v \ell H$$

where

$\alpha$ = degree of rotation

$\ell$ = path length

$H$ = field strength

$k_v$ = Verdet constant

The Verdet constant, $k_v$, as reported in Ref. 2.45 at 10 C (50 F), is shown for various $H_2O_2$-$H_2O$ solutions in Table 2.16.

2.2.5.6 Magnetic Susceptibility. Hydrogen peroxide is diamagnetic. The magnetic susceptibility of liquid $H_2O_2$ has been summarized in Ref. 2.10.

Values of $-0.73 \times 10^{-6}$ cgs-emu/cc at 10 C, $-0.50 \times 10^{-6}$ cgs-emu/g, $-17 \times 10^{-6}$ cgs-emu/g mol, and 0.9999908 are reported for the volume susceptibility (K), mass susceptibility ($X_g$), molar susceptibility (Xm), and permeability (P), respectively. In addition, an equation expressing the mass susceptibility of $H_2O_2$-$H_2O$ solutions at 10 C (50 F) is given as:

$$X_g \times 10^6 = -0.720 + 0.218\,w$$

where

$w$ = weight fraction $H_2O_2$

The susceptibility of the solid becomes more positive upon freezing, while the susceptibility of the vapor is assumed to be the same as the liquid.

2.2.5.7 Other Molecular and Electromagnetic Properties. A number of miscellaneous molecular and electromagnetic properties have been summarized for $H_2O_2$ in Table 2.17. The origin of these data is referenced in the table.

### 2.2.6 Structure and Spectra

The equilibrium geometry of hydrogen peroxide was established by an electron diffraction study (Ref. 2.48). This was supported by an X-ray study (Ref. 2.14) with limited least-squares data reduction, an infrared study (Ref. 2.49 and 2.50), and a microwave study (Ref. 2.37 and 2.51). The results of these studies are summarized in Table 2.18. The infrared study may be regarded as definitive, although the structure of the solid, as determined by X-ray, may be appreciably different from the gas phase. The X-ray study may be questioned, however, because the data analysis used visual intensity estimation and primitive numerical machines. The rotational constants measured in the infrared are $A' = 10.356\ \mathrm{cm}^{-1}$, $B' = 0.8656\ \mathrm{cm}^{-1}$, $C' = 0.8270\ \mathrm{cm}^{-1}$, $D_J = 4.5 \times 10^{-6}\ \mathrm{cm}^{-1}$, $D_K = 7.5 \times 10^{-4}\ \mathrm{cm}^{-1}$, and $D_{JK} = -2 \times 10^{-5}\ \mathrm{cm}^{-1}$. Dipole moments of 3.15 ±0.05 D and 3.24 ±0.05 D were measured (Ref. 2.51) for each of the two potential minima. A far infrared study (Ref. 2.50) showed the angle $\tau$ has two equilibrium values (with the lowest at 111.5 degrees ±0.5) and determined an accurate hindered-rotation potential function. The best geometric parameters are those underlined in Table 2.18.

Hydrogen peroxide forms tetragonal crystals, space group $D_4^4 - P4_12_1$, upon freezing (Ref. 2.14). There are four molecules in the unit cell of dimensions $a = 4.06\ \text{Å}$ and $c = 8.00\ \text{Å}$. The crystal structure has been completely determined, and the volume of the unit cell is $131.9\ \text{Å}^3$ (Ref. 2.14). This gives a crystal density of 1.70 gm/cc.

Hydrogen peroxide is the simplest molecule having an internal rotation motion, and, therefore, has had fairly extensive study with respect to absorption spectra. Hindered internal rotation effects are observed in all regions of the spectrum. Extensive studies have been conducted on the vapor, the crystalline solid, and dilute solutions. Less work has been spent on the concentrated liquid solutions, because of decomposition effects and the difficulty in finding suitable window materials. Since the spectrum as a whole is very complicated, it is considered beyond the scope of this handbook; thus, references to $H_2O_2$ spectrum characterization are provided as a guide for interested individuals.

The infrared absorption by $H_2O_2$ is not very useful for chemical analysis because the spectrum is quite similar to that of water and since suitable window materials are not widely available. Ultraviolet absorption by $H_2O_2$ is quite strong, and (although Beer's law does not hold strictly) if the solution is clear and transparent to ultraviolet, direct spectrophotometry measurements are suitable for analysis of dilute solutions. The ultraviolet spectrum of concentrated hydrogen peroxide has been reported for 50 and 90 w/o solutions in Ref. 2.39, and for 55 and 99 w/o hydrogen peroxide solutions in Ref. 2.24. The infrared absorption spectrum of $H_2O_2$ has been reported in Ref. 2.50, 2.52, and 2.53. The Raman spectrum of concentrated hydrogen peroxide (99+ percent) is probably covered best in Ref. 2.39.

## 2.3 CHEMICAL PROPERTIES

Hydrogen peroxide is a strong oxidizing agent in either acid or alkaline solutions; however, with a very strong oxidizing agent such as $MnO_4^-$, it will also behave as a reducing agent.

Hydrogen ion concentration (pH), the presence and nature of catalysts, and temperature are important controlling parameters in hydrogen peroxide reactions. By proper choice of reaction conditions, it is possible to modify the oxidizing action of concentrated hydrogen peroxide solutions. As an oxidizing agent, hydrogen peroxide has the distinct advantage of producing only water as a by-product. Hydrogen peroxide also forms simple addition complexes, forming compounds similar to hydrates. These compounds are normally called hydroperoxidates. These are generally accepted as hydrogen-bonded compounds, which are analogous to anion water compounds. Hydroperoxidates are readily formed with highly electronegative atoms such as nitrogen, oxygen, and fluorine. Amino groups form stronger bonds with peroxide than carboxyl or hydroxyl groups.

Compilations of typical hydrogen peroxide reactions have been reported in Ref. 2.10 and 2.55. These compilations were combined and are presented in Table 2.19 along with references to the original work.

## 2.4 SOLUBILITY AND MISCIBILITY

Because of hydrogen peroxide's chemical and thermodynamic activity (as noted in Section 2.3), precautions should be observed when considering solutions of $H_2O_2$ with various organic and inorganic compounds. Although violent reactions upon mixing are the exception, such reactions have been observed. Many $H_2O_2$ solutions may be fairly stable when undisturbed but are subject to violent detonation under certain conditions. The addition of any material which may be oxidized or reduced should be suspect, particularly as the relative concentrations approach stoichiometric proportions. For these reasons, it is suggested that appropriate references be consulted in detail to define the chemical nature of the proposed solution as well as the solubility of the solute before solutions of $H_2O_2$ with other materials are attempted.

The solubility and miscibility of hydrogen peroxide and its aqueous solutions with a number of organic and inorganic compounds are referenced in detail in Ref. 2.10. In general, concentrated $H_2O_2$ solutions are completely miscible with most organic liquids (including ethanol, isopropanol, acetone, ethyl cellosolve, pyridine, etc.) that are miscible with water in all proportions. In addition, hydrogen peroxide is more miscible than water in a number of organic materials, such as methyl methacrylate, dimethyl and diethyl phthalate, ethyl acetate, and aniline. Compounds with which hydrogen peroxide is nearly immiscible include petroleum ether, toluene, styrene, carbon tetrachloride, chloroform, kerosene, fuel oil, and gasoline.

Hydrogen peroxide and its aqueous solutions also possess, in general, solvent or solute relationships that are similar to water. The results of several experiments show that sodium fluoride, potassium nitrate, various potassium or sodium phosphates, potassium chloride, and sodium or potassium sulfate are more soluble in $H_2O_2$ than in water. Sodium nitrate, sodium chloride, silver nitrate, lead nitrate, and lithium nitrate and sulfate are less soluble in $H_2O_2$ than in water. Chlorine and iodine are only slightly soluble in anhydrous $H_2O_2$.

In consideration of the materials compatibilities of various lubricants with $H_2O_2$, the solubilities of several organic compounds in propellant-grade $H_2O_2$ are discussed in Table 4.14a, Section 4.

## 2.5 GELATION

Results of gel studies on hydrogen peroxide are given in detail in Ref. 2.99 and 2.100.

## 2.6 HEAT TRANSFER PROPERTIES

Since heat transfer involves a combination of phase, thermodynamic, and transport properties, as well as some consideration of chemical kinetics, this section on heat transfer properties has been included as part of the physico-chemical properties. This section is designed as a reference guide and summary of the various experimental heat transfer studies that have been conducted on propellant-grade hydrogen peroxide solutions.

Experimental heat transfer studies on 90 w/o $H_2O_2$ solutions (reported in Ref. 2.101) indicated that a high flux heat transfer, usually associated with boiling, was obtained from a 347 stainless-steel surface to liquid 90 w/o $H_2O_2$ as a result of the $H_2O_2$ decomposition mechanism. This decomposition, which simulates boiling by the liberation of gas bubbles at the heat transfer surface, is accelerated with temperature increase of the surface. Figure 2.24 illustrates the magnitude of this effect, as well as the lesser effect of pressure and liquid temperature, in terms of heat flux. Because of these effects, the study showed that the temperature difference between the surface and liquid was not significant.

An extension of these studies to high fluid velocities and moderately high temperature differences was reported in Ref. 2.102. At high flowrates and high Reynolds numbers (where decomposition is limited by the short liquid residence time), the resultant heat transfer data agreed with that expected for forced convective heat transfer. It was found that heat fluxes as high as 11.75 Btu/sq in.-sec (at liquid velocities of ~ 80 ft/sec) could be obtained with 90 w/o $H_2O_2$ without complication by decomposition of the hydrogen peroxide. A least-squares fit of the heat transfer data obtained on 90 w/o $H_2O_2$ resulted in the following expression:

$$(N_{Nu})_f = 0.0287\,(N_{Re})_f^{0.8}(N_{Pr})_f^{1/3}$$

The standard deviation of the experimental data from this equation was 10.2 percent.

Heat transfer studies in the forced convective region of both 90 w/o and 98 w/o $H_2O_2$ were reported in Ref. 2.103. Peak heat fluxes of 7.80 Btu/sq in.-sec were measured for 90 w/o $H_2O_2$ at fluid velocities of 41.3 ft/sec. The results obtained for peak heat flux of 98 w/o $H_2O_2$ at the conditions investigated are shown in Fig. 2.25. The correlation of the data on 98 w/o $H_2O_2$ with the Dittus-Boelter, Colburn, and Sieder-Tate equations (Fig. 2.26 through 2.28, respectively) indicated better agreement of the data with the Dittus-Boelter relationship. It has been suggested, however, that some of the apparently low heat transfer coefficients, indicated by the correlations of Fig. 2.26 through 2.28, may be due to slight scaling (oxidation) of heat transfer surfaces.

A current study on the use of 98 w/o hydrogen peroxide for regeneratively cooled rocket engines has reported (Ref. 2.104) that during 18 experimental tests (with fluid velocities from 25 to 198 ft/sec, pressures from 2000 to 4700 psia, and feed temperatures from 60 to 240 F), heat fluxes up to 48.2 Btu/sq in.-sec were achieved. It was found that the heat flux at burnout (under the conditions tested) was directly proportional to the fluid velocity by the relationship: heat $\text{flux}_{BO}$ = 0.21 x velocity. These results indicated good correlation of heat flux and fluid velocity with the studies of Ref. 2.102 and 2.103. During these tests, no appreciable difference in heat transfer could be associated with feed temperature, and no detectable decomposition was evident. Four similar tests with 90 w/o hydrogen peroxide indicated no discernible differences from the results of the 98 w/o hydrogen peroxide tests. As in the studies of Ref. 2.103, the Dittus-Boelter correlation was found to represent the data more closely than either the Colburn or Sieder-Tate relationships.

The results of all of these studies have shown that hydrogen peroxide has coolant properties comparable to those of water. Of course, the difficulty in its use as a regenerative coolant lies in the limited stability of the $H_2O_2$ at higher temperatures. As a result, various bulk liquid temperature limits have been suggested and established in the use of $H_2O_2$ as a regenerative coolant. These limits range from established (Ref. 2.105) maximum allowable temperatures of 225 F (with a 105 F rise over inlet temperature) to suggested operating limits (Ref. 2.106) of 250 F (with red line conditions at 275 F). More detailed analysis of minimum safe design criteria of $H_2O_2$ regenerative-cooling systems, based on the available data from various sources, is presented in terms of ultimate heat flux and fluid velocity in Ref. 2.107. Additional analysis of transient heat transfer for an $H_2O_2$ regeneratively cooled engine model are given in Ref. 2.108.

## 2.7 IGNITION CHARACTERISTICS

Although ignition characteristics are system-related parameters, they are also a direct indication of chemical reactivity and/or stability. As such, these characteristics have been included as a part of the Physico-Chemical Properties Section of this handbook. However, because a detailed characterization of these parameters would involve a discussion of system design variables (such as configuration, intended use environment, operating sequence, etc.) that are beyond the intended scope of this handbook, this review of hydrogen peroxide ignition characteristics is limited to a general and brief summary and reference guide to various ignition studies previously conducted. In addition, this summary is limited further by the security classification of many of these studies as opposed to the unclassified nature of this handbook. For the purpose of clarity, the characterization of hydrogen peroxide ignition is presented in terms of its two primary application areas: monopropellant systems and bipropellant systems.

### 2.7.1 Monopropellant Systems

Studies of the controlled decomposition process, that characterize hydrogen peroxide's use as a monopropellant, are given in Section 7.2. As a result of these studies, which are detailed and referenced in Section 7.2, the initiation period for hydrogen peroxide decomposition in a monopropellant chamber are fairly well-defined for all propellant-grade concentrations. As expected, all the studies demonstrate the effect of many variables, such as the initiating source and type (catalyst or thermal bed), injection technique, chamber configuration, hydrogen peroxide concentration, hydrogen peroxide inlet temperature, initial chamber temperature, exit pressure, etc., on the start transient. (The start transient is defined in these efforts as the time period from injection of hydrogen peroxide into the decomposition chamber to the achievement of 90-percent of the operating chamber pressure.)

In general, the start transient for a hydrogen peroxide catalytic monopropellant decomposition chamber normally ranges from 50 to 150 ms. This start transient is typical of all of the catalysts used in the decomposition of hydrogen peroxide concentrations ranging from 76 w/o (Ref. 2.109) to 98 w/o (Ref. 2.18, 2.110 and 2.111).

The greatest effect on this typical start transient is caused by variation in the hydrogen peroxide and/or catalyst bed temperature. Laboratory studies (Ref. 2.41) have demonstrated the lack of reaction between solid or super-cooled hydrogen peroxide and a typical catalytic material, while studies with actual engine catalyst beds (Ref. 2.110) have shown limited initiation of decomposition and excessive start transient periods when the temperature approaches the propellant's freezing point. However, the low temperature start characteristics of various catalyst beds have been improved through special design of the catalyst chamber and special treatment of the catalyst bed (Ref. 2.18, 2.110, and 2.111). Conversely, an increase in propellant or catalyst bed temperature (such as experienced in pulsing or other heat feedback operations) has resulted in start transients as low as 10 ms (Ref. 2.18, 2.104, 2.109, 2.110, and 2.111).

Although exit pressure has a slight effect on the start transient, this effect is usually within the ranges noted above and controlled by the temperature effects. Of course the start transients are affected by the catalyst life and generally are the best indication of the decline in catalytic effectiveness.

The start transients in a hydrogen peroxide thermal decomposition chamber are entirely related to the technique and configuration employed. Since this concept depends on the initial heating of a thermal pack (see Section 7.2.2) prior to injection of the hydrogen peroxide, the start transient of the main hydrogen peroxide stream should approach the hot bed start transients (~ 10 ms) noted above. However, studies with both 90 w/o (Ref. 2.18) and 98 w/o (Ref. 2.113) have indicated that adequate heating of the thermal pack may require periods ranging

500 ms to several minutes depending on the technique employed. Hypergolic slugs of hydrazine containing mixed cyanide salts (Ref. 2.18) have produced initial start transients (i.e., the period measured from injection of the hypergol) of 10 to 20 ms, but this technique required 300 ms hydrogen peroxide leads and 500 ms hypergol injection periods.

## 2.7.2 Bipropellant Systems

Although some studies have indicated that 90 w/o and 98 w/o hydrogen peroxide solutions are hypergolic (i.e., ignites without producing damaging overpressures to the system) with the hydrazine and 50 w/o $N_2H_4$-50 w/o $(CH_3)_2N_2H_2$ fuels (Ref. 2.111), other studies (Ref. 2.18) have indicated that the hypergolicity of 90 w/o hydrogen perioxide with both hydrazine and $(CH_3)_2N_2H_2$ is questionable. Ignition delays (e.g., the time period from injection of the second propellant into the combustion chamber to 90 percent of the designed chamber pressure) of ~ 5 to 25 ms were reported for $H_2O_2/N_2H_4$ systems in Ref. 2.111; however, large overpressures (e.g., the peak pressure to chamber pressure ratio) and erratic chamber pressure fluctuations were demonstrated in these systems. In the studies reported in Ref. 2.18, which demonstrated ignition delays for this system of 10 to 109 ms (with average delays of 35 to 52 ms recorded for various mixture ratios), it was concluded that hypergolicity was marginal and unreliable.

As a result of these and similar studies of other hydrogen peroxide bipropellant systems, including the $H_2O_2/CH_3N_2H_3$ (Ref. 2.111) and $H_2O_2/B_5H_9$ (Ref. 2.113) systems, it is concluded that the hypergolicity of hydrogen peroxide with various fuels is, at best, marginal. For this reason many hydrogen peroxide bipropellant systems utilize hydrogen peroxide decomposition gases (resulting from injection of the hydrogen peroxide in a catalyst chamber upstream of the main combustion chamber) as the ignition source. Through the use of this concept, successful system ignition has been demonstrated with various liquid (including those noted above, as well as with JP-5 in the AR-2 system), solid (Ref. 2.114) and heterogeneous (Ref. 2.104) fuels. Ignition delays between the hot decomposition gases and the fuels are minimal (5 to 10 ms), although the system design controls the overall start transient period (i.e., from injection of the hydrogen peroxide into the catalyst chamber to the achievement of main chamber combustion). Many system designs employ only a small "pilot light" catalyst chamber with subsequent main stream liquid injection (which bypasses the catalyst chamber), while other systems utilize prior decomposition of all of the hydrogen peroxide throughout the operation of the bipropellant system.

The use of hypergols in the ignition of hydrogen peroxide-oxidized bipropellant systems has been studied (Ref. 2.18) with the hydrazine, $(CH_3)_2N_2H_2$ (UDMH), and JP-5 fuels. In these studies, which were designed to demonstrate the feasibility of direct liquid injection of 90-percent hydrogen peroxide into bipropellant chambers, relatively smooth and rapid ignition was achieved with all three fuels using nitrogen tetroxide as the hypergol for the first two fuels and aluminum triethyl with the latter fuel. In addition, the use of mixed cyanide salts as an ignition aid to the $H_2O_2/N_2H_4$ system is noted in Ref. 2.18.

## 2.8 REFERENCES

2.1 Giguere, P. A. and O. Maass, "Solid Solutions of Hydrogen Peroxide and Water," *Can. J. Res.*, *18B*, 66-73 (1940).

2.2 Foley, W. T. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. II. Phase Equilibrium in the System Hydrogen Peroxide-Water," *Can. J. Chem.*, *29*, 123-32 (1951).

2.3 Matheson, G. L. and O. Maass, "Properties of Pure Hydrogen Peroxide. VI.," *J. Am. Chem. Soc.*, *51*, 674-87 (1929).

2.4 Secco, E. A., Ph.D. Thesis, Laval University, Quebec, Canada, 1953.

2.5 Giguere, P. A., I. D. Liu, J. S. Dugdale, and J. A. Morrison, "Hydrogen Peroxide: the Low-Temperature Heat Capacity of the Solid and Third-Law Entropy," *Can. J. Chem.* *32*, 117-28 (1954).

2.6 Maass, O. and W. H. Hatcher, "Properties of Pure Hydrogen Peroxide. III," *J. Am. Chem. Soc.*, *44*, 2472-80 (1922).

2.7 QFR-LR-15 and 19, *Freezing Point Depressants for $H_2O_2$*, FMC Corporation, Buffalo, New York, Contract NOa(s) 53-1034-c, 1963.

2.8 LR-E2, *Development of Freezing Point Depressants for 90% Hydrogen Peroxide*, FMC Corporation, Buffalo, New York, Contract NOa(s)-52-779-c, 1954.

2.9 LR-78, Part I, *Final Report, Low Freezing Hydrogen Peroxide-Based Propellants and Oxidants*, FMC Corporation, Buffalo, New York, Contract NOa(s)-53-1034-c.

2.10 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, *Hydrogen Peroxide*, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

2.11 Maass, O. and P. G. Hiebert, "The Properties of Pure Hydrogen Peroxide. V. Vapor Pressure," *J. Am. Chem. Soc.*, *46*, 2693-2700 (1924).

2.12 Scatchard, G., G. M. Kavanagh, and L. B. Ticknor, "Vapor-Liquid Equilibrium. VIII. Hydrogen Peroxide-Water Mixtures," *J. Am. Chem. Soc.*, *74*, 3715-20 (1952).

2.13 Kay, W. B., "Density of Hydrocarbon Gases and Vapors at High Temperature and Pressure," *Industrial and Engineering Chemistry*, *28*, 1014 (1936).

2.14 Abrahams, S. C., R. L. Collin, and W. N. Lipscomb, "The Crystal Structure of Hydrogen Peroxide," *Acta Cryst.*, *4*, 15-20 (1951).

2.15 Giguere, P. A. and Pierre Geoffrion, "Changes of Density of Hydrogen Peroxide Solutions on Cooling and Freezing," *Can. J. Research*, *28B*, 599-607 (1950).

2.16 Papousek, D., "Intermolecular Interaction in Liquids. I. Adiabatic Compressibility and Structure in the System Hydrogen Peroxide-Water," *Chem. listy*, *59*, 1781-6 (1957).

2.17 Easton, M. F., A. G. Mitchell, and W. F. K. Wynne-Jones, "Behavior of Mixtures of Hydrogen Peroxide and Water. I. Determination of the Densities of Mixtures of Hydrogen Peroxide and Water," *Trans. Faraday Soc.*, *48*, 796-801 (1952).

2.18 R-2094P, *Summary Report, Research Program on $H_2O_2$*, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 1 March 1960, CONFIDENTIAL.

2.19 AFRPL-TR-66-6, *Final Report, Advanced Propellant Staged Combustion Feasibility Program*, Phase I, Part 2, Aerojet-General Corporation, Sacramento, California, April 1966, CONFIDENTIAL.

2.20 Egerton, A. C., W. Emte, and G. J. Minkoff, "Some Properties of Organic Peroxides," *Discussions Faraday Society*, *1951* (10), 278-82 (1951).

2.21 Giguere, P. A. and O. Maass, "Vapor Pressures and Boiling Points of Binary Mixtures of Hydrogen Peroxide and Water," *Can. J. Research*, *18B*, 181-93 (1940).

2.22 Bulletin No. 67, Hydrogen Peroxide Physical Properties Data Book, FMC Corporation, Buffalo, New York, 1955.

2.23 290-63, Hydrogen Peroxide Decomposition. I, Shell Development Company, Emeryville, California, January 1964.

2.24 Phibbs, M. K. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. I. Density, Refractive Index, Viscosity, and Surface Tension of Deuterium Peroxide-Deuterium Oxide Solutions," Can. J. Chem., 29, 173-31 (1951).

2.25 Giguere, P. A., B. G. Morissette, A. W. Olmos, and O. Knop, "Hydrogen Peroxide and Its Analogues. VII," Can. J. Chem., 33, 804 (1955).

2.26 Giguere, P. A. and J. L. Carmichael, "Heat Capacities for the Water-$H_2O_2$ System Between 25 and 60°," J. Chem. Eng. Data, 7, Pt. 1, 526-7 (1962).

2.27 Giguere, P. A. and I. D. Liu, "Recommended Values for the Thermodynamic Properties of Hydrogen and Deuterium Peroxides," J. Am. Chem. Soc., 77, 6477-9 (1955).

2.28 Giguere, P. A., "The Thermodynamic Functions of Hydrogen Peroxide," Can. J. Res., 28B, 485-91 (1950).

2.29 Giguere, P. A. and Osias Bain, "Force Constants in Hydrogen and Deuterium Peroxides," J. Phys. Chem., 56, 340-2 (1952).

2.30 Satterfield, C. N., R. L. Wentworth, and S. T. Demetriades, "Viscosity of Vapor Mixtures of Hydrogen Peroxide and Water," J. Am. Chem. Soc., 76, 2633-7 (1954).

2.31 Private communication, L. H. Dierdorff, FMC Corporation, to M. T. Constantine, Rocketdyne, December 1966.

2.32 Stern, K. G., Berichte, 66, 547 (1933), as given by Ref. 2.22.

2.33 McMurtrie, R. L. and F. G. Keyes, J. Am. Chem. Soc., 70, 3755 (1948), as given by Ref. 2.22.

2.34 Montgomery, R. B., J. Meteorology, 4, 193 (1947), as given by Ref. 2.22.

2.35 Jatkar, S. K. K., "Dipole Moments of Polyatomic Molecules," Nature, 153, 316-17 (1944).

2.36 Amako, Y. and P. A. Giguere, "Calculation of the $H_2O_2$ Molecule by the LCAO-MO-SCF Method," Can. J. Chem., 40, 765-74 (1962).

2.37 Massey, J. T. and D. R. Bianco, "The Microwave Spectrum of Hydrogen Peroxide," J. Chem. Phys., 22, 442-8 (1954).

2.38 Linton, C. P. and O. Maass, "The Electric Moment of Hydrogen Peroxide," Can. J. Research, 7, 81-5 (1932).

2.39 Gross, P. M., Jr., and R. C. Taylor, "The Dielectric Constants of Water, Hydrogen Peroxide, and Hydrogen Peroxide-Water Mixtures," J. Am. Chem. Soc., 72, 2075-80 (1950).

2.40 Talat-Erben, "The Dielectric Constant of Pure Hydrogen Peroxide as a Function of Temperature," Bull. Soc. Chim. France, 1952, 176 (1952).

2.41 AFRPL-TR-66-13, Final Report Research on the Stability of High Strength $H_2O_2$, E. I. duPont de Nemours and Company, Inc., Wilmington, Delaware, Contract AF04(611)-10216, March 1966.

2.42 Cuthbertson, A. C. and O. Maass, "Hydrogen Peroxide. VII. The Dielecteio Constants, Refractive Indices and Ionizing Power of Hydrogen Peroxide and its Aqueous Solutions," J. Am. Chem. Soc., 52, 489-99 (1930).

2.43 Schumb, W. C., "The Stability of Concentrated Hydrogen Peroxide Solutions," Ind. Eng. Chem., 41, 992 (1949).

2.44 Roth, E. M., Jr., and E. S. Shanley, "Stability of Pure Hydrogen Peroxide," Ind. Eng. Chem., 45, 2343-9 (1953).

2.45 Giguere, P. A. and H. Feeny, Can. J. Res., 21A, 69 (1943), as given by Ref. 2.22.

2.46 Savithri, K. and S. R. Rao, "Magnetic Susceptibility of Some Peroxides," Proc. Indian Acad. Sci., 16A, 221-30 (1942).

2.47 Gray, F. W. and J. Farquharson, "Diamagnetism and Submolecular Structure," Phil. Mag. (7), 10, 191-216 (1930).

2.48 Giguere, P. A. and V. V. Schomaker, "An Electron-Diffraction Study of $H_2O_2$ and Hydrazine," J. Am. Chem. Soc., 65, 2025-9 (1943).

2.49 Redington, R. L., W. B. Olson, and P. C. Cross, "Hydrogen Peroxide, Infrared Spectrum and the Internal Rotation Problem," J. Chem. Phys., 36, 1311-26 (1962).

2.50 Hunt, R. H., R. A. Leacock, C. W. Peters, and K. T. Hecht, "Internal Rotation in Hydrogen Peroxide: the Far-Infrared Spectrum and the Determination of the Hindering Potential," J. Chem. Phys., 42 (6), 1931-46 (1965).

2.51 Massey, J. T. and R. W. Hart, "Effect of a High cis-Barrier on the Microwave Spectrum of Hydrogen Peroxide," J. Chem. Phys., 23, 942-6 (1955).

2.52 Giguere, P. A. and C. Chapados, "The Far Infrared Spectra of $H_2O_2$ and $D_2O_2$ in the Solid States," Spectrochimica Acta, 22 1131-1137 (1966).

2.53 Miller, R. L. and K. B. Hornig, "Infrared Spectrum of Crystalline $H_2O_2$," J. Chem. Phys., 34, 265 (1961).

2.54 Calculated, this study.

2.55 Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide--Physical and Chemical Properties," Ind. Eng. Chem., 39, 1536-43 (1947).

2.56 Klunstuck, M., Berichte, 51, 108 (1918); J. Chem. Soc., 114 (II), 107 (1918).

2.57 Jamieson, G. S., Am. J. Sci., 44, 150 (1917); E. Wedekind, Chem. Ztg., 48, 185 (1924).

2.58 Quartaroli, A., Gazz. Chim. ital., 55, 619 (1925).

2.59 Ageno, F. and E. Barzetti, Atti R. Acad. dei Linceidi Roma (3), 191, I, 381.

2.60 Moser, L., Z. anorg. Chem., 50, 33 (1906).

2.61 Hasebrack, K., Berichte, 20, 213 (1887); J. Hanus and O. Kallauner, Z. anorg. Chem., 70, 232 (1911).

2.62 Masson, O., Proc. Chem. Soc., 23, 117; J. Chem. Soc., 91, 1449 (1907).

2.63 Schuster, F., Z. anorg. allgem. Chem., 186, 253 (1930).

2.64 Connick, R. E., J. Am. Chem. Soc., 69, 1509 (1947).

2.65 Mack, E. S., J. Phys. Chem., 21, 238 (1917).

2.66 Broughton, D. B., R. L. Wentworth, and M. E. Farnsworth, unpublished work of the M.I.T. Hydrogen Peroxide Project, 1947.

2.67 Spitalsky, E., Z. anorg. Chem., 69, 179 (1910); E. Pietsch, A. Kotowski, and F. G. Berend, Z. physik. Chem., 5B, 1 (1929); D. G. Nickerson, J. Am. Chem. Soc., 58, 2525 (1936); F. Muller and R. Pietsch, Korrosion u. Metallschutz, 15, 122 (1939); L. A. Nikolaev and N. I. Kobozev, J. Phys. Chem., (U.S.S.R), 19, 562 (1945).

2.68 Glauner, R. and R. Glocker, Z. Metallkunde, 20, 144 (1928); J. Aldridge and M. P. Applebey, J. Chem. Soc., 121, 238 (1922); J. Sperber, Schweiz. Apoth. Ztg., 53, 717 (1915); Buntin and Vlasar, Acta Univ. Voronegiensis, 8, No. 4, 6 (1935),

2.69 Glasner, A., J. Chem. Soc., 1951, 904 (1951).

2.70 Kistiakowksy, W., Z. physik. Chem., 35, 431 (1900); E. Lueck, Apoth. Ztg., 34, 87 (1919); M. Kohn, Monatsh, 66, 393 (1935); O. Baudisch, Science, 108, 443 (1948); B. B. Lal, Proc. Indian Acad. Sci., 36A, 244 (1952); D. D. DeFord and A. W. Davidson, J. Am. Chem. Soc., 73, 1469 (1951).

2.71 Bray, W. C. and H. A. Liebhafsky, J. Am. Chem. Soc., 53, 38 (1931).

2.72 Watson, G., Chem. News, 46, 9 (1882); G. Pellini and G. Meneghini, Z. anorg. Chem., 60, 178 (1908).

2.73 Audrieth, L. F. and B. A. Ogg, The Chemistry of Hydrazine, pp. 118-134, New York, John Wiley and Sons, Inc., 1951; C. C. Clark, Hydrazine, p. 8, Baltimore, Maryland, Mathieson Chemical Corp., 1953; A. W. Browne, J. Am. Chem. Soc., 27, 551 (1903); R. E. Kirk and A. W. Browne, J. Am. Chem. Soc., 50, 337 (1928); A. S. Gordon, Third Symposium on Combustion, p. 493, Baltimore, Maryland, Williams & Wilkins Co., 1949; P. Davis and W. C. E. Higginson, J. Chem. Soc., 1953, 1902; J. W. Cahn and R. E. Powell, J. Am. Chem. Soc., 76, 2568 (1954); E. J. Bowen and A. W. Birley, *Trans. Faraday Soc.*, *47*, 580 (1951); W. C. E. Higginson, D. Sutton, and P. Wright, *J. Chem. Soc.*, *1953*, 1380 (1953).

2.74 Wurster, C., *Berichte*, *20*, 2631 (1887).

2.75 Weith, W. and A. Weber, *Berichte*, *7*, 1745 (1874); I. Trifonow, *Z. anorg. allgem. Chem.*, *124*, 123 (1922); K. Gleu and R. Hubold, *Z. anorg. allgem. Chem.*, *223*, 305 (1935); E. A. Shilov and Z. S. Stepanova, *Zhur. Fiz. Khim.*, *24*, 820 (1950); E. Halfpenney and P. L. Robinson, *J. Chem. Soc.*, *1952*, 928 (1952).

2.76 Rothmund, V., *8th Intern. Congr. Appl. Chem.*, *Orig. Comm.*, *26*, 611 (1912); V. Rothmund and A. Burgstaller, *Monatsh.*, *38*, 295 (1917); *J. Chem. Soc.*, *114*, II, 16 (1918).

2.77 Weyl, T., *Berichte*, *39*, 1307 (1906).

2.78 Schmidlin, J. and P. Massini, *Berichte*, *43*, 1162 (1910); J. d'Ans and W. Frederick, *ibid.*, p. 1880.

2.79 Nerz, K. and C. Wagner, *Berichte*, *70B*, 446 (1937).

2.80 Zotier, V., *Bull. soc. Chim.* (4), *13*, 61 (1913); *21*, 241 (1917); A. Bach and M. Monosson, *Berichte*, *57B*, 735 (1924).

2.81 Joliot, F., *J. chim. physique*, *27*, 119 (1930).

2.82 Marie, C., *J. chim. physique*, *6*, 596 (1908).

2.83 Satterfield, C. N., R. C. Reid, and D. R. Briggs, *J. Am. Chem. Soc.*, *76*, 3922 (1954).

2.84 Classen, A. and F. Bauer, *Berichte*, *16*, 1062 (1883).

2.85 Halperin, J. and H. Taube, *J. Am. Chem. Soc.*, *74*, 380 (1952); E. R. S. Winter and H. V. A. Briscoe, *J. Am. Chem. Soc.*, *73*, 496 (1951); H. W. Albu and H. D. von Schweinitz, *Berichte*, *65*, 729 (1935); S. Glasstone and A. Hickling, *Electrolytic Oxidation and Reduction*, p. 257, New York, D. Van Nostrand Co., Inc., 1936; R. Willstatter, *Berichte*, *36*, 1831 (1903); N. Tarugi and G. Vitali, *Gazz. chim. ital.*, *39*, I, 418 (1909); K. Sandved and J. B. Holte, *Kgl. Norske Videnskab. Selskabs, Forh.*, *11*, 189 (1938) (Pub. 1939);

E. Abel, Monatsh., 28, 1239 (1907); E. Abel, Monatsh., 34, 821 (1913); E. Abel, Z. Elektrochem., 18, 705 (1912); E. Abel, Monatsh., 81, 798 (1950); Y. Usumasa and T. Okura, J. Chem. Soc. Japan, Pure Chem. Sect., 71, 48 (1950).

2.86 Raschig, F., Berichte, 18, 2743 (1885).

2.87 Roseman, R., R. W. Neptune, and B. W. Allen, United States Patent 2,616,791 (4 November 1952).

2.88 Gilbertson, L. I. and G. B. King, Inorganic Syntheses, Vol. III, p. 137, McGraw-Hill Book Co., New York, 1950; J. Am. Chem. Soc., 58, 180 (1936).

2.89 Thomsen, Ann. Phys., (2), 151, 194 (1874); S. Hasselskog, Svensk. Farm. Tids., 25, 149 (1921); H. Endo and G. Yokoyama, Science, Repts. Research Insts., Tohoku University, Ser. A, 2, 449 (1950).

2.90 Schluck, G., Monatsh., 37, 489 (1916).

2.91 Higginson, W. C. E., D. Sutton, and P. Wright, J. Chem. Soc., 1953, 1380 (1953).

2.92 Jahr, K. J., FIAT Rev. Ger. Sci., Part III, P. 170 (1948).

2.93 Klyachko, Y. A. and E. I. Bleshchunova, Doklady Akad. Nauk. S.S.S.R., 56, 823 (1947); Chem. Zentr. (Russian Zone Ed.), 1948, II, 555.

2.94 Nees, H., P. B. Report 74717 (frames 199-205).

2.95 Oddo, B. and R. Binaghi, Gazz. chim. ital., 51, II, 343 (1921); B. Oddo and R. Binaghi, Atti. R. Acad. Lincei Roma (5), 32, 349 (1923).

2.96 Greenspan, F. P. Ind. Eng. Chem., 39, 847-8 (1947), as given by Ref. 2.55.

2.97 D'Ans, J. and A. Kneip, Berichte, 48, 1136-46 (1915), as given by Ref. 2.55.

2.98 Boeseken, J. and M. L. Von Konigsfeldt, Rec. trav. chim., 54, 313-16 (1935), as given by Ref. 2.55.

2.99 RTD-TDR-63-1062, TP 206, Design Criteria for Advanced Propellant Systems, Texaco Experiment, Incorporated, Richmond, Virginia, June 1963.

2.100 RR65-26, Modifying Certain Physico-Chemical Parameters of Liquid Propellants, Technidyne, Incorporated, West Chester, Pennsylvania, April 1965, Contract DA-36-034-AMC-0153Z, CONFIDENTIAL.

2.101 Sanborn, C. E., H. J. Baumgartner, G. C. Hood, and J. M. Monger, "Decomposition Heat Transfer to Liquid 90% Hydrogen Peroxide," Presented at the 6th National Heat Transfer Conference, A.I.Ch.E.-A.S.M.E., Boston, Massachusetts, August 1963, A.I.Ch.E. Preprint 20.

2.102 Sanborn, C. E., H. J. Baumgartner, G. C. Hood, and J. M. Monger, "Convective Heat Transfer to Liquid 90% Hydrogen Peroxide at High Heat Flux," Presented at the 6th National Heat Transfer Conference, A.I.Ch.E.-A.S.M.E., Boston, Massachusetts, August 1963, A.I.Ch.E. Preprint 21.

2.103 Studies done by Pratt and Whitney, as reported by James McCormick, Hydrogen Peroxide Rocket Manual, FMC Corporation, Buffalo, New York, 1965.

2.104 AGC 10785-Q3, Quarterly Report, Advanced Propellant Staged-Combustion Feasibility Program, Aerojet-General Corporation, Sacramento, California, June 1966, Contract AF04(611)-10785, CONFIDENTIAL.

2.105 Private communication, F. Hoffman, FMC Corporation, to M. T. Constantine, Rocketdyne.

2.106 Private communication, J. McCormick, FMC Corporation, to M. T. Constantine, Rocketdyne.

2.107 Van Huff, N. E. and D. C. Rouser, "Ultimate Heat Flux Limits of Storable Propellants," Aerojet-General Corporation, Sacramento, California, as presented to the CPIA 8th Liquid Propulsion Symposium, Cleveland, Ohio, November 1966, CONFIDENTIAL.

2.108 AFRPL-TR-66-263, Special Report, Advanced Propellant Staged-Combustion Feasibility Program, Aerojet-General Corporation, Sacramento, California, August 1966, Contract AF04(611)-10785, CONFIDENTIAL

2.109 R-2985, Redstone Catalyst Improvement Program, Final Report for Period October 1958 to December 1960, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 29 May 1961.

2.110 AFRPL-TR-67-80, Investigation of Decomposition Catalysts for 98% Hydrogen Peroxide, Final Report, FMC Corporation, Princeton, New Jersey, March 1967, Contract AF04(611)-11208, CONFIDENTIAL.

2.111 McCormick, J., Hydrogen Peroxide Rocket Manual, FMC Corporation, Buffalo, New York, 1965.

2.112 Kazanjian, A. R., "Thermal Decomposition Studies of 98% $H_2O_2$," Unpublished Data (RM 316-92), Rocketdyne, a Division of North Amercian Aviattion, Inc., Canoga Park, California, 19 March 1958.

2.113 AFFTC-TR-60-8, Experimental Performance of $B_5H_9$-$H_2O_2$ Propellant Combination in 100 Pound Thrust Rocket Engine, Air Force Flight Test Center, Edwards Air Force Base, California, May 1960, CONFIDENTIAL.

2.114 AFRPL-TR-65-216, Final Report, Development of a Light Metal Hydride Hybrid System (16 November 1964 through 16 August 1965, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, December 1965, Contract AF04(611)-9070, CONFIDENTIAL.

## TABLE 2.1

## PHYSICAL PROPERTIES OF HYDROGEN PEROXIDE AT

| Property | Units | | 100 Percent $H_2O_2$ | | 98 Percent $H_2O_2$ | | 95 Percent $H_2O_2$ | |
|---|---|---|---|---|---|---|---|---|
| | Metric | English | Metric | English | Metric | English | Metric | English |
| **General Identification** | | | | | | | | |
| Identification | | | Hydrogen Peroxide | | Hydrogen Peroxide | | Hydrogen Peroxide | |
| Molecular Formula | | | $H_2O_2$ | | $(H_2O_2)$ 0.9628 | $(H_2O)$ 0.0372 | $(H_2O_2)$ 0.9096 | $(H_2O)$ 0.0904 |
| Molecular Weight | g-mole | lb-mole | 34.016 | 34.016 | 33.424 | 33.424 | 32.571 | 32.571 |
| Freezing Point | C | F | −0.5 | 31.1 | −2.1 | 28.2 | −5.1 | 22.8 |
| Triple Point | C | F | −0.42 | 31.24 | | | | |
| Normal Boiling Point | C | F | 150.0 | 302.0 | 148.7 | 299.0 | 146.0 | 294.5 |
| Critical Properties | | | | | | | | |
| Temperature | C | F | 460 | 860 | 456.5 | 854 | 452 | 846 |
| Pressure | atm | psia | 247 | 3630 | 246 | 3615 | 244.5 | 3591 |
| Density | g/cc | | | | | | | |
| **Phase Properties** | | | | | | | | |
| Density | | | | | | | | |
| Solid | g/cc | lb/cu ft | 1.71 at −20 C | 106.76 at −4 F | | | | |
| Liquid | g/cc | lb/cu ft | 1.444 | 90.[illegible] | 1.432 | 89.4 | 1.415 | 88.3 |
| Gas | g/cc | lb/cu ft | See Section 2.2.2.1 | | See Section 2.2.2.1 | | See Section 2.2.2.1 | |
| Thermal Expansion | $C^{-1}$ | $F^{-1}$ | $7.502 \times 10^{-4}$ | $4.105 \times 10^{-4}$ | $7.508 \times 10^{-4}$ | $4.165 \times 10^{-4}$ | $7.508 \times 10^{-4}$ | $4.168 \times 10^{-4}$ |
| ~~Compressibility (cubic)~~ | | | | | | | | |
| Adiabatic | $atm^{-1}$ | $psia^{-1}$ | $2.411 \times 10^{-5}$ | $1.640 \times 10^{-6}$ | $2.445 \times 10^{-5}$ | $1.665 \times 10^{-5}$ | $2.496 \times 10^{-5}$ | $1.699 \times 10^{-5}$ |
| Isothermal | $atm^{-1}$ | $psia^{-1}$ | $2.617 \times 10^{-5}$ at 20 C | $5.840 \times 10^{-4}$ at 68 F | | | | |
| Vapor Pressure | mm Hg | psia | 2.08 | 0.042 | 2.30 | 0.045 | 2.53 | 0.053 |
| Surface Tension | dyne/cm | lb/ft | 80.15 at 20 C | 5.490 at 68 F | 79.95 at 20 C | 5.477 at 68 F | 79.64 at 20 C | 5.456 at 68 F |

## TABLE 2.1
## (Continued)

| Property | Units |  | 100 Percent $H_2O_2$ |  | 98 Percent $H_2O_2$ |  | 95 Percent $H_2O_2$ |  |
|---|---|---|---|---|---|---|---|---|
|  | Metric | English | Metric | English | Metric | English | Metric | English |
| **Thermodynamic Properties** |  |  |  |  |  |  |  |  |
| Heats of |  |  |  |  |  |  |  |  |
| Formation | cal/g | Btu/lb | -1320 | -2376 | -1369 | -2464 | -1445 | -2601 |
| Fusion | cal/g | Btu/lb | 86 | 155 | 87 | 157 | 85 | 153 |
| Vaporisation | cal/g | Btu/lb | 364 | 654.5 | 368 | 661.5 | 376 | 677 |
| Sublimation | cal/g | Btu/lb | 457.8 | 824 |  |  |  |  |
| Mixing | cal/g (solution) | Btu/lb (solution) | 0 | 0 | 1.0 | 1.8 | 2.4 | 4.2 |
| Decomposition | cal/g | Btu/lb |  |  |  |  | See Fig. 2.16 and |  |
| Heat Capacity |  |  |  |  |  |  |  |  |
| Solid | cal/g-C | Btu/lb-F | 0.461 at melting point | 0.461 at melting point | 0.461 at melting point | 0.461 at melting point | 0.414 at melting point | 0.414 at melting poi |
| Liquid | cal/g-C | Btu/lb-F | 0.625 | 0.626 | 0.633 | 0.633 | 0.645 | 0.645 |
| Gas |  |  |  |  |  |  |  |  |
| $C_p$ | cal/g-C | Btu/lb-F | 0.303 | 0.303 | 0.306 | 0.306 | 0.310 | 0.310 |
| $C_v$ | cal/g-C | Btu/lb-F |  |  |  |  |  |  |
| Entropy | cal/g-C | Btu/lb-F |  |  |  |  | See Section 2.2 |  |
| Enthalpy | cal/g | Btu/lb |  |  |  |  | See Section 2.2 |  |
| **Transport Properties** |  |  |  |  |  |  |  |  |
| Viscosity |  |  |  |  |  |  |  |  |
| Liquid | Contipoises | lb/ft-sec | 1.153 | $0.770 \times 10^{-3}$ | 1.158 | $0.772 \times 10^{-3}$ | 1.160 | $0.775 \times 10^{-}$ |
| Gas | Centipoises | lb/ft-sec | $1.91 \times 10^{-2}$ | $1.283 \times 10^{-5}$ |  |  |  |  |
| Thermal Conductivity |  |  |  |  |  |  |  |  |
| Liquid | cal/cm-sec-C | Btu/ft-hr-F |  |  | $1.40 \times 10^{-3}$ | 0.34 |  |  |
| Gas | cal/cm-sec-C | Btu/ft-hr-F |  |  |  |  |  |  |
| Coefficient of Diffusion | $cm^2$/sec | $in.^2$/sec |  |  |  |  |  |  |
| Sonic Velocity |  |  |  |  |  |  |  |  |
| Liquid | m/sec | ft/sec | 1781.0 | 5843 | 1774.6 | 5821 | 1767.0 | 5794 |
| Gas | m/sec | ft/sec |  |  |  |  |  |  |

TABLE 2.1
(Continued)

| $_2$ | 95 Percent $H_2O_2$ | | 90 Percent $H_2O_2$ | | 75 Percent $H_2O_2$ | | 70 Percent $H_2O_2$ | | Figure and Table Number | Reference Number |
|---|---|---|---|---|---|---|---|---|---|---|
| lish | Metric | English | Metric | English | Metric | English | Metric | English | | |
| | -1445 | -2601 | -1571 | -2828 | -1946 | -3503 | -2070 | -3726 | T2.3 - 2.14,<br>F2.12 - 2.13a | 2.25, 2.54 |
| | 85 | 153 | 82 | 148 | 77 | 138 | 72 | 129 | T2.3 - 2.8 | 2.2 |
| | 376 | 677 | 389 | 700 | 427 | 768 | 438 | 789 | T2.3 - 2.14<br>F2.14, F2.14a | 2.26 |
| | | | | | | | | | | 2.10 |
| | 2.4 | 4.2 | 4.3 | 7.6 | 8.15 | 14.65 | 9.0 | 16.05 | F2.15, F2.15a | 2.26 |
| | See Fig. 2.16 and 2.16a | | | | | | | | F2.16, F2.16a | 2.25 |
| at<br>ng point | 0.414 at melting point | 0.414 at melting point | 0.417 at melting point | 0.417 at melting point | 0.377 at melting point | 0.377 at melting point | 0.415 at melting point | 0.415 at melting point | T2.3 - 2.8<br>F2.17, F2.17a | 2.5 |
| | 0.645 | 0.645 | 0.663 | 0.663 | 0.720 | 0.720 | 0.738 | 0.738 | T2.3 - 2.8<br>F2.17, F2.17a | 2.18, 2.25, 2.26 |
| | 0.310 | 0.310 | 0.317 | 0.317 | 0.338 | 0.338 | 0.346 | 0.346 | T2.9 - T2.14 | 2.27 |
| | See Section 2.2.3.6 | | | | | | | | T2.3 - T2.14 | 2.54 |
| | See Section 2.2.3.8 | | | | | | | | T2.3 - T2.14 | 2.54 |
| $x 10^{-3}$ | 1.160 | $0.775 \times 10^{-3}$ | 1.158 | $0.777 \times 10^{-3}$ | 1.136 | $0.769 \times 10^{-3}$ | 1.123 | $0.758 \times 10^{-3}$ | F2.18, F2.18a<br>F2.19, F2.19a | 2.6, 2.22, 2.24 |
| | | | | | | | | | F2.20 | 2.30 |
| | | | | | | | | | F2.21 | 2.31 |
| | 1767.0 | 5794 | 1752.5 | 5745 | 1706.9 | 5598 | 1690.3 | 5543 | F2.22, F2.22a | 2.16 |

## TABLE 2.1
## (Concluded)

| Property | Units | | 100 Percent $H_2O_2$ | | 98 Percent $H_2O_2$ | | 95 Percent $H_2O_2$ | |
|---|---|---|---|---|---|---|---|---|
| | Metric | English | Metric | English | Metric | English | Metric | English |
| Electromagnetic Properties | | | | | | | | |
| Index of Refraction | (Sodium D-Line) | | | | | | | |
| Solid | | | | | | | | |
| Liquid | | | 1.4067 | | 1.4049 | | 1.4083 | |
| Gas | | | | | | | | |
| Dipole Moment | Debye Units | | 2.13 | | | | | |
| Dielectric Constant | | | 70.5 | | 71.6 | | 73.0 | |
| Liquid | | | | | | | | |
| Gas | | | | | | | | |
| Electrical Conductivity | micro-ohms$^{-1}$ | | | | | | | See Section |
| Verdet Constant | | | | | | | | See Table 2. |
| Magnetic Susceptibility | cgs-emu/g | | $-0.50 \times 10^{-6}$ at 10 C (50 F) | | | | | |

## TABLE 2.1
## (Concluded)

| 95 Percent $H_2O_2$ | | 90 Percent $H_2O_2$ | | 75 Percent $H_2O_2$ | | 70 Percent $H_2O_2$ | | Figure and Table Number | Reference Number |
|---|---|---|---|---|---|---|---|---|---|
| Metric | English | Metric | English | Metric | English | Metric | English | | |
| 1.4023 | | 1.3980 | | 1.3854 | | 1.3814 | | T2.15 | 2.15 |
| 73.0 | | 75.0 | | 78.6 | | 79.5 | | F2.23 | 2.38<br>2.39 |
| See Section 2.2.5.4 | | | | | | | | | 2.41, 2.42, 2.43<br>2.44 |
| See Table 2.16 | | | | | | | | T2.16 | 2.45<br>2.10 |

## TABLE 2.2

## CALCULATED SATURATION PRESSURE, ACTIVITY COEFFICIENTS, AND VAPOR COMPOSITIONS FOR HYDROGEN PEROXIDE-WATER SOLUTIONS AT HIGH TEMPERATURES AND PRESSURES

| $H_2O_2$ Concentration, w/o | System Pressure, psia | Mole Fraction $H_2O$ in Liquid | Temperature | | Vapor Pressure | | Activity Coefficient, $H_2O_2$ | Activity Coefficient, $H_2O$ | $\theta_{H_2O_2}$ | $\theta_{H_2O}$ | Mole Fraction $H_2O_2$ in Vapor | Mole Fraction $H_2O$ in Vapor | Partial Pressure | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | C | F | $H_2O_2$, psia | $H_2O$, psia | | | | | | | $H_2O_2$, psia | $H_2O$, psia |
| 90 | 37.4* | 0.1734 | 175 | 347 | 30.7 | 129.5 | 0.5635 | 0.5782 | 0.9948 | 1.0454 | 0.6706 | 0.3294 | 25.1 | 12.3 |
| | 64.7 | | | | | | | | 0.9803 | 1.0322 | 0.3921 | 0.1927 | 25.4 | 12.5 |
| | 114.7 | | | | | | | | 0.9502 | 1.0125 | 0.2290 | 0.1112 | 26.2 | 12.7 |
| | 314.7 | | | | | | | | 0.8161 | 0.9258 | 0.0971 | C.0443 | 30.6 | 13.9 |
| | 514.7 | | | | | | | | 0.6958 | 0.8427 | 0.0696 | 0.0298 | 35.9 | 15.3 |
| | 1014.7 | | | | | | | | 0.4650 | 0.6642 | 0.0528 | 0.0191 | 53.7 | 19.4 |
| | 2014.7 | | | | | | | | G.2075 | 0.4122 | 0.0597 | 0.0156 | 120.2 | 30.4 |
| 81.5 | 44.7* | 0.3000 | 175 | | | | 0.9470 | 0.6526 | 0.9893 | 1.0414 | 0.4592 | 0.5408 | 20.5 | 24.2 |
| | 64.7 | | | | | | | | 0.9785 | 1.0316 | 0.3203 | 0.3766 | 20.8 | 24.4 |
| | 114.7 | | | | | | | | 0.9487 | 1.0116 | 0.1870 | 0.2174 | 21.4 | 24.9 |
| | 314.7 | | | | | | | | 0.8155 | 0.9254 | 0.0792 | 0.0865 | 24.9 | 27.2 |
| | 514.7 | | | | | | | | 0.6955 | 0.8424 | 0.0568 | 0.0581 | 29.2 | 29.8 |
| | 1014.7 | | | | | | | | 0.4650 | 0.6641 | 0.0431 | 0.0374 | 43.7 | 38.0 |
| | 2014.7 | | | | | | | | 0.2075 | 0.4123 | 0.0487 | 0.0304 | 97.8 | 61.2 |
| 65.4 | 61.7* | 0.5000 | 175 | | | | 0.8402 | 0.7790 | 0.9769 | 1.0326 | 0.2136 | 0.7864 | 13.1 | 48.6 |
| | 64.7 | | | | | | | | 0.9751 | 1.0310 | 0.2037 | 0.7496 | 13.2 | 48.6 |
| | 114.7 | | | | | | | | 0.9452 | 1.0096 | C.1190 | 0.4334 | 13.6 | 49.6 |
| | 314.7 | | | | | | | | 0.8140 | 0.9242 | 0.0503 | 0.1723 | 15.8 | 54.2 |
| | 514.7 | | | | | | | | 0.6946 | 0.8417 | 0.0360 | 0.1157 | 18.5 | 59.5 |
| | 1014.7 | | | | | | | | 0.4646 | 0.6638 | 0.0273 | 0.0744 | 27.7 | 75.4 |
| | 2014.7 | | | | | | | | 0.2075 | 0.4122 | 0.0309 | 0.0604 | 62.0 | 121.6 |
| 90 | 69.6* | 0.1734 | 200 | 392 | 58.9 | 226 | 0.9847 | 0.5922 | 0.9935 | 1.0624 | 0.6928 | 0.3072 | 48.2 | 21.4 |
| | 114.7 | | | | | | | | 0.9734 | 1.0440 | 0.4297 | 0.1906 | 49.2 | 21.8 |
| | 314.7 | | | | | | | | 0.8724 | 0.9755 | 0.1745 | 0.0742 | 54.8 | 23.5 |
| | 514.7 | | | | | | | | 0.7712 | 0.9055 | 0.1207 | 0.0489 | 62.0 | 25.2 |
| | 1014.7 | | | | | | | | 0.5612 | 0.7470 | 0.0842 | 0.0301 | 85.4 | 30.5 |
| | 2014.7 | | | | | | | | 0.2955 | 0.5064 | 0.0306 | 0.0224 | 162 | 45.0 |
| 81.5 | 81.5* | 0.3000 | | | | | 0.9504 | 0.6634 | 0.9863 | 1.0570 | 0.4872 | 0.5128 | 39.7 | 41.8 |
| | 114.7 | | | | | | | | 0.9715 | 1.0433 | G.3519 | 0.3696 | 40.3 | 42.3 |
| | 314.7 | | | | | | | | 0.8713 | 0.9747 | 0.1428 | 0.1440 | 44.8 | 45.3 |
| | 514.7 | | | | | | | | 0.7706 | 0.9050 | 0.0988 | 0.0948 | 50.8 | 48.8 |
| | 1014.7 | | | | | | | | 0.5610 | 0.7468 | 0.0688 | 0.0583 | 69.8 | 59.1 |
| | 2014.7 | | | | | | | | 0.2955 | 0.5064 | 0.0659 | 0.0434 | 132 | 87.1 |

*Saturated vapor pressure at the temperature and liquid composition indicated.
**Black's imperfection term (AIChE Journal, 5, 249, 1959)

# TABLE 2.2 (Concluded)

| $H_2O_2$ Concentration, w/o | System Pressure, psia | Fraction $H_2O$ in Liquid | Temperature C | Temperature F | Vapor Pressure $H_2O_2$, psia | Vapor Pressure $H_2O$, psia | Activity Coefficient, $H_2O_2$ | Activity Coefficient, $H_2O$ | $\phi_{H_2O_2}$ | $\phi_{H_2O}$ | Mole Fraction $H_2O_2$ in Vapor | Mole Fraction $H_2O$ in Vapor | Partial Pressure $H_2O_2$, psia | Partial Pressure $H_2O$, psia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65.4 | 109.0* | 0.5000 | 200 | 392 | 58.9 | 226 | 0.8482 | 0.7848 | 0.3705 | 1.0452 | 0.2360 | 0.7640 | 25.7 | 83.3 |
| | 114.7 | | | | | | | | 0.9677 | 1.0429 | 0.2252 | 0.7290 | 25.8 | 83.4 |
| | 314.7 | | | | | | | | 0.8683 | 0.9726 | 0.0914 | 0.2845 | 28.7 | 89.4 |
| | 514.7 | | | | | | | | 0.7687 | 0.9035 | 0.0631 | 0.1873 | 32.5 | 96.4 |
| | 1014.7 | | | | | | | | 0.5602 | 0.7461 | 0.0439 | 0.1150 | 44.5 | 116.4 |
| | 2014.7 | | | | | | | | 0.2954 | 0.5062 | 0.0420 | 0.0855 | 84.5 | 172 |
| 90 | 198.1* | 0.1734 | 250 | 482 | 177 | 578 | 0.9867 | 0.6170 | 0.9908 | 1.1038 | 0.7327 | 0.2673 | 145 | 53.1 |
| | 314.7 | | | | | | | | 0.9534 | 1.0682 | 0.4792 | 0.1744 | 150 | 54.8 |
| | 514.7 | | | | | | | | 0.8889 | 1.0188 | 0.3143 | 0.1118 | 161 | 57.4 |
| | 1014.7 | | | | | | | | 0.7270 | 0.8964 | 0.1949 | 0.0645 | 197 | 65.4 |
| | 2014.7 | | | | | | | | 0.4740 | 0.6836 | 0.1508 | 0.0426 | 304 | 85.6 |
| 81.5 | 222.5* | 0.5000 | | | | | 0.9562 | 0.6023 | 0.9809 | 1.0955 | 0.5403 | 0.4597 | 120.1 | 102.4 |
| | 314.7 | | | | | | | | 0.9516 | 1.0675 | 0.3941 | 0.3338 | 124 | 105 |
| | 514.7 | | | | | | | | 0.8873 | 1.0177 | 0.2584 | 0.2141 | 133 | 110 |
| | 1014.7 | | | | | | | | 0.7262 | 0.8958 | 0.1601 | 0.1234 | 162 | 125 |
| | 2014.7 | | | | | | | | 0.4739 | 0.6935 | 0.1238 | 0.0816 | 249 | 164 |
| 65.4 | 281.5* | 0.5000 | | | | | 0.8621 | 0.7848 | 0.9578 | 1.0769 | 0.2818 | 0.7182 | 79.2 | 202.1 |
| | 314.7 | | | | | | | | 0.9483 | 1.0668 | 0.2546 | 0.6465 | 80 | 203 |
| | 514.7 | | | | | | | | 0.8841 | 1.0157 | 0.1670 | 0.4165 | 86 | 214 |
| | 1014.7 | | | | | | | | 0.7246 | 0.8945 | 0.1034 | 0.2399 | 105 | 244 |
| | 2014.7 | | | | | | | | 0.4736 | 0.6832 | 0.0798 | 0.1585 | 160 | 319 |
| 90 | 461.0* | 0.1734 | 300 | 572 | 429 | 1254 | 0.988 | 0.658 | 0.9901 | 1.1515 | 0.7678 | 0.2327 | 354 | 107 |
| | 514.7 | | | | | | | | 0.9750 | 1.1365 | 0.6983 | 0.2112 | 359 | 108 |
| | 1014.7 | | | | | | | | 0.8495 | 1.0277 | 0.4065 | 0.1185 | 412 | 120 |
| | 2014.7 | | | | | | | | 0.6295 | 0.8417 | 0.2768 | 0.0730 | 556 | 147 |
| 81.5 | 499.7* | 0.5000 | | | | | 0.961 | 0.698 | 0.9787 | 1.1408 | 0.5898 | 0.4102 | 295 | 204.7 |
| | 1014.7 | | | | | | | | 0.8695 | 1.0337 | 0.3271 | 0.2230 | 332 | 226 |
| | 2014.7 | | | | | | | | 0.6570 | 0.8563 | 0.2184 | 0.1358 | 434 | 273 |
| 65.4 | 598.8* | 0.5000 | | | | | 0.874 | 0.803 | 0.9504 | 1.1158 | 0.3291 | 0.6709 | 197.2 | 401.6 |
| | 1014.7 | | | | | | | | 0.8634 | 1.0301 | 0.2140 | 0.4299 | 217 | 435 |
| | 2014.7 | | | | | | | | 0.6542 | 0.8549 | 0.1425 | 0.2610 | 286 | 525 |

*Saturated vapor pressure at the temperature and liquid composition indicated.

**Black's imperfection term (<u>AIChE Journal</u>, <u>5</u>, 249, 1959)

## TABLE 2.3

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES OF 100 w/o $H_2O_2$*

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 0 | 0 | 0 | 0 | -160.2 | -288.4 | -1359 | -2446 | Solid |
| 20 | 36 | 0.000 | 0.00 | -160.2 | -288.4 | -1368 | -2462 | ↓ |
| 40 | 72 | 0.05 | 0.02 | -159.7 | -287.5 | -1374 | -2473 | |
| 60 | 108 | 0.100 | 0.050 | -158.2 | -284.8 | -1383 | -2489 | |
| 80 | 144 | 0.144 | 0.085 | -155.7 | -280.3 | -1389 | -2500 | |
| 100 | 180 | 0.181 | 0.121 | -152.5 | -274.5 | -1395 | -2511 | |
| 120 | 216 | 0.210 | 0.157 | -148.6 | -267.5 | -1398 | -2516 | |
| 140 | 252 | 0.236 | 0.192 | -144.1 | -259.4 | -1401 | -2522 | |
| 160 | 288 | 0.259 | 0.225 | -139.5 | -251.1 | -1404 | -2527 | |
| 180 | 324 | 0.281 | 0.257 | -134.7 | -242.5 | -1407 | -2533 | |
| 200 | 360 | 0.302 | 0.287 | -128.9 | -232.0 | -1409 | -2536 | |
| 220 | 396 | 0.325 | 0.311 | -122.6 | -220.7 | -1411 | -2540 | |
| 240 | 432 | 0.349 | 0.346 | -115.9 | -208.6 | -1412 | -2542 | |
| 260 | 468 | 0.382 | 0.376 | -108.6 | -195.5 | -1413 | -2543 | |
| 272.7 | 490.8 | 0.461 | 0.394 | -103.2 | -185.8 | -1412 | -2542 | |

*Refer to Section 2.2.3

TABLE 2.3

(Concluded)

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy $(H_T - H_{298})$ | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 272.7 | 490.8 | 0.626 | 0.716 | -17.4 | -31.3 | -1326 | -2387 | Liquid |
| 280 | 504 | 0.626 | 0.734 | -11.4 | -20.5 | -1324 | -2383 | |
| 298.1 | 536.7 | 0.626 | 0.774 | 0.0 | 0.0 | -1320 | -2376 | |
| 300 | 540 | 0.626 | 0.777 | 1.11 | 2.0 | -1319 | -2374 | |
| 310 | 558 | 0.626 | 0.798 | 7.40 | 13.32 | -1317 | -2371 | |
| 320 | 576 | 0.626 | 0.819 | 13.68 | 24.62 | -1314 | -2365 | |
| 330 | 594 | 0.627 | 0.838 | 19.96 | 35.93 | -1312 | -2362 | |
| 340 | 612 | 0.627 | 0.857 | 26.23 | 47.21 | -1310 | -2358 | |
| 350 | 630 | 0.627 | 0.876 | 32.51 | 58.52 | -1308 | -2354 | |
| 360 | 648 | 0.627 | 0.894 | 38.73 | 69.71 | -1306 | -2351 | |
| 370 | 666 | 0.628 | 0.911 | 45.07 | 81.13 | -1304 | -2347 | |
| 380 | 684 | 0.628 | 0.928 | 51.34 | 92.41 | -1301 | -2342 | |
| 390 | 702 | 0.628 | 0.945 | 57.62 | 103.72 | -1299 | -2338 | |
| 400 | 720 | 0.628 | 0.961 | 63.90 | 115.02 | -1298 | -2336 | |

## TABLE 2.4

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES OF 98 w/o $H_2O_2$ SOLUTIONS*

| Temperature |  | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T$ - $H_{298}$) |  | Heat of Formation |  | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R |  |  | cal/g | Btu/lb | cal/g | Btu/lb |  |
| 0 | 0 | 0 | 0 | -160.44 | -288.79 | -1402 | -2524 | Solid |
| 20 | 36 | 0.00 | 0.017 | -160.40 | -288.72 | -1408 | -2534 |  |
| 40 | 72 | 0.05 | 0.031 | -159.92 | -287.86 | -1425 | -2565 |  |
| 60 | 108 | 0.100 | 0.072 | -158.82 | -285.87 | -1430 | -2574 |  |
| 80 | 144 | 0.144 | 0.108 | -156.38 | -281.45 | -1439 | -2590 |  |
| 100 | 180 | 0.181 | 0.138 | -153.14 | -275.65 | -1445 | -2601 |  |
| 120 | 216 | 0.210 | 0.168 | -143.72 | -258.70 | -1443 | -2597 |  |
| 140 | 252 | 0.236 | 0.197 | -144.74 | -260.53 | -1452 | -2614 |  |
| 160 | 288 | 0.260 | 0.225 | -139.78 | -251.60 | -1454 | -2617 |  |
| 180 | 324 | 0.282 | 0.253 | -134.63 | -242.33 | -1456 | -2621 |  |
| 200 | 360 | 0.303 | 0.281 | -128.50 | -231.30 | -1458 | -2624 |  |
| 220 | 396 | 0.326 | 0.310 | -122.20 | -219.96 | -1460 | -2628 |  |
| 240 | 432 | 0.351 | 0.338 | -115.42 | -207.76 | -1461 | -2630 |  |
| 260 | 468 | 0.384 | 0.366 | -108.08 | -194.54 | -1463 | -2633 |  |
| 271.1 | 488 | 0.461 | 0.357 | -103.51 | -186.32 | -1462 | -2632 |  |

*Refer to Section 2.2.3

TABLE 2.4

(Concluded)

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 271.1 | 488 | 0.633 | 0.682 | -17.14 | -30.85 | -1375 | -2475 | Liquid |
| 280 | 504 | 0.633 | 0.699 | -11.49 | -20.68 | -1374 | -2473 | ↓ |
| 290 | 522 | 0.633 | 0.720 | -5.16 | -9.29 | -1371 | -2468 | |
| 298.1 | 536.7 | 0.633 | 0.739 | 0.0 | 0.0 | -1369 | -2464 | |
| 300 | 540 | 0.633 | 0.743 | 1.17 | 2.11 | -1369 | -2464 | |
| 310 | 558 | 0.633 | 0.764 | 7.50 | 13.50 | -1367 | -2461 | |
| 320 | 576 | 0.633 | 0.784 | 13.83 | 24.89 | -1365 | -2457 | |
| 330 | 594 | 0.633 | 0.803 | 20.16 | 36.29 | -1362 | -2452 | |
| 340 | 612 | 0.634 | 0.820 | 26.49 | 47.68 | -1360 | -2448 | |
| 350 | 630 | 0.634 | 0.836 | 32.83 | 59.09 | -1358 | -2444 | |
| 360 | 648 | 0.635 | 0.854 | 39.17 | 70.51 | -1357 | -2443 | |
| 370 | 666 | 0.635 | 0.872 | 45.51 | 81.92 | -1354 | -2437 | |
| 380 | 684 | 0.635 | 0.889 | 51.86 | 93.35 | -1352 | -2434 | |
| 390 | 702 | 0.636 | 0.907 | 58.22 | 104.80 | -1350 | -2430 | |
| 400 | 720 | 0.636 | 0.925 | 64.58 | 116.24 | -1347 | -2425 | |

## TABLE 2.5

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES
## OF 95 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 0 | 0 | 0 | 0 | -160.19 | -288.34 | -1483 | -2669 | Solid |
| 20 | 36 | 0.001 | 0.017 | -160.15 | -288.27 | -1492 | -2686 | |
| 40 | 72 | 0.051 | 0.037 | -159.65 | -287.37 | -1500 | -2700 | |
| 60 | 108 | 0.101 | 0.072 | -158.13 | -284.63 | -1508 | -2714 | |
| 80 | 144 | 0.145 | 0.108 | -155.67 | -280.21 | -1513 | -2723 | |
| 100 | 180 | 0.182 | 0.138 | -152.35 | -274.23 | -1519 | -2734 | |
| 120 | 216 | 0.211 | 0.168 | -148.49 | -267.28 | -1523 | -2741 | |
| 140 | 252 | 0.238 | 0.197 | -143.99 | -259.18 | -1526 | -2747 | |
| 160 | 288 | 0.261 | 0.225 | -139.01 | -250.22 | -1529 | -2752 | |
| 180 | 324 | 0.284 | 0.253 | -133.555 | -240.39 | -1531 | -2756 | |
| 200 | 360 | 0.305 | 0.281 | -127.67 | -229.81 | -1533 | -2759 | |
| 220 | 396 | 0.329 | 0.310 | -121.33 | -218.39 | -1535 | -2763 | |
| 240 | 432 | 0.354 | 0.338 | -114.49 | -206.08 | -1536 | -2765 | |
| 260 | 468 | 0.387 | 0.366 | -107.02 | -192.64 | -1536 | -2765 | |
| 268.1 | 482.6 | 0.414 | 0.368 | -103.85 | -186.93 | -1537 | -2767 | |

*Refer to Section 2.2.3

TABLE 2.5

(Concluded)

| Temperature |  | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy $(H_T - H_{298})$ |  | Heat of Formation |  | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R |  |  | cal/g | Btu/lb | cal/g | Btu/lb |  |
| 268.1 | 482.6 | 0.645 | 0.683 | -19.38 | -34.88 | -1452 | -2614 | Liquid |
| 280 | 504 | 0.645 | 0.702 | -11.71 | -21.08 | -1450 | -2610 |  |
| 290 | 522 | 0.645 | 0.723 | -5.30 | -9.54 | -1448 | -2606 |  |
| 298.1 | 536.7 | 0.645 | 0.742 | -0.0 | 0.0 | -1445 | -2601 |  |
| 300 | 540 | 0.645 | 0.746 | 1.19 | 2.14 | -1445 | -2601 |  |
| 310 | 558 | 0.645 | 0.767 | 7.63 | 13.73 | -1443 | -2597 |  |
| 320 | 576 | 0.645 | 0.787 | 14.07 | 25.33 | -1441 | -2594 |  |
| 330 | 594 | 0.645 | 0.809 | 20.51 | 36.92 | -1439 | -2590 |  |
| 340 | 612 | 0.645 | 0.826 | 26.95 | 48.51 | -1436 | -2585 |  |
| 350 | 630 | 0.645 | 0.845 | 33.40 | 60.12 | -1434 | -2581 |  |
| 360 | 648 | 0.645 | 0.863 | 39.85 | 71.73 | -1432 | -2578 |  |
| 370 | 666 | 0.646 | 0.880 | 46.30 | 83.34 | -1430 | -2574 |  |
| 380 | 684 | 0.646 | 0.897 | 52.76 | 94.97 | -1427 | -2569 |  |
| 390 | 702 | 0.647 | 0.914 | 59.22 | 106.60 | -1425 | -2565 |  |
| 400 | 720 | 0.648 | 0.930 | 65.69 | 118.24 | -1423 | -2561 |  |

## TABLE 2.6

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES OF 90 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 0 | 0 | 0 | 0 | -160.62 | -289.12 | -1606 | -2891 | Solid |
| 20 | 36 | 0.003 | 0.004 | -160.58 | -289.04 | -1615 | -2907 | ↓ |
| 40 | 72 | 0.053 | 0.023 | -160.08 | -288.14 | -1624 | -2923 | |
| 60 | 108 | 0.103 | 0.054 | -158.52 | -285.34 | -1631 | -2936 | |
| 80 | 144 | 0.147 | 0.090 | -156.02 | -280.84 | -1638 | -2948 | |
| 100 | 180 | 0.184 | 0.127 | -152.72 | -274.90 | -1644 | -2959 | |
| 120 | 216 | 0.213 | 0.163 | -148.74 | -267.73 | -1647 | -2965 | |
| 140 | 252 | 0.240 | 0.193 | -144.20 | -259.56 | -1651 | -2972 | |
| 160 | 288 | 0.264 | 0.223 | -139.16 | -250.49 | -1654 | -2977 | |
| 180 | 324 | 0.287 | 0.252 | -133.66 | -240.59 | -1656 | -2981 | |
| 200 | 360 | 0.309 | 0.281 | -127.70 | -229.86 | -1658 | -2984 | |
| 220 | 396 | 0.333 | 0.309 | -121.28 | -218.30 | -1660 | -2988 | |
| 240 | 432 | 0.358 | 0.338 | -114.38 | -205.88 | -1662 | -2992 | |
| 260 | 468 | 0.392 | 0.366 | -106.92 | -192.46 | -1663 | -2993 | |
| 263.3 | 473.9 | 0.417 | 0.368 | -105.59 | -190.06 | -1662 | -2992 | |

*Refer to Section 2.2.3

## TABLE 2.6

(Concluded)

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 263.3 | 473.9 | 0.664 | 0.680 | -23.11 | -41.59 | -1580 | -2844 | Liquid |
| 280 | 504 | 0.664 | 0.714 | -12.03 | -21.65 | -1575 | -2835 | |
| 290 | 522 | 0.663 | 0.735 | -5.40 | -9.72 | -1573 | -2831 | |
| 298.1 | 536.7 | 0.663 | 0.755 | 0.0 | 0 | -1571 | -2828 | |
| 300 | 540 | 0.663 | 0.759 | 1.22 | 2.20 | -1571 | -2828 | |
| 310 | 558 | 0.663 | 0.781 | 7.86 | 14.15 | -1568 | -2822 | |
| 320 | 576 | 0.663 | 0.802 | 14.48 | 26.06 | -1566 | -2819 | |
| 330 | 594 | 0.663 | 0.822 | 21.11 | 38.00 | -1564 | -2815 | |
| 340 | 612 | 0.664 | 0.842 | 27.74 | 49.93 | -1561 | -2810 | |
| 350 | 630 | 0.664 | 0.861 | 34.38 | 61.88 | -1559 | -2806 | |
| 360 | 648 | 0.664 | 0.880 | 41.02 | 73.84 | -1557 | -2803 | |
| 370 | 666 | 0.664 | 0.898 | 47.66 | 85.79 | -1555 | -2799 | |
| 380 | 684 | 0.665 | 0.916 | 54.31 | 97.76 | -1552 | -2794 | |
| 390 | 702 | 0.666 | 0.933 | 60.96 | 109.73 | -1550 | -2790 | |
| 400 | 720 | 0.667 | 0.950 | 67.62 | 121.72 | -1548 | -2786 | |

## TABLE 2.7

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES
## of 75 w/o $H_2O_2$ SOLUTIONS *

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 0 | 0 | 0 | 0 | -164.94 | -296.89 | -1975 | -3555 | Solid |
| 20 | 36 | 0.007 | 0.010 | -164.91 | -296.84 | -1987 | -3577 | |
| 40 | 72 | 0.057 | 0.032 | -164.27 | -295.68 | -1996 | -3593 | |
| 60 | 108 | 0.107 | 0.065 | -162.63 | -292.73 | -2004 | -3607 | |
| 80 | 144 | 0.152 | 0.102 | -160.07 | -288.13 | -2010 | -3618 | |
| 100 | 180 | 0.188 | 0.140 | -156.67 | -282.01 | -2017 | -3631 | |
| 120 | 216 | 0.218 | 0.171 | -152.61 | -274.70 | -2021 | -3638 | |
| 140 | 252 | 0.245 | 0.202 | -147.99 | -266.38 | -2025 | -3645 | |
| 160 | 288 | 0.271 | 0.232 | -142.83 | -257.09 | -2028 | -3650 | |
| 180 | 324 | 0.296 | 0.262 | -137.15 | -246.87 | -2030 | -3654 | |
| 200 | 360 | 0.319 | 0.292 | -131.01 | -235.82 | -2033 | -3659 | |
| 220 | 396 | 0.345 | 0.321 | -124.35 | -233.83 | -2035 | -3663 | |
| 240 | 432 | 0.372 | 0.350 | -117.19 | -210.94 | -2037 | -3667 | |
| 241.1 | 444 | 0.377 | 0.355 | -116.78 | -210.20 | -2038 | -3668 | |

*Refer to Section 2.2.3

TABLE 2.7

(Concluded)

| Temperature | | Heat Capacity, cal g-K (Btu lb-R) | Entropy, cal/g-K (Btu lb-R) | Enthalpy $(H_T - H_{298})$ | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 241.1 | 444 | 0.736 | 0.662 | -41.54 | -74.77 | -1961 | -3530 | Liquid |
| 260 | 468 | 0.736 | 0.717 | -27.63 | -49.73 | -1956 | -3521 | |
| 280 | 504 | 0.726 | 0.771 | -13.07 | -23.53 | -1950 | -3510 | |
| 290 | 522 | 0.720 | 0.794 | -6.31 | -11.3 | -1948 | -3506 | |
| 298.1 | 536.7 | 0.720 | 0.816 | 0.0 | 0 | -1946 | -3503 | |
| 300 | 540 | 0.720 | 0.820 | 1.33 | 2.39 | -1945 | -3501 | |
| 310 | 558 | 0.720 | 0.844 | 8.52 | 15.34 | -1943 | -3497 | |
| 320 | 576 | 0.720 | 0.866 | 15.71 | 28.28 | -1940 | -3492 | |
| 330 | 594 | 0.720 | 0.889 | 22.90 | 41.22 | -1938 | -3488 | |
| 340 | 612 | 0.720 | 0.910 | 30.09 | 54.16 | -1935 | -3483 | |
| 350 | 630 | 0.720 | 0.931 | 37.28 | 67.10 | -1932 | -3478 | |
| 360 | 648 | 0.721 | 0.952 | 44.48 | 80.06 | -1930 | -3474 | |
| 370 | 666 | 0.721 | 0.972 | 51.69 | 93.04 | -1927 | -3469 | |
| 380 | 684 | 0.722 | 0.992 | 58.91 | 106.04 | -1925 | -3465 | |
| 390 | 702 | 0.723 | 1.011 | 66.16 | 119.09 | -1922 | -3460 | |
| 400 | 720 | 0.726 | 1.030 | 73.43 | 132.17 | -1919 | -3454 | |

## TABLE 2.8

## SOLID- AND LIQUID-PHASE THERMODYNAMIC PROPERTIES OF 70 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/g-K (Btu/lb-R) | Entropy, cal/g-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) | | Heat of Formation | | Phase |
|---|---|---|---|---|---|---|---|---|
| K | R | | | cal/g | Btu/lb | cal/g | Btu/lb | |
| 0 | 0 | 0 | 0 | -174.66 | -314.39 | -2109 | -3796 | Solid |
| 20 | 36 | 0.009 | 0.013 | -174.58 | -314.24 | -2119 | -3814 | |
| 40 | 72 | 0.059 | 0.036 | -173.94 | -313.09 | -2129 | -3832 | |
| 60 | 108 | 0.109 | 0.070 | -172.22 | -310.00 | -2136 | -3845 | |
| 80 | 144 | 0.153 | 0.107 | -169.60 | -305.28 | -2143 | -3857 | |
| 100 | 180 | 0.189 | 0.145 | -166.18 | -299.12 | -2150 | -3870 | |
| 120 | 216 | 0.220 | 0.176 | -162.10 | -291.78 | -2154 | -3877 | |
| 140 | 252 | 0.248 | 0.207 | -157.42 | -283.36 | -2157 | -3883 | |
| 160 | 288 | 0.273 | 0.237 | -152.22 | -274.00 | -2161 | -3890 | |
| 180 | 324 | 0.299 | 0.267 | -146.50 | -263.70 | -2164 | -3895 | |
| 200 | 360 | 0.323 | 0.297 | -140.26 | -252.47 | -2166 | -3899 | |
| 220 | 396 | 0.349 | 0.326 | -133.54 | -240.37 | -2168 | -3902 | |
| 233.1 | 419.6 | 0.415 | 0.345 | -128.55 | -231.39 | -2164 | -3895 | |

*Refer to Section 2.2.3

TABLE 2.8

(Concluded)

| Temperature K | Temperature R | Heat Capacity, cal/gm-K (Btu/lb-R) | Entropy, cal/gm-K (Btu/lb-R) | Enthalpy ($H_T - H_{298}$) cal/gm | Enthalpy ($H_T - H_{298}$) Btu/lb | Heat of Formation cal/gm | Heat of Formation Btu/lb | Phase |
|---|---|---|---|---|---|---|---|---|
| 233.1 | 419.6 | 0.746 | 0.649 | -55.81 | -100.46 | -2092 | -3766 | Liquid |
| 240 | 432 | 0.757 | 0.670 | -43.25 | -77.85 | -2087 | -3757 | |
| 260 | 468 | 0.745 | 0.730 | -28.23 | -50.81 | -2081 | -3746 | |
| 280 | 504 | 0.739 | 0.785 | -13.39 | -24.10 | -2075 | -3735 | |
| 290 | 522 | 0.739 | 0.810 | -6.00 | -10.80 | -2073 | -3731 | |
| 298.1 | 536.7 | 0.738 | 0.831 | 0.0 | 0 | -2070 | -3726 | |
| 300 | 540 | 0.738 | 0.836 | 1.36 | 2.45 | -2069 | -3724 | |
| 310 | 558 | 0.738 | 0.860 | 8.74 | 15.73 | -2067 | -3721 | |
| 320 | 576 | 0.738 | 0.883 | 16.12 | 29.02 | -2064 | -3715 | |
| 330 | 594 | 0.738 | 0.906 | 23.50 | 42.30 | -2061 | -3710 | |
| 340 | 612 | 0.738 | 0.928 | 30.90 | 55.62 | -2059 | -3706 | |
| 350 | 630 | 0.739 | 0.949 | 38.26 | 68.87 | -2056 | -3701 | |
| 360 | 648 | 0.739 | 0.970 | 45.64 | 82.15 | -2053 | -3695 | |
| 370 | 666 | 0.740 | 0.991 | 53.05 | 95.45 | -2051 | -3692 | |
| 380 | 684 | 0.742 | 1.010 | 60.43 | 108.77 | -2047 | -3685 | |
| 390 | 702 | 0.746 | 1.030 | 67.85 | 122.13 | -2045 | -3681 | |
| 400 | 720 | 0.749 | 1.048 | 75.32 | 135.58 | -2042 | -3676 | |

## TABLE 2.9

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 100 w/o $H_2O_2$*

| Temperature | | Heat Capacity, cal/gm-K (Btu/lb-R) | Entropy, cal/gm-K (Btu/lb-R) | Enthalpy ($H_T$ - $H_{298}$) | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0 | -76.26 | -137.27 | -912.08 | -1641.74 |
| 100 | 180 | 0.235 | 1.310 | -52.86 | -95.15 | -931.45 | -1676.61 |
| 200 | 360 | 0.259 | 1.479 | -25.78 | -46.40 | -942.56 | -1696.61 |
| 298 | 536.4 | 0.303 | 1.636 | 0.0 | 0 | -956.38 | -1721.48 |
| 300 | 540 | 0.304 | 1.638 | 0.56 | 1.01 | -956.86 | -1722.35 |
| 400 | 720 | 0.340 | 1.743 | 32.81 | 59.06 | -965.61 | -1738.10 |
| 500 | 900 | 0.369 | 1.810 | 68.35 | 123.03 | -972.11 | -1749.80 |
| 600 | 1080 | 0.391 | 1.879 | 106.46 | 191.63 | -976.81 | 1758.26 |
| 700 | 1260 | 0.407 | 1.941 | 146.41 | 263.54 | -980.34 | -1764.61 |
| 800 | 1440 | 0.420 | 1.996 | 187.83 | 338.09 | -983.13 | -1769.63 |
| 900 | 1620 | 0.432 | 2.046 | 230.47 | 414.85 | -985.37 | -1773.67 |
| 1000 | 1800 | 0.441 | 2.092 | 270.15 | 486.27 | -987.13 | -1776.83 |
| 1100 | 1980 | 0.451 | 2.135 | 318.78 | 573.80 | -988.48 | -1779.26 |
| 1200 | 2160 | 0.459 | 2.175 | 364.27 | 655.69 | -989.54 | -1781.17 |
| 1300 | 2340 | 0.466 | 2.211 | 410.42 | 738.76 | -990.31 | -1782.56 |
| 1400 | 2520 | 0.474 | 2.246 | 457.55 | 823.59 | -990.87 | -1783.57 |
| 1500 | 2700 | 0.480 | 2.279 | 505.18 | 909.32 | -991.31 | -1784.36 |

*Refer to Section 2.2.3

## TABLE 2.10

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 98 w/o $H_2O_2$ SOLUTIONS *

| Temperature | | Heat Capacity cal/g-K (Btu/lb-R) | Entropy cal/g-K (Btu/lb-R) | Enthalpy $(H_T - H_{298})$ | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0 | -77.36 | -139.25 | -957.2 | -1723.0 |
| 100 | 180 | 0.239 | 1.32 | -53.55 | -96.39 | -976.6 | -1757.9 |
| 200 | 360 | 0.262 | 1.49 | -26.13 | -47.03 | -987.6 | -1777.7 |
| 298 | 536.4 | 0.306 | 1.65 | 0.0 | 0 | -1001.4 | -1802.5 |
| 300 | 540 | 0.307 | 1.65 | 0.56 | 1.01 | -1001.9 | -1803.4 |
| 400 | 720 | 0.342 | 1.74 | 33.07 | 59.53 | -1010.7 | -1819.3 |
| 500 | 900 | 0.370 | 1.83 | 68.82 | 123.88 | -1017.3 | -1831.1 |
| 600 | 1080 | 0.393 | 1.90 | 107.11 | 192.80 | -1022.2 | -1840.0 |
| 700 | 1260 | 0.409 | 1.96 | 147.25 | 265.05 | -1025.9 | -1846.6 |
| 800 | 1440 | 0.422 | 2.01 | 188.84 | 339.91 | -1028.8 | -1851.8 |
| 900 | 1620 | 0.434 | 2.06 | 231.67 | 417.01 | -1031.2 | -1856.2 |
| 1000 | 1800 | 0.443 | 2.11 | 271.64 | 488.95 | -1033.2 | -1859.8 |
| 1100 | 1980 | 0.453 | 2.15 | 320.41 | 576.74 | -1034.6 | -1862.3 |
| 1200 | 2160 | 0.461 | 2.19 | 366.13 | 659.03 | -1035.8 | -1864.4 |
| 1300 | 2340 | 0.469 | 2.23 | 412.53 | 742.55 | -1036.7 | -1866.1 |
| 1400 | 2520 | 0.477 | 2.25 | 449.55 | 809.19 | -1037.4 | -1867.3 |

*Refer to Section 2.2.3

## TABLE 2.11

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 95 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity cal/g-K (Btu/lb-R) | Entropy cal/g-K (Btu/lb-R) | Enthalpy ($H_T$ - $H_{298}$) | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0 | -79.0 | -142.2 | -1024.9 | -1844.8 |
| 100 | 180 | 0.245 | 1.345 | -55.1 | -99.2 | -1044.2 | -1879.6 |
| 200 | 360 | 0.268 | 1.52 | -26.7 | -48.1 | -1055.2 | -1899.4 |
| 298 | 536.4 | 0.310 | 1.68 | 0.0 | 0 | -1068.9 | -1924.0 |
| 300 | 540 | 0.311 | 1.68 | 0.6 | 1.1 | -1069.4 | -1924.9 |
| 400 | 720 | 0.346 | 1.75 | 33.5 | 60.3 | -1078.4 | -1941.1 |
| 500 | 900 | 0.374 | 1.80 | 69.5 | 125.1 | -1085.2 | -1953.4 |
| 600 | 1080 | 0.395 | 1.86 | 108.1 | 194.6 | -1090.3 | -1962.5 |
| 700 | 1260 | 0.411 | 1.92 | 148.5 | 267.3 | -1094.2 | -1969.6 |
| 800 | 1440 | 0.425 | 2.05 | 190.4 | 342.7 | -1097.4 | -1975.3 |
| 900 | 1620 | 0.437 | 2.09 | 233.5 | 420.3 | -1100.0 | -1980.0 |
| 1000 | 1800 | 0.446 | 2.14 | 273.9 | 493.0 | -1102.2 | -1984.0 |
| 1100 | 1980 | 0.457 | 2.18 | 322.8 | 581.0 | -1103.9 | -1987.0 |
| 1200 | 2160 | 0.465 | 2.22 | 368.9 | 664.0 | -1105.2 | -1989.4 |
| 1300 | 2340 | 0.472 | 2.26 | 415.6 | 748.1 | -1106.3 | -1991.3 |
| 1400 | 2520 | 0.481 | 2.32 | 463.5 | 834.3 | -1107.0 | -1992.6 |

*Refer to Section 2.2.3

## TABLE 2.12

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 90 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/gm-K (Btu/lb-R) | Entropy, cal/gm-K (Btu/lb-R) | Enthalpy ($H_T-H_{298}$) | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0.0 | -81.76 | -147.17 | -1137.8 | -2048.0 |
| 100 | 180 | 0.256 | 1.38 | -56.34 | -101.41 | -1157.0 | -2082.6 |
| 200 | 360 | 0.277 | 1.56 | -27.55 | - 49.59 | -1167.9 | -2102.2 |
| 298 | 536.4 | 0.317 | 1.72 | 0.0 | 0 | -1181.5 | -2126.7 |
| 300 | 540 | 0.318 | 1.72 | 0.58 | 1.04 | -1182.0 | -2127.6 |
| 400 | 720 | 0.351 | 1.81 | 34.11 | 61.40 | -1191.2 | -2144.2 |
| 500 | 900 | 0.379 | 1.90 | 70.69 | 127.24 | -1198.3 | -2156.9 |
| 600 | 1080 | 0.400 | 1.96 | 109.73 | 197.51 | -1203.8 | -2166.8 |
| 700 | 1260 | 0.416 | 2.03 | 151.53 | 272.75 | -1208.1 | -2174.6 |
| 800 | 1440 | 0.429 | 2.09 | 192.91 | 347.24 | -1211.7 | -2181.1 |
| 900 | 1620 | 0.442 | 2.15 | 236.50 | 425.70 | -1214.7 | -2186.5 |
| 1000 | 1800 | 0.452 | 2.19 | 277.59 | 499.66 | -1217.2 | -2191.0 |
| 1100 | 1980 | 0.462 | 2.23 | 326.92 | 588.46 | -1219.2 | -2194.6 |
| 1200 | 2160 | 0.471 | 2.27 | 373.57 | 672.43 | -1220.9 | -2197.6 |
| 1300 | 2340 | 0.479 | 2.31 | 420.97 | 757.75 | -1222.2 | -2200.0 |
| 1400 | 2520 | 0.488 | 2.39 | 469.42 | 844.96 | -1223.3 | -2201.9 |

*Refer to Section 2.2.3

## TABLE 2.13

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 75 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/gm-K (Btu/lb-R) | Entropy, cal/gm-K (Btu/lb-R) | Enthalpy ($H_T$-$H_{298}$) | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0 | -90.02 | -162.04 | -1476.4 | -2657.5 |
| 100 | 180 | 0.287 | 0.98 | -61.57 | -110.83 | -1495.5 | -2691.9 |
| 200 | 360 | 0.305 | 1.64 | -30.21 | -54.38 | -1505.8 | -2710.4 |
| 298 | 536.4 | 0.338 | 1.80 | 0.0 | 0 | -1519.2 | -2734.6 |
| 300 | 540 | 0.339 | 1.80 | 0.62 | 1.12 | -1519.6 | -2735.3 |
| 400 | 720 | 0.368 | 1.90 | 36.06 | 64.91 | -1529.5 | -2753.1 |
| 500 | 900 | 0.393 | 1.99 | 74.21 | 133.58 | -1537.7 | -2767.9 |
| 600 | 1080 | 0.413 | 2.06 | 114.64 | 206.35 | -1544.2 | -2779.6 |
| 700 | 1260 | 0.429 | 2.13 | 156.83 | 282.29 | -1549.8 | -2789.6 |
| 800 | 1440 | 0.443 | 2.19 | 200.52 | 360.94 | -1554.6 | -2798.3 |
| 900 | 1620 | 0.456 | 2.24 | 245.55 | 441.99 | -1558.8 | -2805.8 |
| 1000 | 1800 | 0.467 | 2.29 | 288.76 | 519.77 | -1562.4 | -2812.3 |
| 1100 | 1980 | 0.479 | 2.33 | 339.13 | 610.43 | -1565.4 | -2817.7 |
| 1200 | 2160 | 0.489 | 2.37 | 387.53 | 697.55 | -1568.0 | -2822.4 |
| 1300 | 2340 | 0.498 | 2.41 | 436.81 | 786.26 | -1570.2 | -2826.4 |
| 1400 | 2520 | 0.508 | 2.58 | 487.24 | 877.03 | -1572.0 | -2829.6 |
| 1500 | 2700 | | | | | | |

*Refer to Section 2.2.3

# TABLE 2.14

## VAPOR-PHASE THERMODYNAMIC PROPERTIES OF 70 w/o $H_2O_2$ SOLUTIONS*

| Temperature | | Heat Capacity, cal/gm-K (Btu/lb-R) | Entropy, cal/gm-K (Btu/lb-R) | Enthalpy ($H_T-H_{298}$) | | Heat of Formation | |
|---|---|---|---|---|---|---|---|
| K | R | | | cal/gm | Btu/lb | cal/gm | Btu/lb |
| 0 | 0 | 0 | 0 | -92.8 | -167.0 | -1589.2 | -2860.6 |
| 100 | 180 | 0.297 | 1.52 | -63.3 | -113.9 | -1608.3 | -2894.9 |
| 200 | 360 | 0.314 | 1.75 | -31.1 | -56.0 | -1618.5 | -2913.3 |
| 298 | 536.4 | 0.346 | 1.89 | 0.0 | 0 | -1631.8 | -2937.2 |
| 300 | 540 | 0.346 | 1.90 | 0.63 | 1.13 | -1632.2 | -2938.0 |
| 400 | 720 | 0.374 | 1.99 | 36.7 | 66.1 | -1642.3 | -2956.1 |
| 500 | 900 | 0.398 | 2.09 | 75.4 | 135.7 | -1650.8 | -2971.4 |
| 600 | 1080 | 0.418 | 2.16 | 116.2 | 209.2 | -1657.8 | -2984.0 |
| 700 | 1260 | 0.434 | 2.23 | 158.9 | 286.0 | -1663.8 | -2994.8 |
| 800 | 1440 | 0.448 | 2.28 | 203.1 | 365.6 | -1668.9 | -3004.0 |
| 900 | 1620 | 0.461 | 2.34 | 248.6 | 447.5 | -1673.4 | -3012.1 |
| 1000 | 1800 | 0.473 | 2.39 | 292.5 | 526.5 | -1677.4 | -3019.3 |
| 1100 | 1980 | 0.485 | 2.40 | 343.2 | 617.8 | -1680.8 | -3025.4 |
| 1200 | 2160 | 0.495 | 2.50 | 392.2 | 706.0 | -1683.7 | -3030.7 |
| 1300 | 2340 | 0.505 | 2.52 | 442.1 | 795.8 | -1686.1 | -3035.0 |
| 1400 | 2520 | 0.515 | 2.71 | 493.2 | 887.6 | -1688.2 | -3038.8 |

*Refer to Section 2.2.3

# TABLE 2.15

## REFRACTIVE INDEX (SODIUM D-LINE) OF PROPELLANT-GRADE $H_2O_2$-$H_2O$ SOLUTIONS AT 25 C*

| $H_2O_2$, w/o | 0.3, percent | 0.2, percent | 0.4, percent | 0.6, percent | 0.8, percent |
|---|---|---|---|---|---|
| 66 | 1.3782 | 1.3784 | 1.3785 | 1.3787 | 1.3788 |
| 67 | 790 | 792 | 793 | 796 | 796 |
| 68 | 798 | 800 | 801 | 803 | 804 |
| 69 | 806 | 808 | 809 | 811 | 812 |
| 70 | 1.3814 | 1.3816 | 1.3817 | 1.3819 | 1.3820 |
| 71 | 822 | 824 | 825 | 827 | 828 |
| 72 | 830 | 832 | 833 | 835 | 836 |
| 73 | 838 | 840 | 841 | 843 | 844 |
| 74 | 846 | 848 | 849 | 851 | 852 |
| 75 | 854 | 856 | 857 | 859 | 860 |
| 76 | 862 | 864 | 865 | 867 | 868 |
| 77 | 870 | 872 | 873 | 875 | 876 |
| 78 | 878 | 880 | 881 | 883 | 884 |
| 79 | 886 | 888 | 889 | 891 | 892 |
| 80 | 1.3894 | 1.3896 | 1.3897 | 1.3899 | 1.3901 |
| 81 | 903 | 904 | 906 | 908 | 909 |
| 82 | 911 | 913 | 915 | 916 | 918 |
| 83 | 920 | 921 | 923 | 925 | 927 |
| 84 | 928 | 930 | 932 | 933 | 935 |
| 85 | 937 | 939 | 940 | 942 | 944 |
| 86 | 945 | 947 | 949 | 950 | 952 |
| 87 | 954 | 956 | 957 | 959 | 961 |
| 88 | 962 | 964 | 966 | 968 | 969 |
| 89 | 971 | 973 | 974 | 976 | 978 |

*Refer to Section 2.2.5.1

NOTE: Temperature correction is $-0.34 \times 10^{-5}$/C from 15 to 25 C.

## TABLE 2.15
(Concluded)

| $H_2O_2$, w/o | 0.3, percent | 0.2, percent | 0.4, percent | 0.6, percent | 0.8, percent |
|---|---|---|---|---|---|
| 90 | 1.3880 | 1.3981 | 1.3983 | 1.3985 | 1.3986 |
| 91 | 988 | 990 | 992 | 993 | 995 |
| 92 | 997 | 999 | 1.4000 | 1.4002 | 1.4004 |
| 93 | 1.4006 | 1.4007 | 009 | 011 | 013 |
| 94 | 014 | 016 | 018 | 020 | 021 |
| 95 | 023 | 025 | 027 | 028 | 030 |
| 96 | 032 | 034 | 035 | 037 | 039 |
| 97 | 041 | 042 | 044 | 046 | 048 |
| 98 | 049 | 051 | 053 | 055 | 056 |
| 99 | 058 | 060 | 062 | 063 | 065 |
| 100 | 1.4067 | | | | |

## TABLE 2.16

## VERDET CONSTANT OF HYDROGEN PEROXIDE-WATER SOLUTIONS AT 10 C*

| $H_2O_2$, w/o | $-k_v$, min/gauss-cm x $10^3$ | | | |
|---|---|---|---|---|
| | 5893 Å | 5780 Å | 5461 Å | 4358 Å |
| 100 | 11.48 | 11.90 | 13.52 | 22.65 |
| 96 | 11.60 | 12.03 | 13.64 | 22.70 |
| 78.5 | 11.98 | 12.45 | 14.07 | 23.45 |
| 62.0 | 12.30 | 12.80 | 14.43 | 24.11 |
| 50.9 | 12.53 | 12.98 | 14.60 | 24.22 |
| 38.1 | 12.69 | 13.15 | 14.86 | 24.47 |
| 18.1 | 12.91 | 13.38 | 15.13 | 25.00 |
| 0 | 13.09 | 13.64 | 15.40 | 25.21 |

*Refer to Section 2.2.5.5

## TABLE 2.17

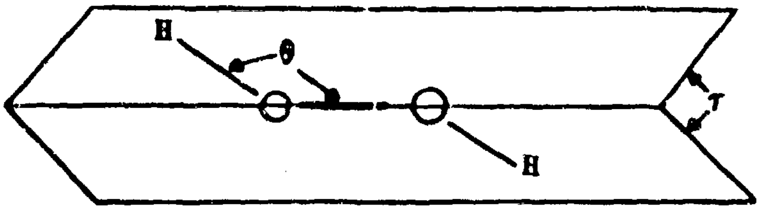
## MISCELLANEOUS MOLECULAR AND ELECTROMAGNETIC PROPERTIES OF HYDROGEN PEROXIDE

| Property | Value | Temperature | Reference |
|---|---|---|---|
| Specific Refraction | 0.1705 cm$^3$/gm | 25 C | 2.15 |
| Molar Refraction | 5.801 cm$^3$/mole | 25 C | 2.15 |
| Polarizability | 2.30 x 10$^{-24}$ cm$^3$/mole | 25 C | 2.45 |
| Molar Dispersion | 1.3576 cm$^3$/mole | — | 2.45 |
| Dispersion Constant | 8.479 x 10$^{30}$ sec$^{-2}$ | — | 2.45 |
| Characteristic Frequency | 2.979 x 10$^{15}$ sec$^{-1}$ | — | 2.45 |
| Molecular Radius | 1.32 Å | — | 2.45 |
| Molecular Susceptibility | -21.0 ±4 | 25 C | 2.46 |
| Molecular Diamagnetism | 16.73 ±0.20 | 25 C | 2.47 |

## TABLE 2.18

## STRUCTURE AND STRUCTURAL PARAMETERS OF HYDROGEN PEROXIDE

### Structure



### Structural Parameters

| | R(O-O), Å | R(O-H), Å | $\theta$(OOH), degrees | $\tau$ (HOOH), degrees |
|---|---|---|---|---|
| Electron Diffraction | 1.47 | | | |
| Crystal Diffraction | 1.49 | | 97 | 94 |
| Far Infrared | 1.475 ±0.004 | 0.950 ±0.005 | 94.8 ±2 | (119.8 ±3) |
| Microwave | | | | 111.5 |

## TABLE 2.19

## REACTIONS OF HYDROGEN PEROXIDE

|  | Reference |
|---|---|
| INORGANIC COMPOUNDS |  |
| $Ag + H_2O_2 \xrightarrow{\text{acid}}$ dissolves $(Ag^+)$ | 2.56 |
| $Al + H_2O_2 \longrightarrow Al(OH)_3$ | 2.10 |
| $As + H_2O_2 \longrightarrow H_3AsO_4$ | 2.10 |
| $AsO_3^{-3} + H_2O_2 \longrightarrow AsO_4^{-3}$ | 2.57 |
| $As(OH)_3 + H_2O_2 \longrightarrow H_3AsO_4$ | 2.10 |
| $Au + H_2O_2 \xrightarrow{\text{HCl}}$ dissolves | 2.58 |
| Oxide of gold $+ H_2O_2 \xrightarrow{\text{alkaline}}$ reduction | 2.58 |
| B (colloidal) $+ H_2O_2 \longrightarrow H_3BO_3$ | 2.59 |
| $Ba(OH)_2 + H_2O_2 \longrightarrow BaO_2 + H_2O$ | 2.10 |
| $Bi_2O_3 + H_2O_2 \longrightarrow Bi_2O_4$ | 2.60 |
| $Bi(NO_3)_3 + H_2O_2 \xrightarrow{\text{alkaline}} Bi(OH)_3$ | 2.61 |
| $BrO_3^{-1} + H_2O_2 \longrightarrow Br^{-1} + Br_2$ | 2.10 |
| $CN^{-1} + H_2O_2 \longrightarrow CO_3^{-2} + CNO^{-1}$ | 2.62 |
| $CNS^{-1} + H_2O_2 \longrightarrow NH_3 \xrightarrow{H_2O_2} NO_3^{-1}$ | 2.63 |

## TABLE 2.19
(Continued)

| | Reference |
|---|---|
| INORGANIC COMPOUNDS (cont.) | |
| $Cl_2 + H_2O_2 \xrightarrow{} Cl^{-1}$ | 2.64 |
| $ClO_3^{-1} + H_2O_2 \xrightarrow[\text{neutral}]{\text{alkaline or}} \text{no reaction}$ | 2.65 |
| $ClO_3^{-1} + H_2O_2 \xrightarrow{\text{acid}} Cl_2 + ClO_2$ | 2.65 |
| $HClO_4 + H_2O_2 \xrightarrow{} \text{no reaction}$ | 2.10 |
| $HOCl + H_2O_2 \xrightarrow{} Cl^{-1}$ | 2.64 |
| $Co + H_2O_2 \xrightarrow{} \text{dissolves}$ | 2.66 |
| $Co + H_2O_2 \xrightarrow{\text{alkaline}} Co(HO)_3$ | 2.10 |
| $Cr + H_2O_2 \xrightarrow{} \text{slow solution}$ | 2.10 |
| $CrO_3 + H_2O_2 \xrightarrow{} Cr^{+3}$ | 2.67 |
| $Cu + H_2O_2 \xrightarrow{\text{acid}} \text{dissolves}$ | 2.68 |
| $CuO + H_2O_2 \xrightarrow{} CuO_2 + H_2O$ | 2.69 |
| $CuO_2 + H_2O_2 \xrightarrow{} CuO + H_2O + O_2$ | 2.69 |
| $Fe + H_2O_2 \xrightarrow{} Fe^{+2} \xrightarrow{H_2O_2} Fe^{+3}$ | 2.10 |
| $Fe(CN)_6^{-4} + H_2O_2 \xrightarrow{\text{acid}} Fe(CN)_6^{-3}$ | 2.70 |

## TABLE 2.19
(Continued)

| | Reference |
|---|---|
| INORGANIC COMPOUNDS (cont.) | |
| $Fe(CN)_6^{-3} + H_2O_2 \xrightarrow{\text{alkaline}} Fe(CN)_6^{-4}$ | 2.70 |
| $Hg + H_2O_2 \xrightarrow{\text{acid}}$ dissolves | 2.10 |
| $Hg + H_2O_2 \xrightarrow{\text{alkaline}}$ oxides of mercury | 2.10 |
| $I_2 + H_2O_2 \longrightarrow I^{-1} \xrightarrow{pH=1} IO_3^{-1}$ | 2.71 |
| $HI + H_2O_2 \longrightarrow I_2 + H_2O$ | 2.10 |
| $Li^{+1} + H_2O_2 \longrightarrow Li_2O_2$ | 2.10 |
| $Mg + H_2O_2 \longrightarrow Mg(OH)_2$ | 2.10 |
| $MnO_4^{-1} + H_2O_2 \xrightarrow{\text{acid}} Mn^{+2} + H_2O + O_2$ | 2.10 |
| $MnO_4^{-1} + H_2O_2 \xrightarrow{\text{alkaline}} MnO_2$ | 2.10 |
| $MoS_2 + H_2O_2 \longrightarrow SO_4^{-2}$ | 2.10 |
| $Ni + H_2O_2 \xrightarrow[H_2SO_4]{\text{HCl or}}$ dissolves | 2.10 |
| $NiSO_4 + H_2O_2 \xrightarrow{H^+}$ no reaction | 2.72 |
| $N_2H_4 + H_2O_2 \longrightarrow$ various products depending upon conditions | 2.73 |
| $HONH_2 + H_2O_2 \longrightarrow NO_3^{-1}$ | 2.74 |

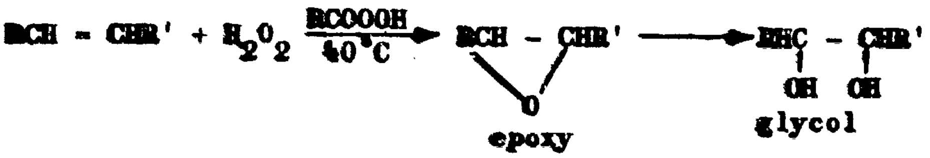
## TABLE 2.19
## (Continued)

| | Reference |
|---|---|
| INORGANIC COMPOUNDS (cont.) | |
| $NO_2^{-1} + H_2O_2 \longrightarrow NO_3^{-1}$ | 2.75 |
| $NO_3^{-1} + H_2O_2 \longrightarrow$ no reaction | 2.10 |
| $O_3 + H_2O_2 \longrightarrow H_2O + O_2$ | 2.76 |
| $P + H_2O_2 \longrightarrow PH_3 + H_3PO_4$ | 2.77 |
| $P_2O_5 + H_2O_2 + H_2O \longrightarrow H_3PO_5$ | 2.78 |
| $PO_4^{-3} + H_2O_2 \longrightarrow$ no reaction | 2.10 |
| $PO_3^{-3} + H_2O_2 \longrightarrow PO_4^{-3}$ | 2.79 |
| $Pb + H_2O_2 \xrightarrow{H^+}$ dissolves | 2.80 |
| $Pb + H_2O_2 \xrightarrow{\text{alkaline}} PbO_2$ | 2.80 |
| $Po + H_2O_2 \longrightarrow$ dissolves | 2.81 |
| $Pt + H_2O_2 \longrightarrow$ no reaction | 2.82 |
| $S + H_2O_2 \longrightarrow$ no reaction | 2.10 |
| $H_2S$ (aq.) $+ H_2O_2 \xrightarrow{\text{acid}} S^{\circ}$ | 2.83 |
| $H_2S$ (aq.) $+ H_2O_2 \xrightarrow{\text{alkaline}} SO_4^{-2}$ | 2.84 |
| $M_2S + H_2O_2 \longrightarrow SO_4^{-2}$ plus various products depending upon metal | 2.84 |

## TABLE 2.19
(Continued

| | **Reference** |
|---|---|
| **INORGANIC COMPOUNDS (cont.)** | |
| $SO_3^{-2} + H_2O_2 \longrightarrow SO_4^{-2} + S_2O_6^{-2}$ | 2.85 |
| $Sb + H_2O_2 \longrightarrow$ no reaction | 2.10 |
| $Sb_2S_3 + H_2O_2 \xrightarrow{NH_3}$ antimoniate | 2.86 |
| $Se + H_2O_2 \longrightarrow SeO_2$ | 2.87 |
| $\phantom{Se + H_2O_2} \longrightarrow H_2SeO_4$ | 2.10 |
| $H_2Se + H_2O_2 \longrightarrow$ rapidly attacked | 2.10 |
| $SeO_3^{-2} + H_2O_2 \longrightarrow SeO_4^{-2}$ | 2.88 |
| $Sn^{+2} + H_2O_2 \longrightarrow Sn^{+4}$ | 2.89 |
| $SnO_2 + H_2O_2 \longrightarrow$ no reaction | 2.10 |
| $Te + H_2O_2 \longrightarrow H_6TeO_6$ | 2.90 |
| $Ti^{+3} + H_2O_2 \longrightarrow TiO_3$ | 2.91 |
| $TiO_2^{+2} + H_2O_2 \longrightarrow Ti(O_2)_4^{-4}$ | 2.92 |
| $Tl + H_2O_2 \longrightarrow TlOH$ | 2.10 |
| $TlO_2 + H_2O_2 \longrightarrow Tl_2O_3$ | 2.10 |
| $W + H_2O_2 \longrightarrow H_2WO_4$ | 2.10 |

## TABLE 2.19
(Continued)

| | **Reference** |
|---|---|
| **INORGANIC COMPOUNDS** (cont.) | |
| $Zn + H_2O_2 \longrightarrow ZnO$ | 2.10 |
| $Zn + H_2O_2 \xrightarrow[\text{alcoholic}]{\text{alkaline}} \text{dissolves}$ | 2.93 |
| $Zr + H_2O_2 \longrightarrow \text{no reaction}$ | 2.94 |
| $Zr(SO_4)_2 + H_2O_2 \longrightarrow \text{no reaction}$ | 2.94 |
| **ORGANIC COMPOUNDS** | |
| **Alkanes:** | |
| Saturated paraffins + $H_2O_2 \xrightarrow[\text{catalysts}]{\text{with and without}} \text{no reaction}$ | 2.55 |
| Cyclic alkanes + $H_2O_2 \xrightarrow[\text{catalysts}]{\text{with and without}} \text{no reaction}$ | 2.55 |
| Grignard reagent (RMgX) + $H_2O_2 \longrightarrow \text{alcohol}$ | 2.95 |
| **Alkenes:** | |
| $RCH = CHR' + H_2O_2 \xrightarrow[\text{catalysts}]{\text{with and without}} \text{no reaction}$ | 2.55 |
|  $RCH = CHR' + H_2O_2 \xrightarrow[40^\circ C]{RCOOOH} \underset{\text{epoxy}}{\underset{O}{RCH - CHR'}} \longrightarrow \underset{\text{glycol}}{\underset{OH \quad OH}{RHC - CHR'}}$ | 2.10,<br>2.55 |

## TABLE 2.19

(Continued)

| | Reference |
|---|---|
| **ORGANIC COMPOUNDS (cont.)** | |
| **Alcohols:** | |
| $ROH + H_2O_2 \xrightarrow[\text{no catalyst}]{\text{cold}} \text{no reaction}$ | 2.55 |
| $RCH_2OH + H_2O_2 \xrightarrow{Fe^{+3}} RCOOH \longrightarrow CO_2$ | 2.55 |
| **Carboxylic Acids:** | |
| $RCOOH + H_2O_2 \xrightarrow{1\%\ H_2SO_4} \underset{\text{peroxy acid}}{RCOOOH} + H_2O$ | 2.55 |
| **Aldehydes:** | |
| $R\text{-}CHO + H_2O_2 \xrightarrow[H^+]{80\ C} RCOOH$ | 2.55 |
| **Aromatics:** | |
| Benzene or toluene + $H_2O_2 \xrightarrow{\text{no catalyst}}$ no reaction | 2.10 |
| Benzene + $H_2O_2 \xrightarrow[\text{Al strips}]{Fe^{++}\ \text{catalyst}}$ phenol | 2.55 |
| β-naphthol + $\underset{\text{(in acetic acid)}}{H_2O_2} \xrightarrow{RCOOOH}$ o-carboxycinnamic acid | 2.96,<br>2.98 |
| Hydrazobenzene + $H_2O_2 \xrightarrow{22\text{-}23C}$ azobenzene | 2.55 |
| Azobenzene + $\underset{\text{(in acetic acid)}}{H_2O_2} \xrightarrow[RCOOOH]{1\%\ H_2SO_4}$ azoxybenzene | 2.55 |

## TABLE 2.19
(Concluded)

|  | Refcrence |
|---|---|
| **ORGANIC COMPOUNDS (cont.)** |  |
| Aromatics: |  |
| Aniline + $H_2O_2$ $\xrightarrow{22\text{-}23C}$ aniline black products | 2.55 |
| Aniline + $H_2O_2$ (in acetic acid) $\xrightarrow[\text{added to water slurry of aniline containing Na bicarbonate}]{22\text{-}23C;\ \text{oxidant}}$ nitrobenzene + azoxybenzene | 2.96 |
| Benzaldehyde + $H_2O_2$ (in acetic acid) $\xrightarrow[1\%\ H_2SO_4]{22\text{-}23C}$ benzoic acid<br>RCOOOH | 2.97 |
| Anthracene + $H_2O_2$ (in acetic acid) $\xrightarrow{RCOOOH}$ anthraquinone | 2.96 |
| Primary Amines: |  |
| $RNH_2 + H_2O_2 \longrightarrow$ vigorous decomposition of peroxide; reaction difficult to control; no products isolated | 2.55 |
| Secondary Amines: |  |
| $(R)_2NH + H_2O_2 \longrightarrow (R)_2NOH$<br>hydroxylamine | 2.55 |
| Tertiary Amines: |  |
| $(R)_3N + H_2O_2 \longrightarrow R_3NO$<br>amineoxide | 2.55 |

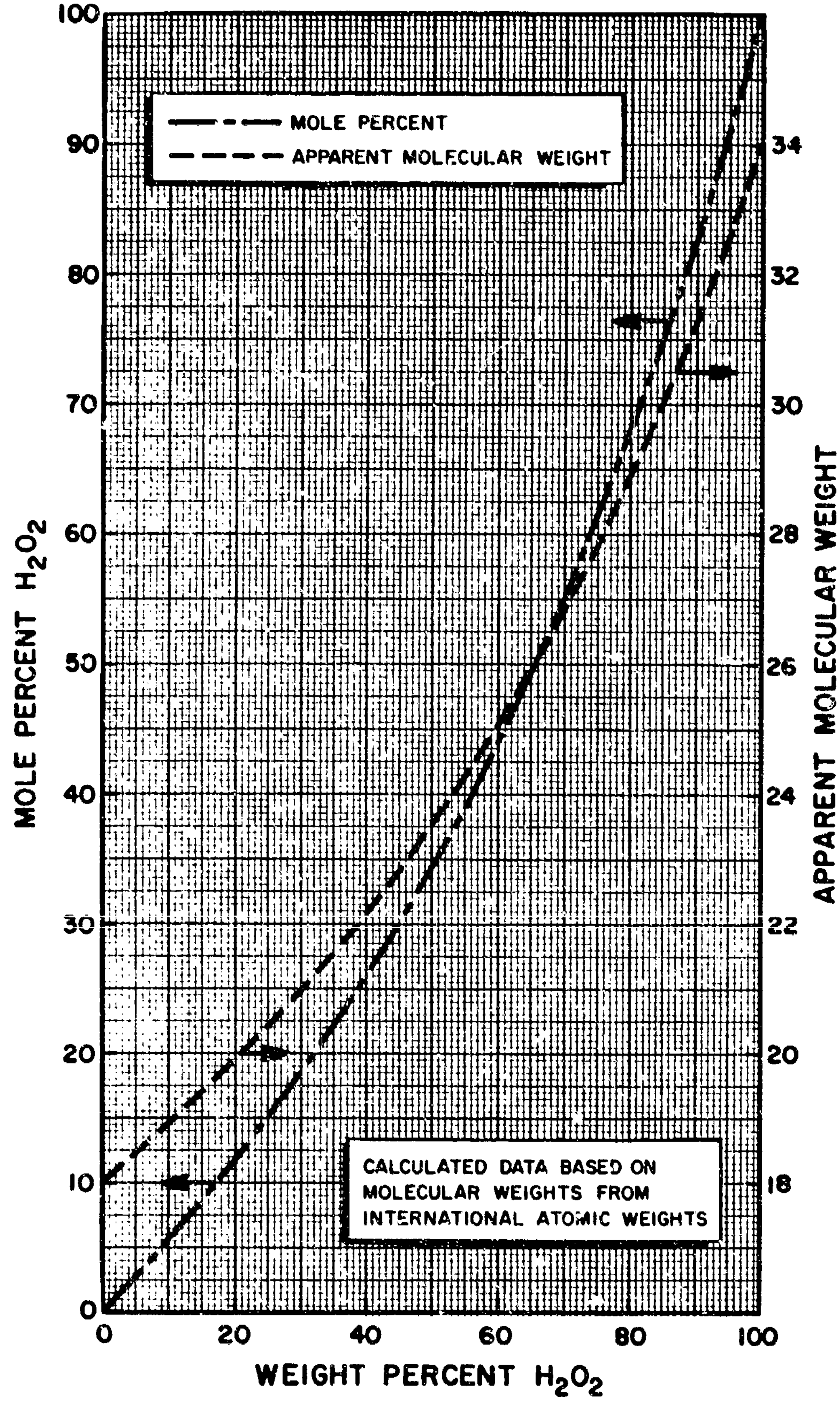


Figure 2.1. Concentration and Apparent Molecular Weight of Aqueous Hydrogen Peroxide Solutions

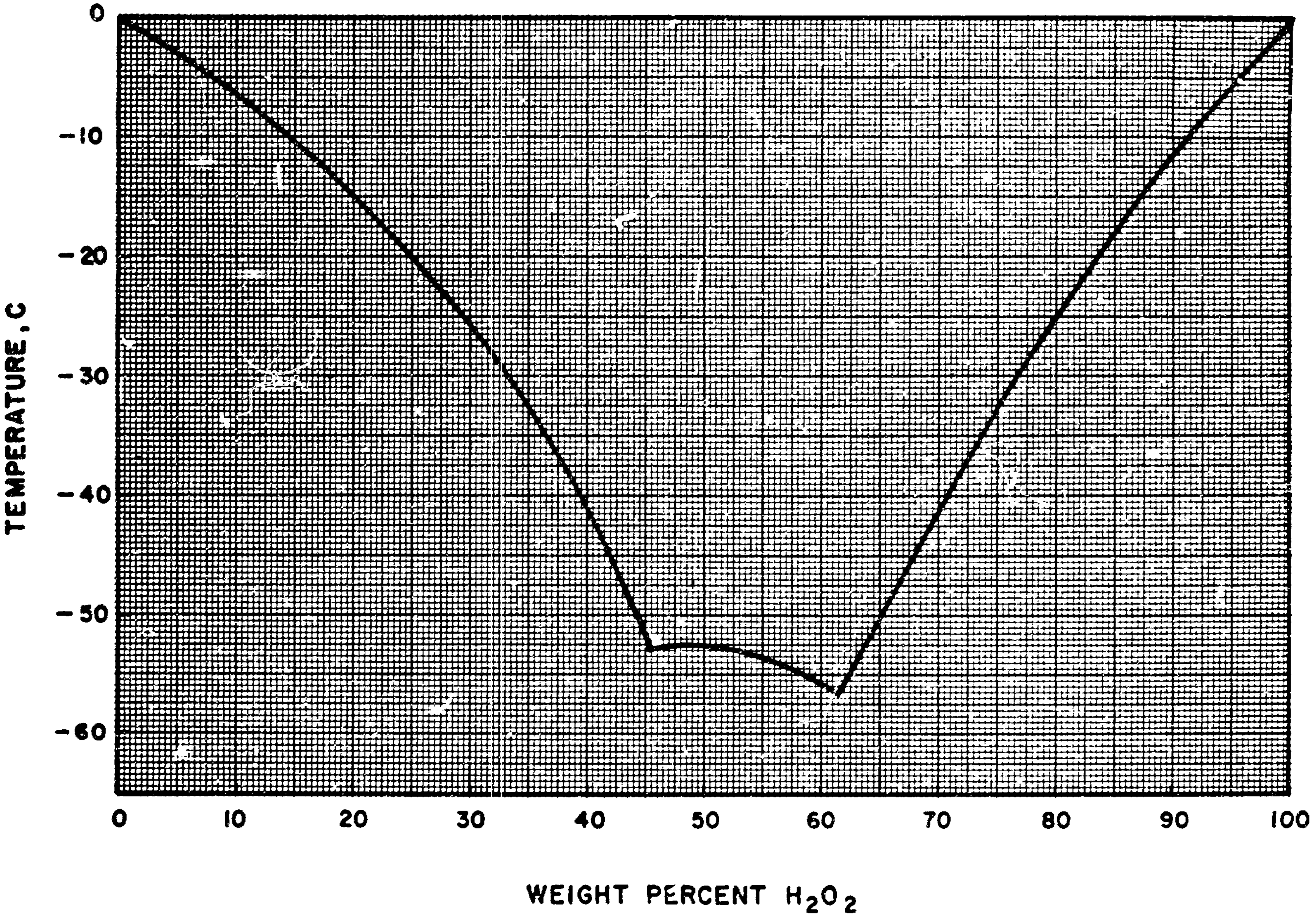


Figure 2.2. Freezing Points of Hydrogen Peroxide-Water Solutions (Ref. 2.2)

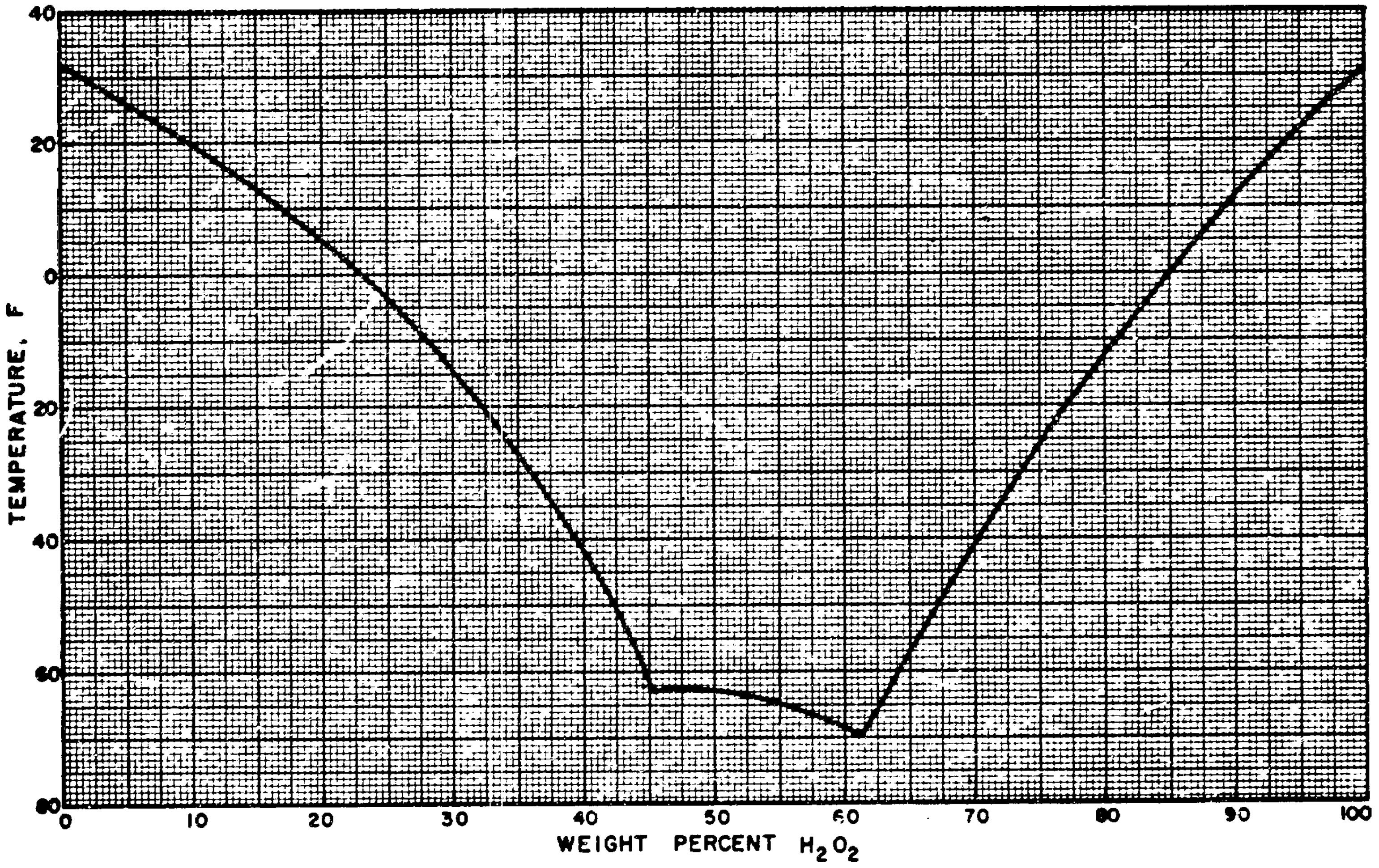
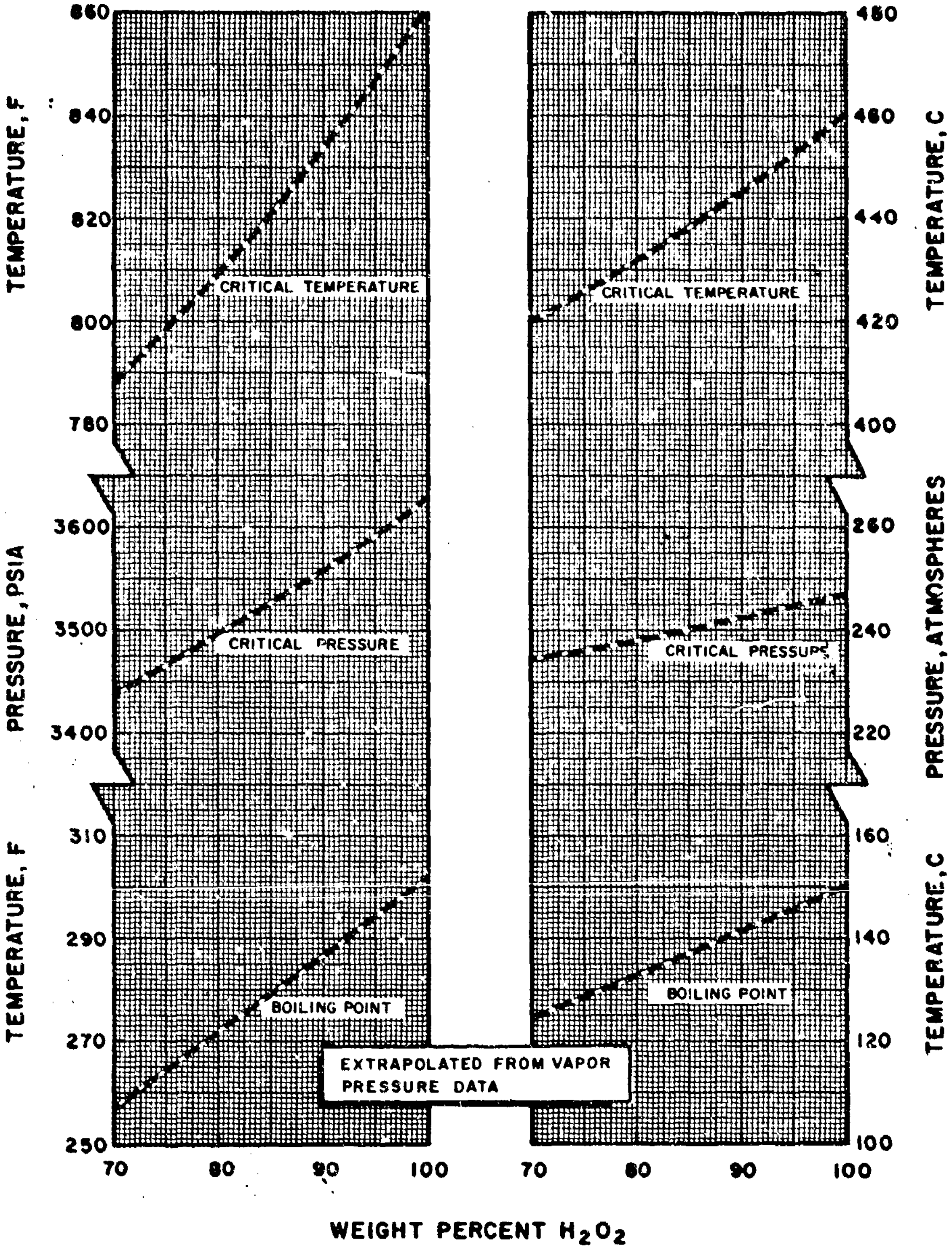


Figure 2.2a. Freezing Points of Hydrogen Peroxide-Water Solutions (Ref. 2.2)



**WEIGHT PERCENT $H_2O_2$**

Figure 2.3. Critical Temperature, Critical Pressure, and Boiling Point of Propellant-Grade Hydrogen Peroxide-Water Solutions

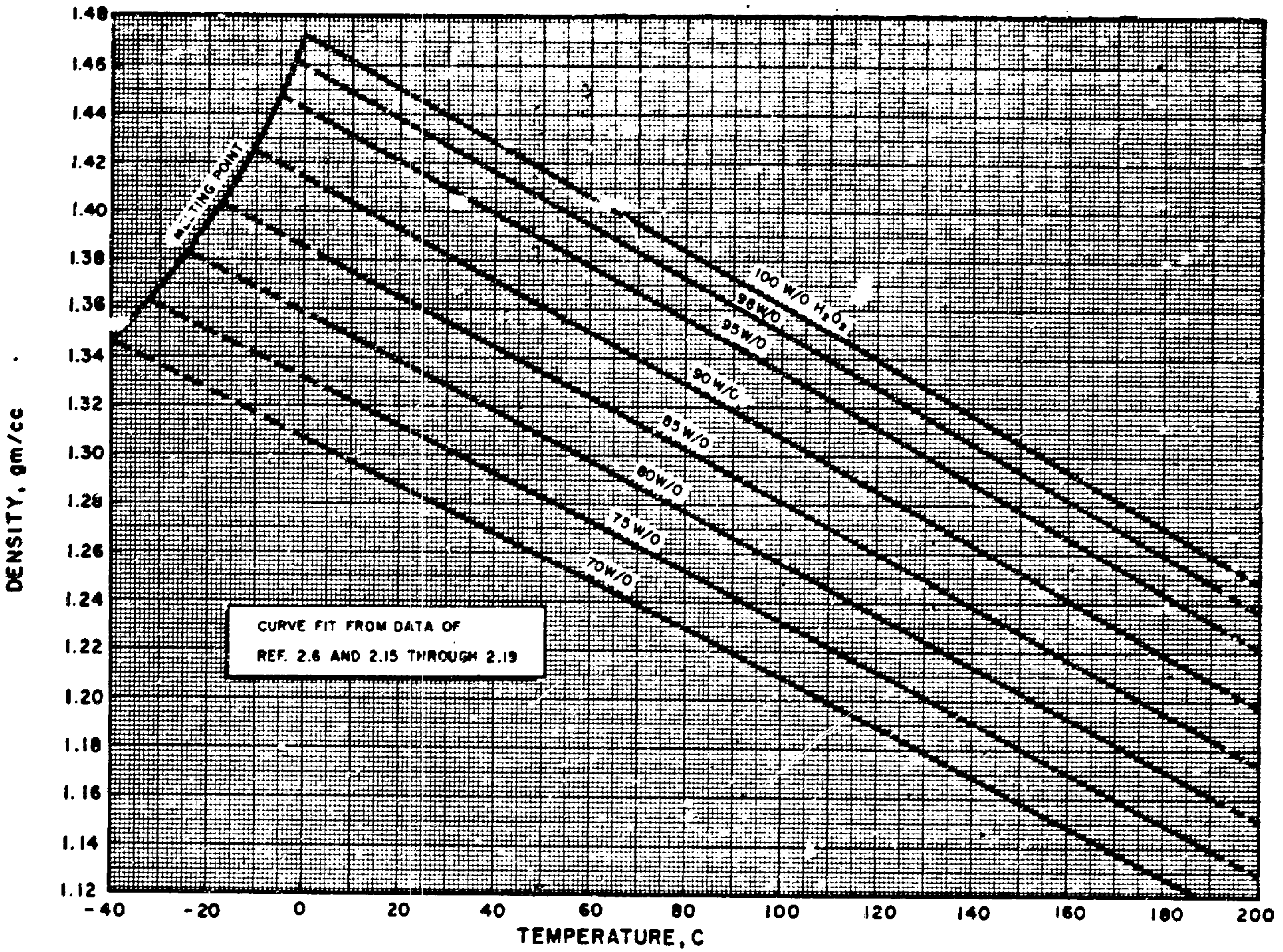


Figure 2.4. Density of Propellant-Grade Hydrogen Peroxide-Water Solutions

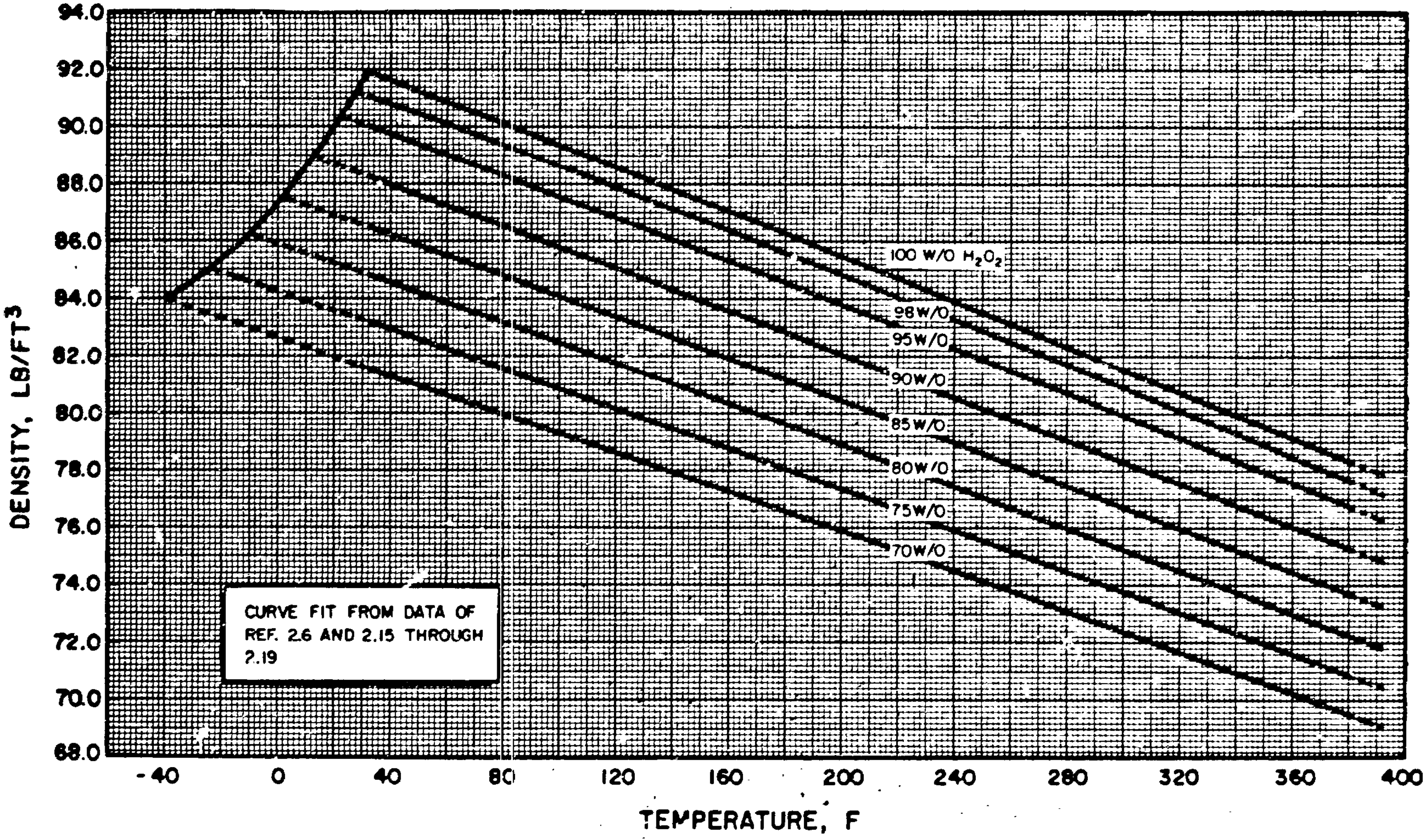


Figure 2.4a. Density of Propellant-Grade Hydrogen Peroxide-Water Solutions

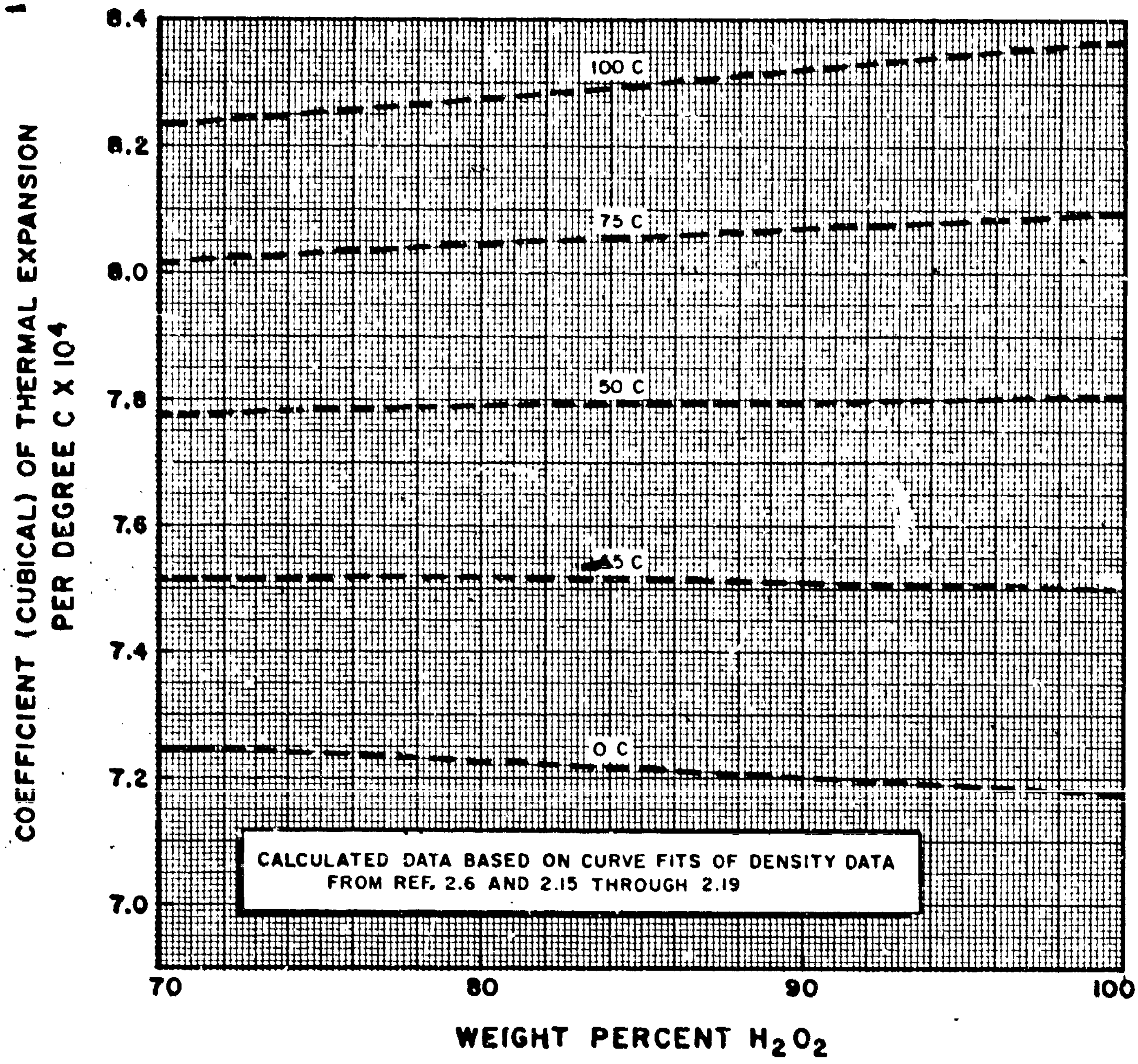


Figure 2.5. Coefficients (Cubical) of Thermal Expansion for Propellant-Grade Hydrogen Peroxide-Water Solutions

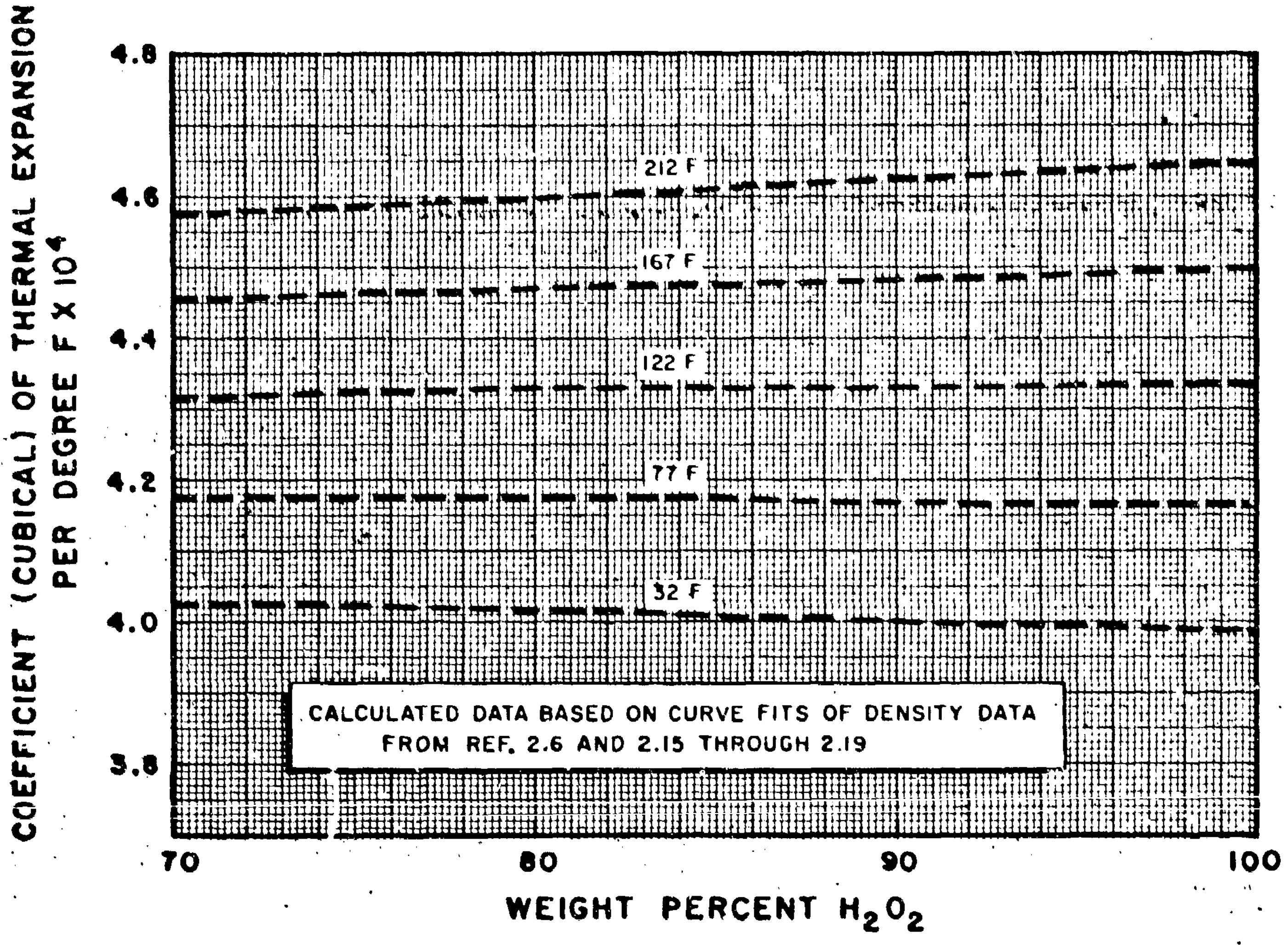


Figure 2.5a. Coefficients (Cubical) of Thermal Expansion for Propellant-Grade Hydrogen Peroxide-Water Solutions

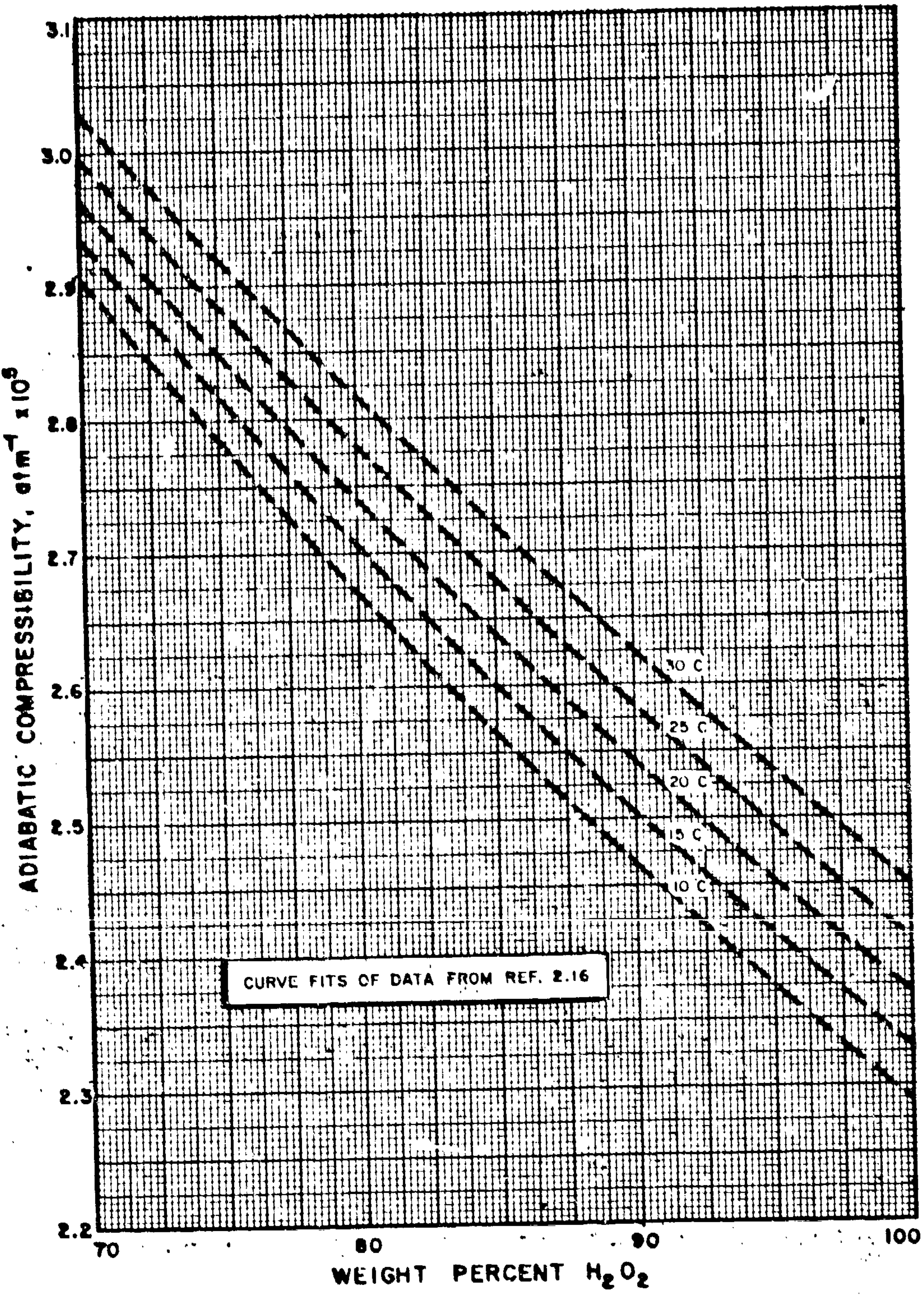


Figure 2.6. Adiabatic Compressibility of Propellant-Grade Hydrogen Peroxide-Water Solutions

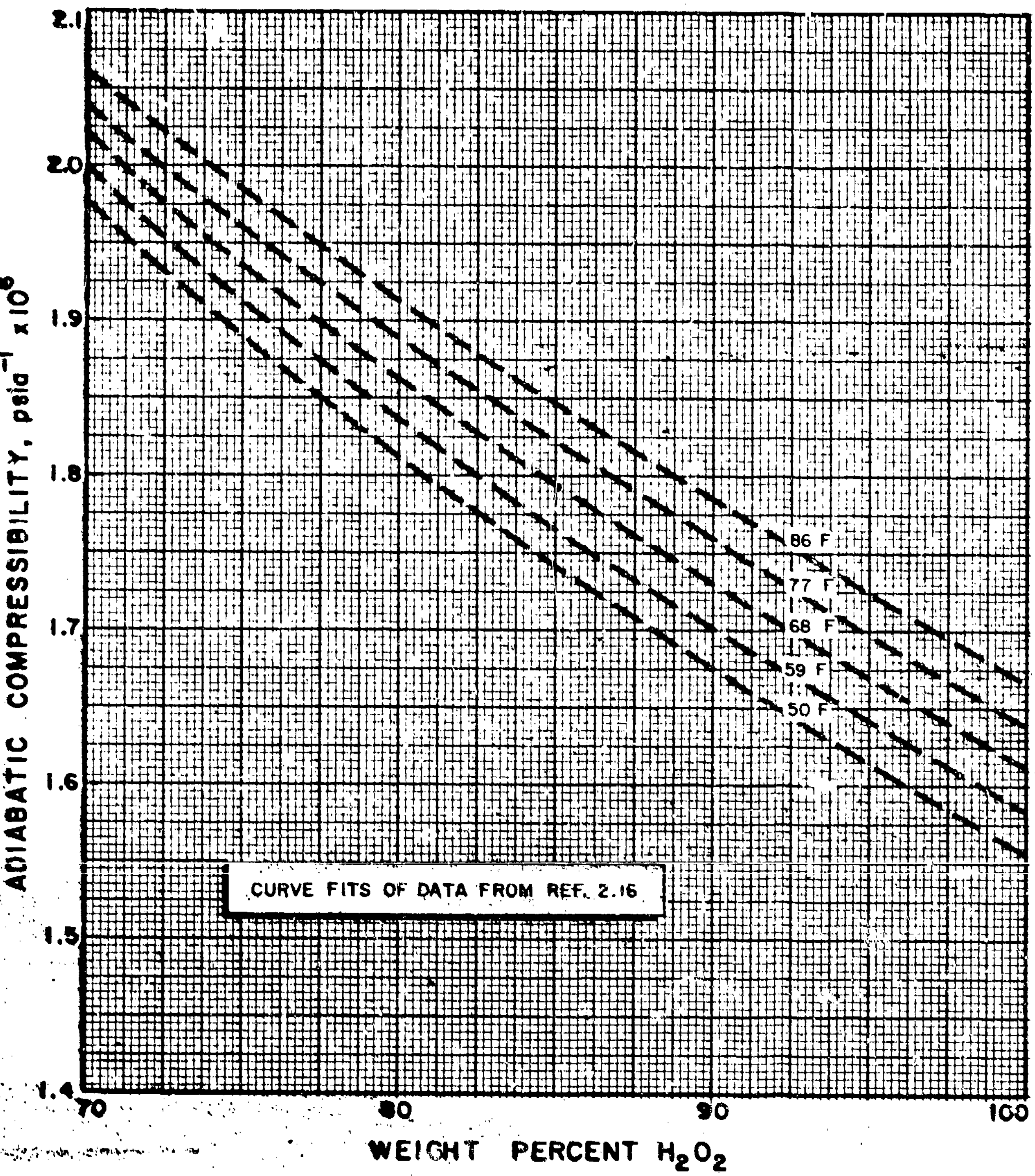


Figure 2.6a. Adiabatic Compressibility of Propellant-Grade Hydrogen Peroxide-Water Solutions

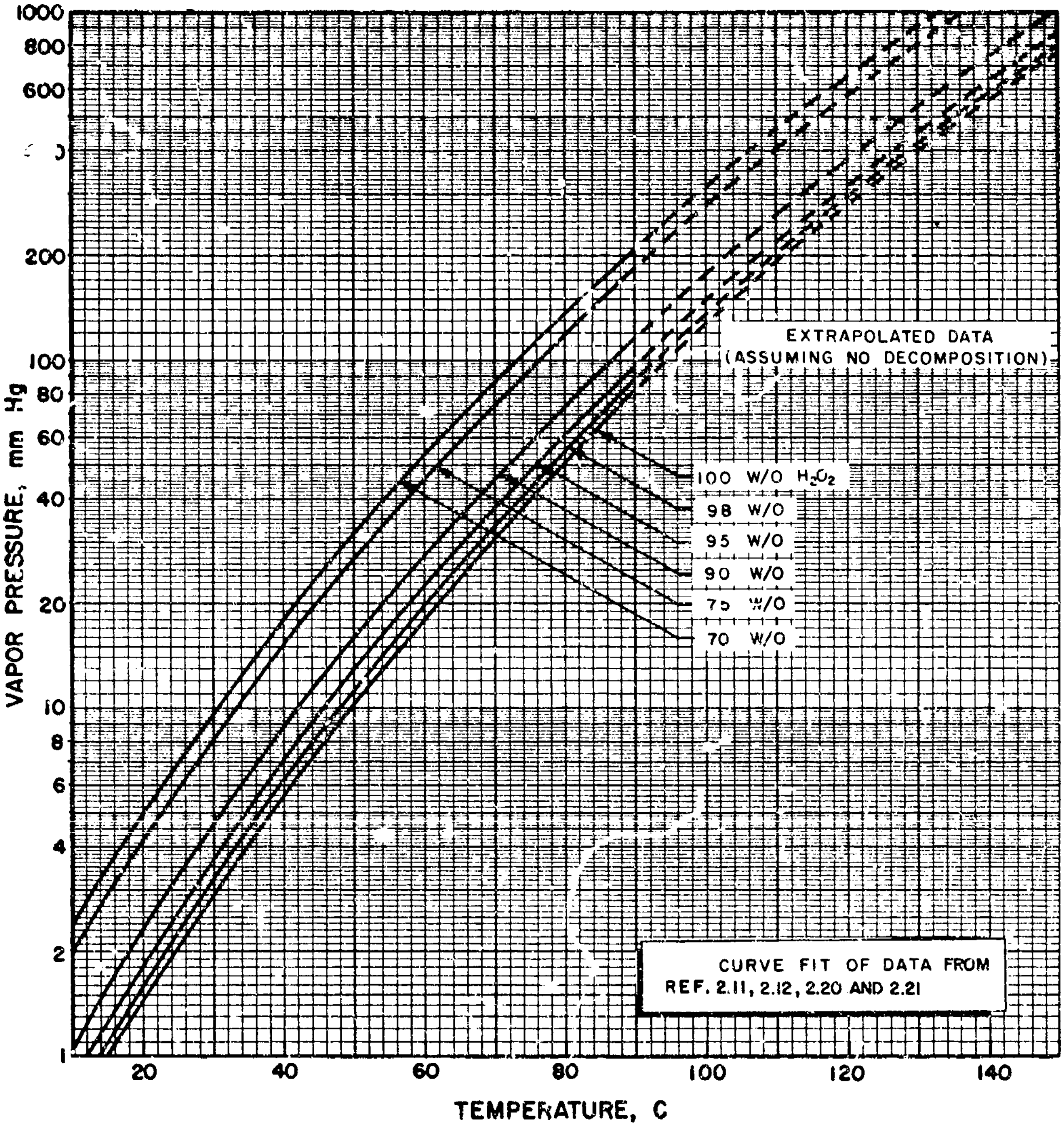


Figure 2.7. Vapor Pressure of Propellant-Grade Hydrogen Peroxide-Water Solutions

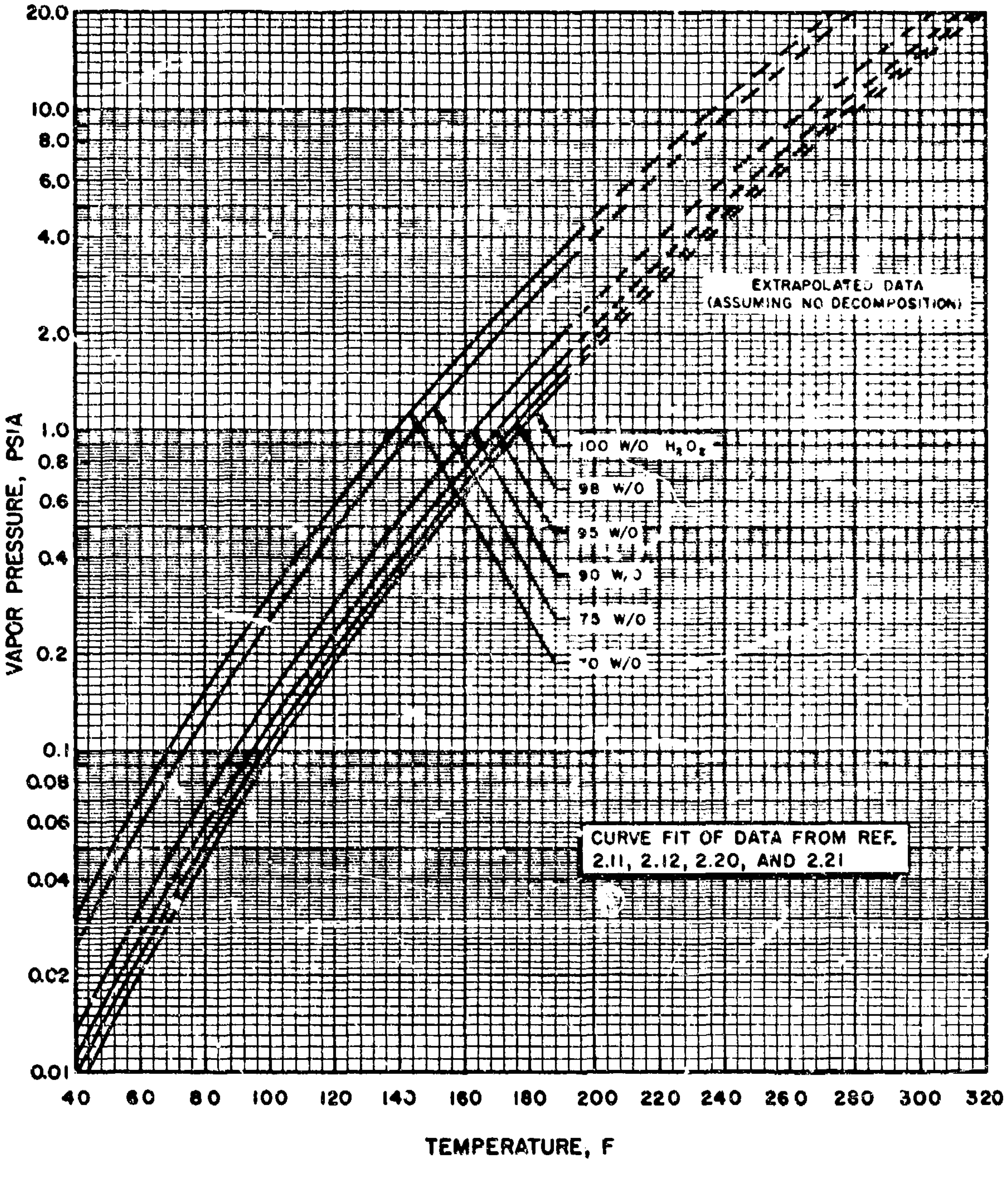


Figure 2.7a. Vapor Pressure of Propellant-Grade Hydrogen Peroxide-Water Solutions

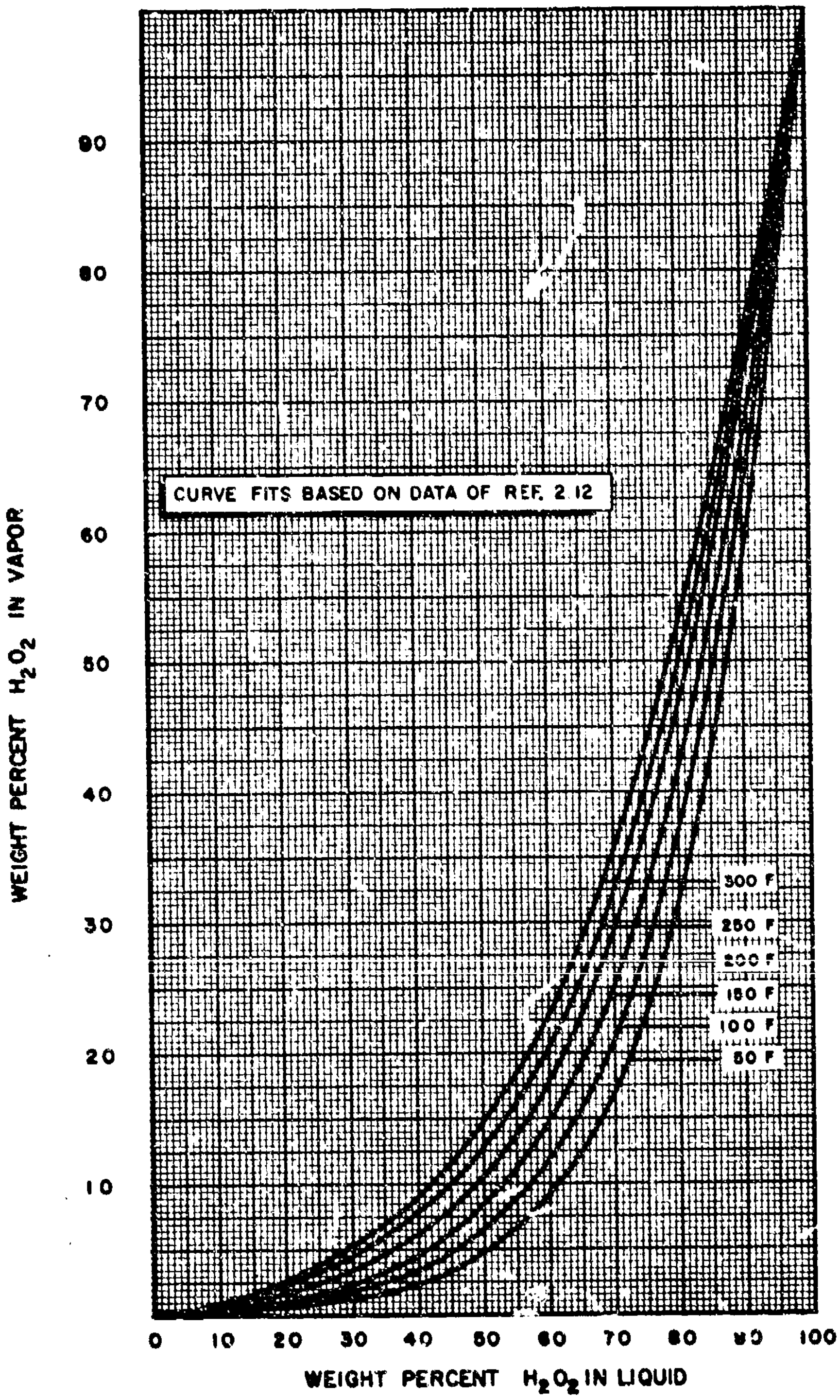


Figure 2.8. Vapor Composition Over Hydrogen Peroxide-Water Solutions (Ref. 2.22)

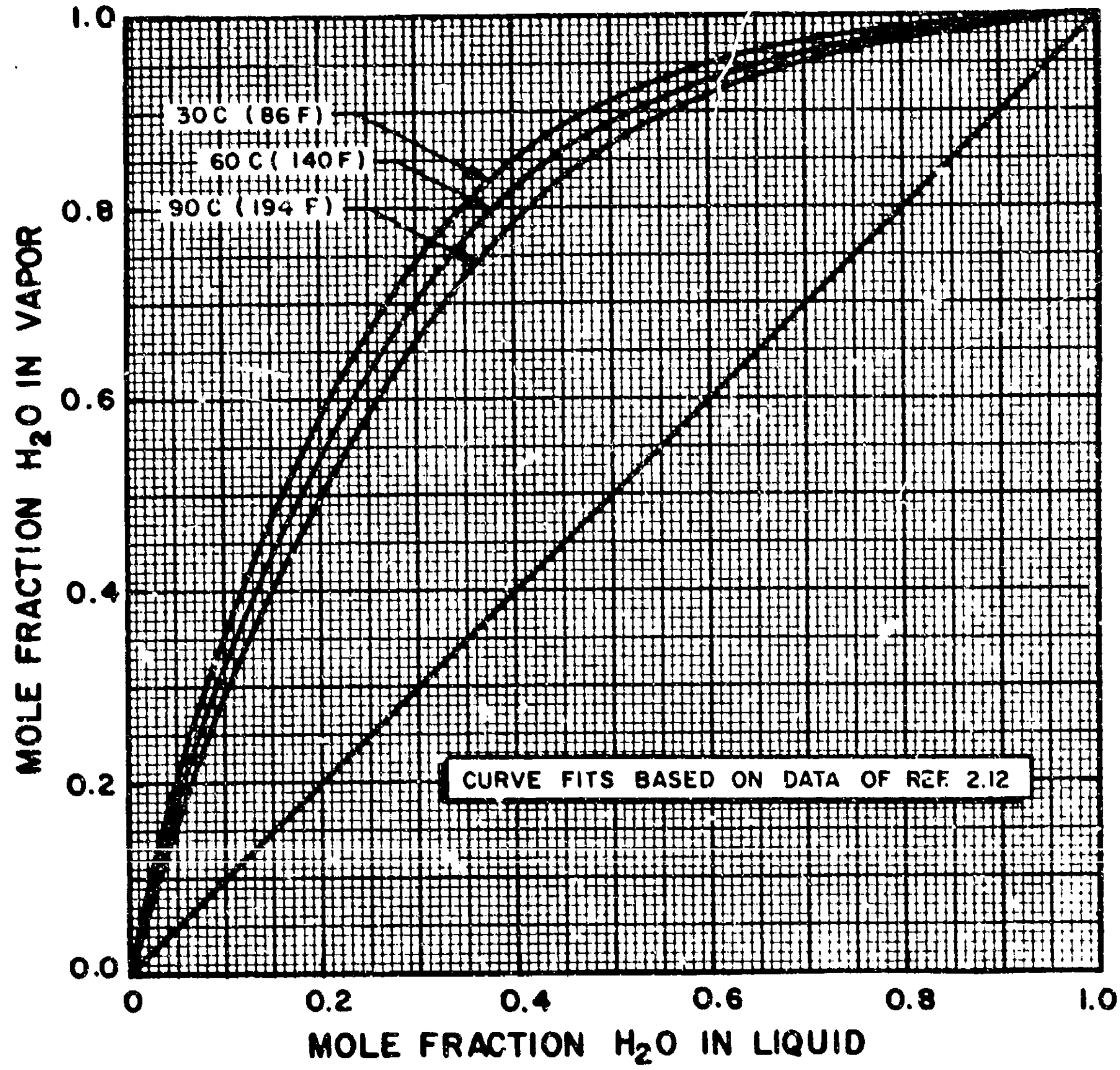


Figure 2.9. Vapor-Liquid Equilibrium for the Hydrogen Peroxide-Water System (Ref. 2.22)

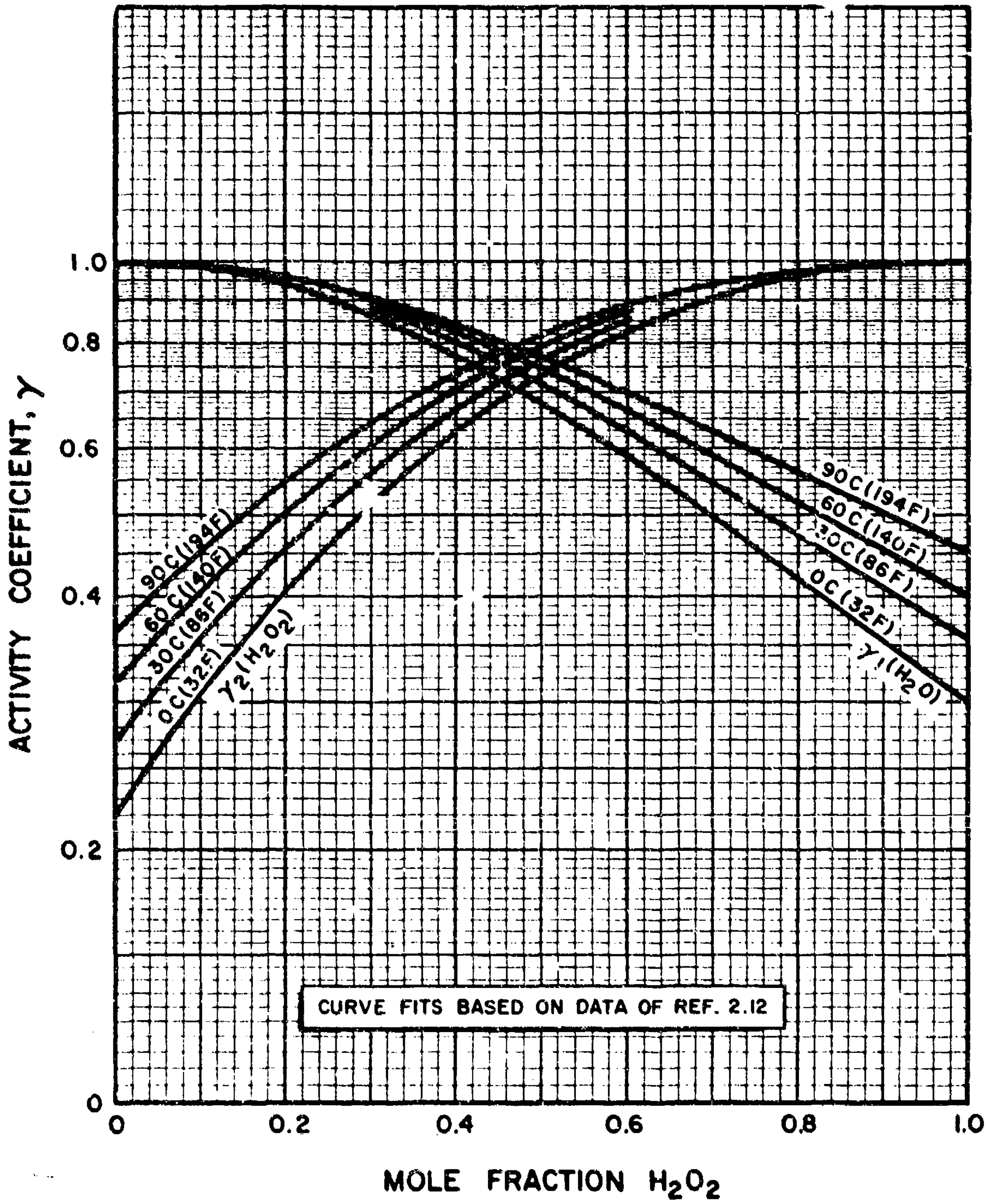


Figure 2.10. Activity Coefficients for Hydrogen Peroxide-Water Solutions (Ref. 2.22)

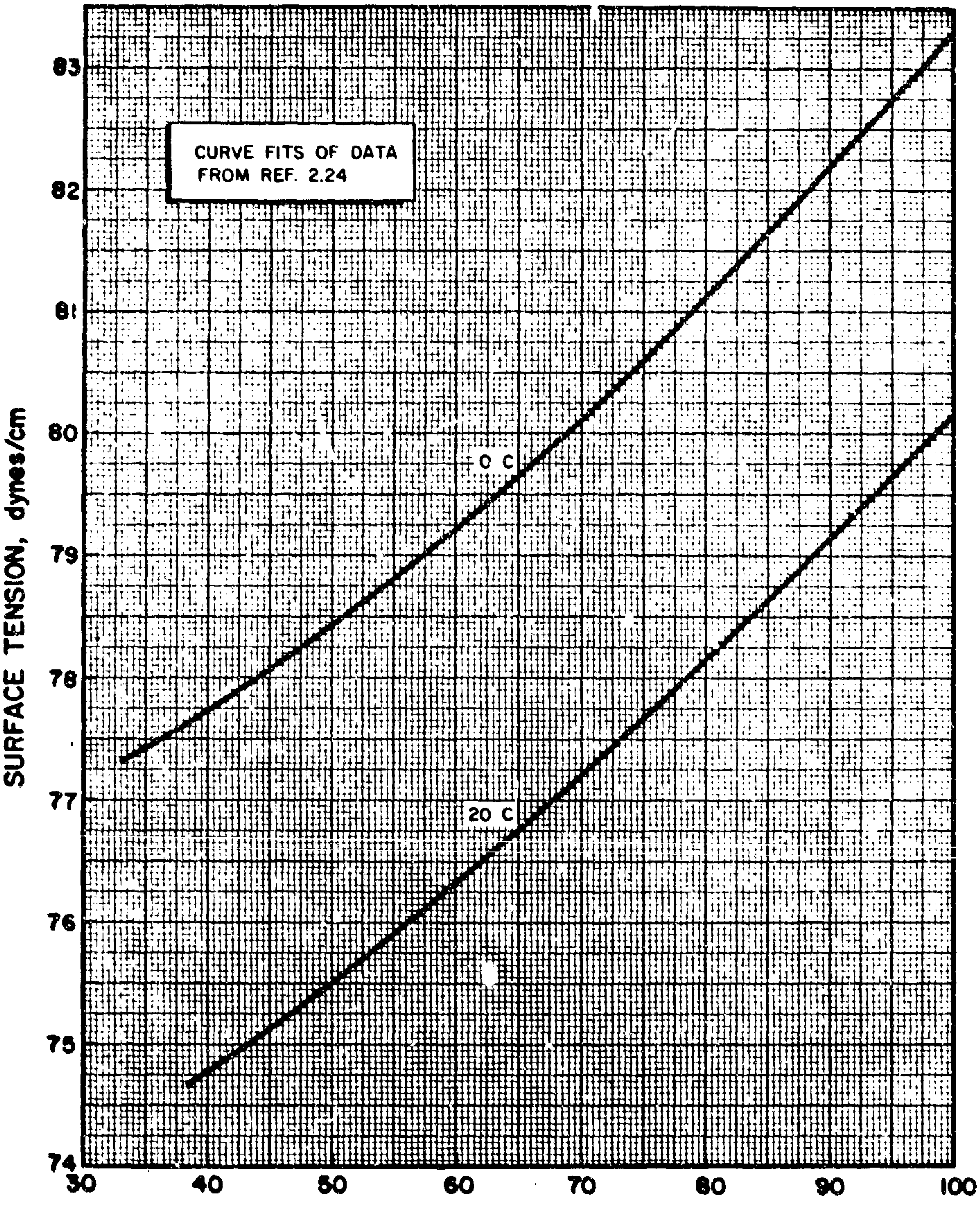


Figure 2.11. Surface Tension of Hydrogen Peroxide-Water Solutions

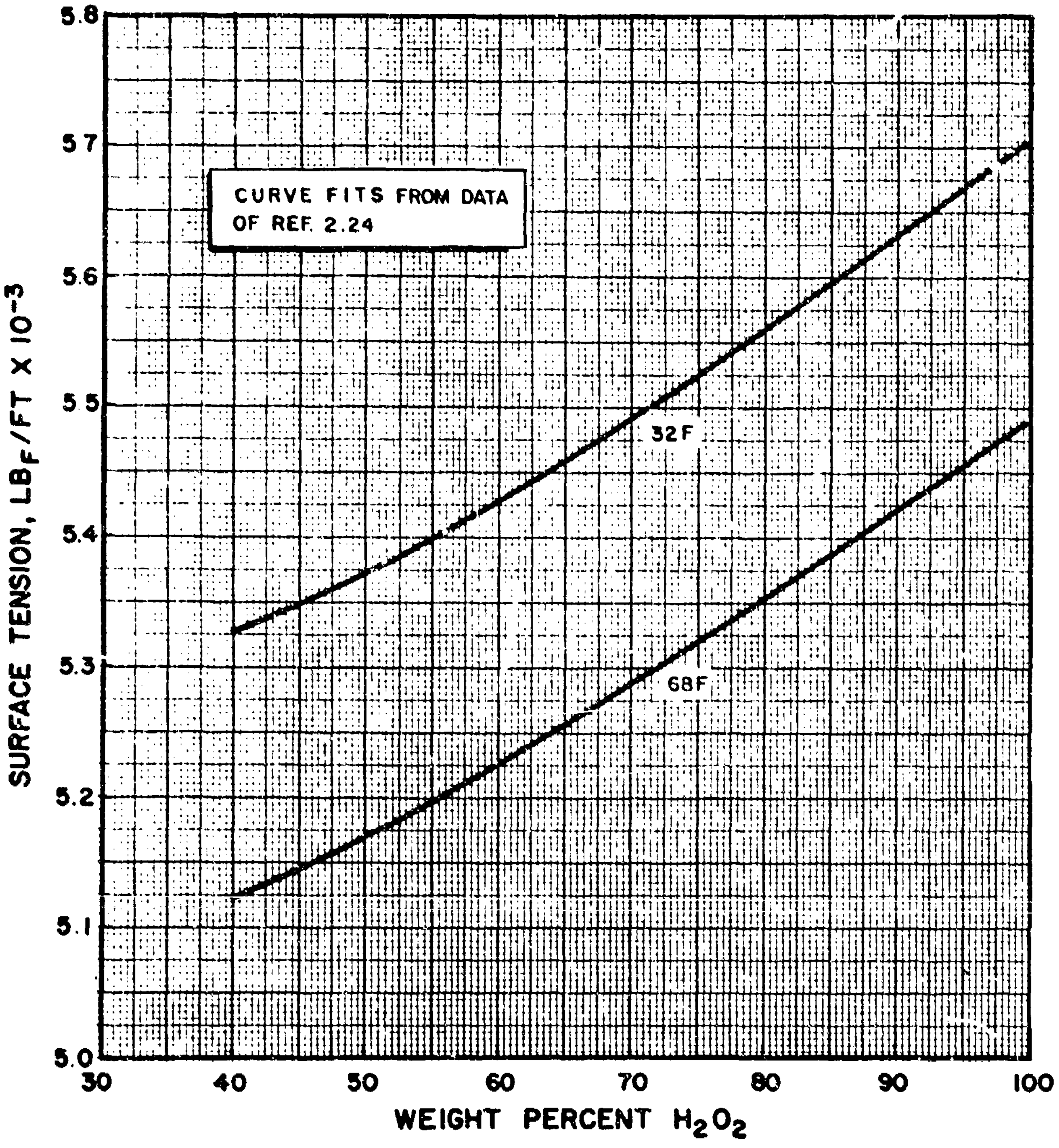


Figure 2.11a. Surface Tension of Hydrogen Peroxide-Water Solutions

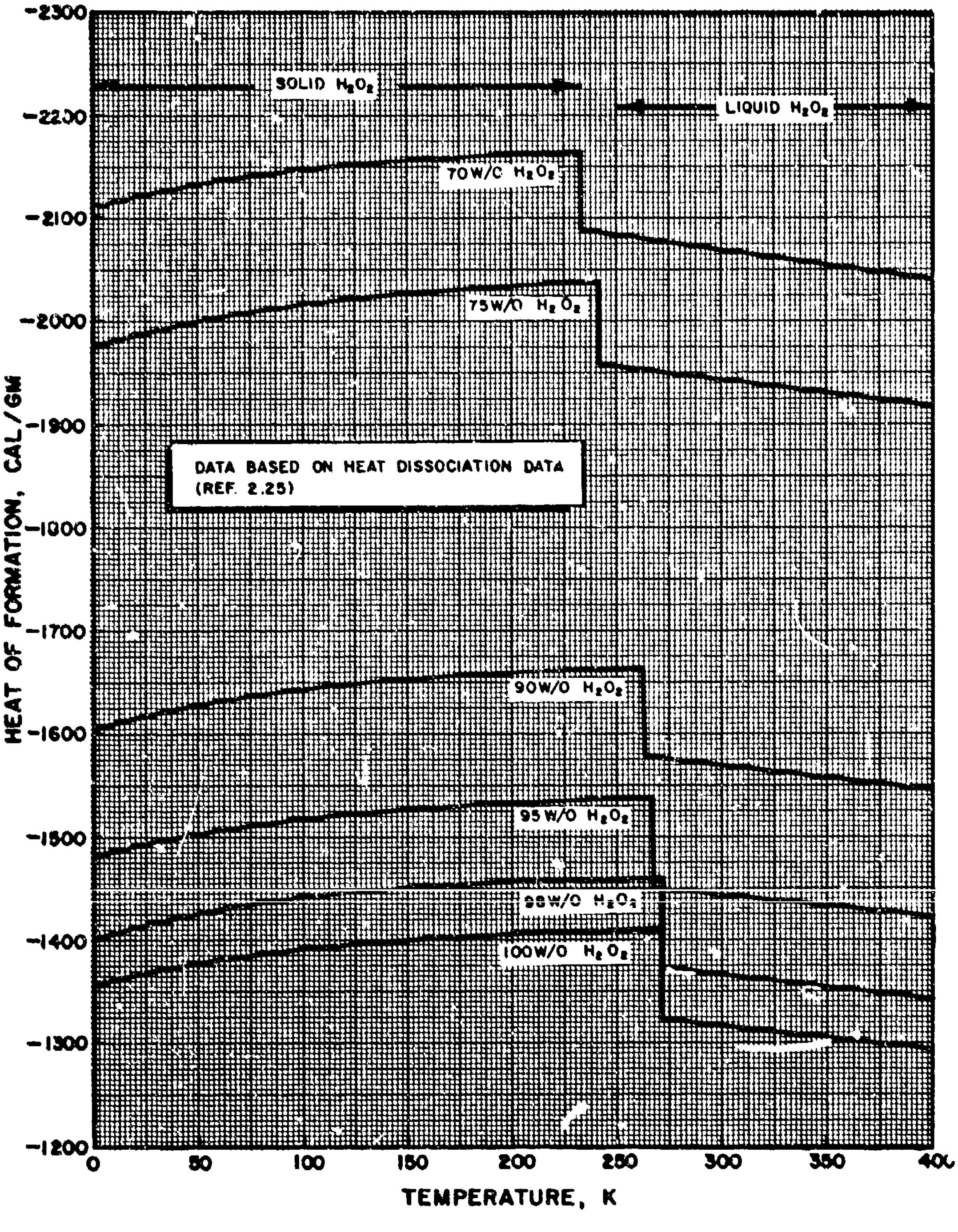


Figure 2.12. Heats of Formation of Propellant-Grade Hydrogen Peroxide-Water Solutions

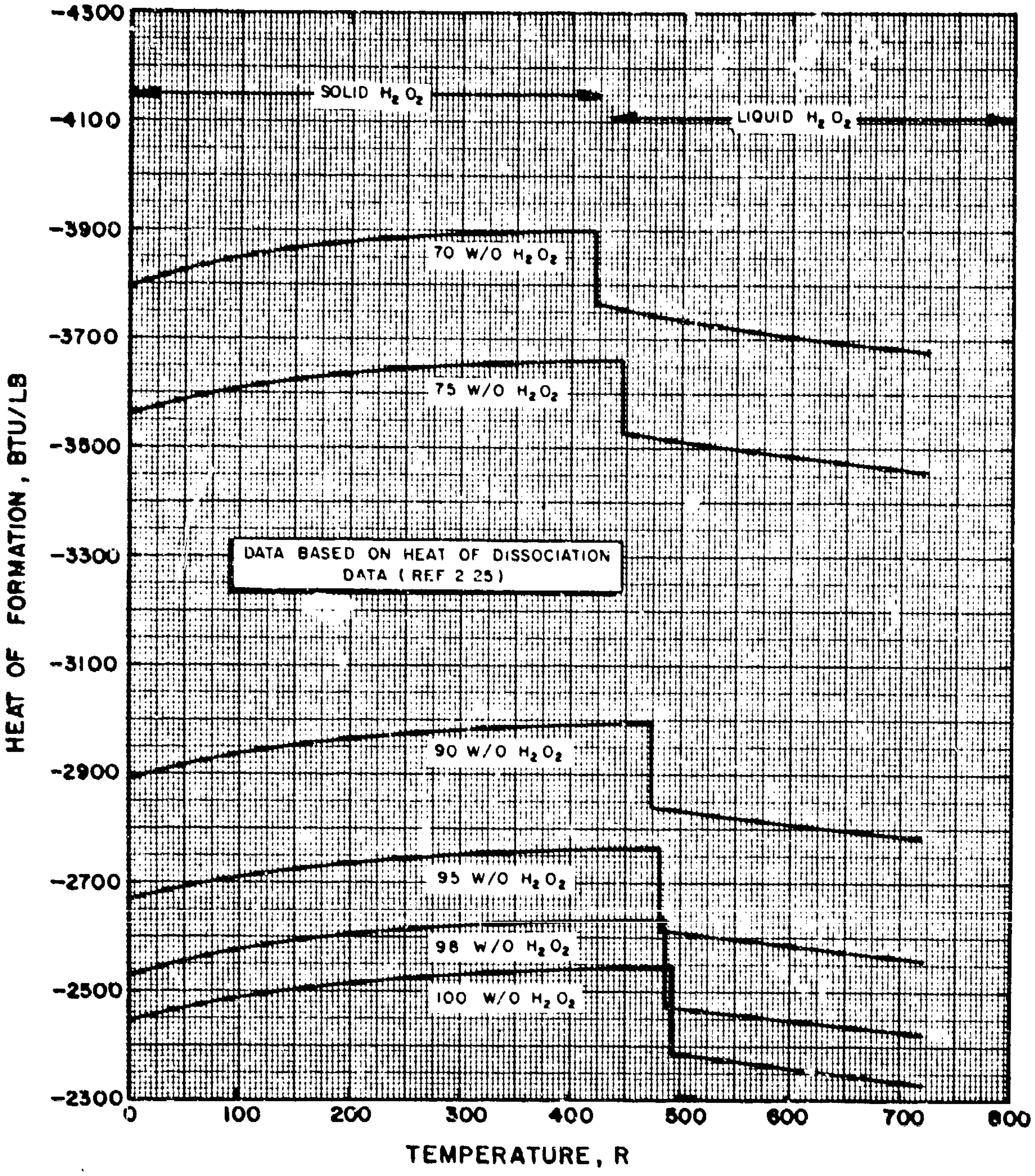


Figure 2.12a. Heats of Formation of Propellant-Grade Hydrogen Peroxide-Water Solutions

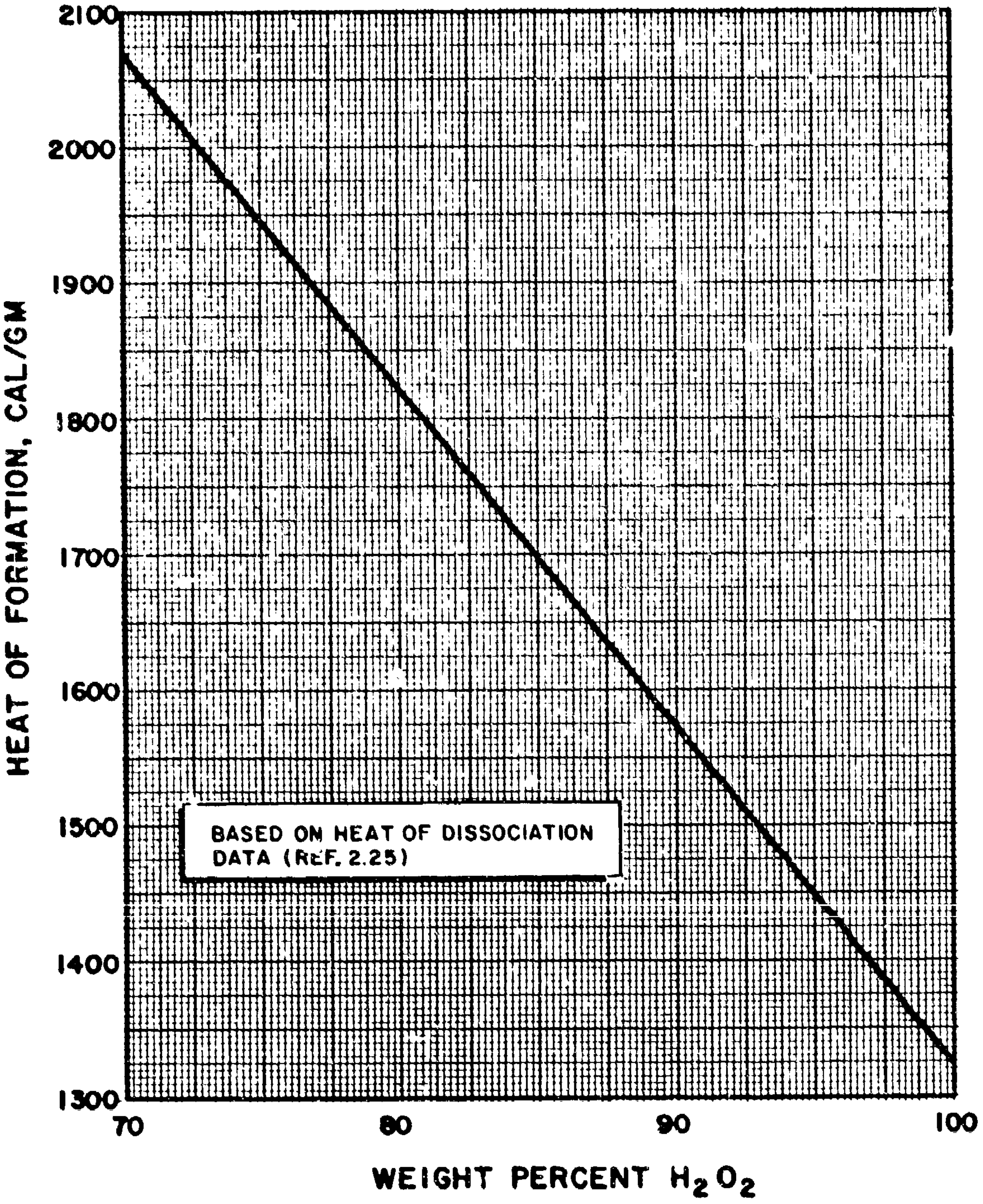


Figure 2.13. Heats of Formation of Propellant-Grade Hydrogen Peroxide-Water Solutions at 25 C

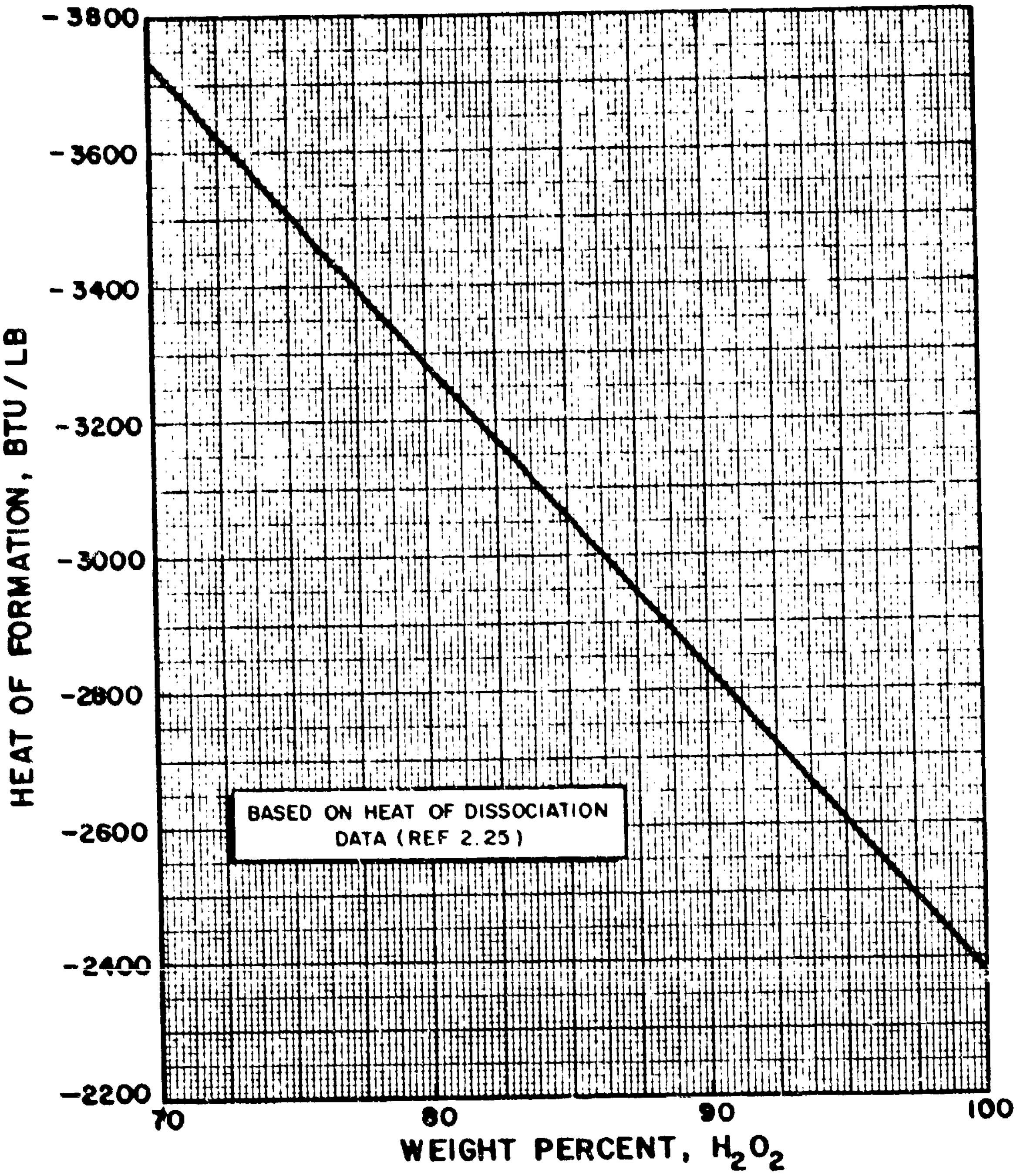


Figure 2.13a. Heats of Formation of Propellant-Grade Hydrogen Peroxide-Water Solutions at 77 F

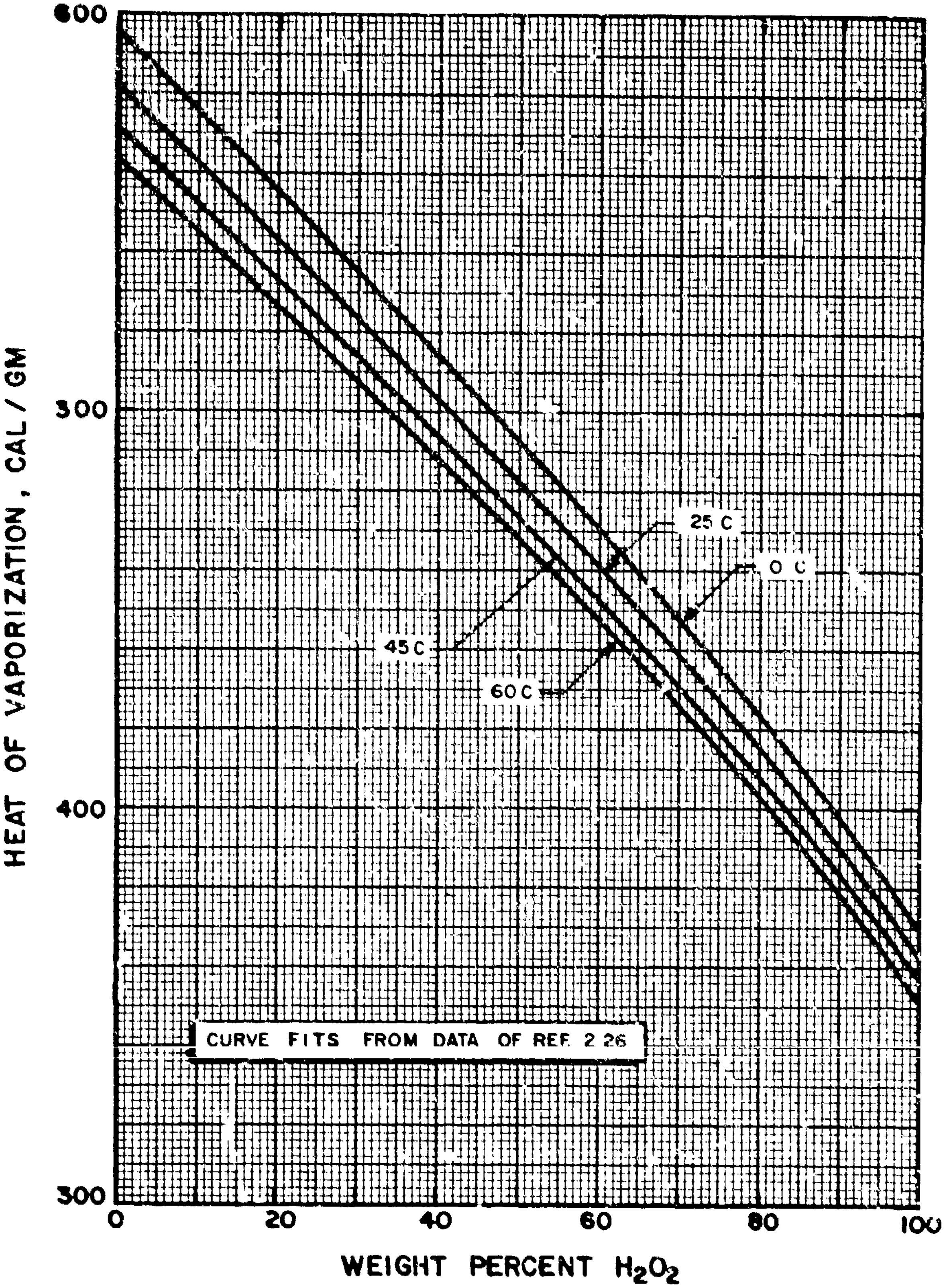


Figure 2.14. Heats of Vaporization of Hydrogen Peroxide-Water Solutions

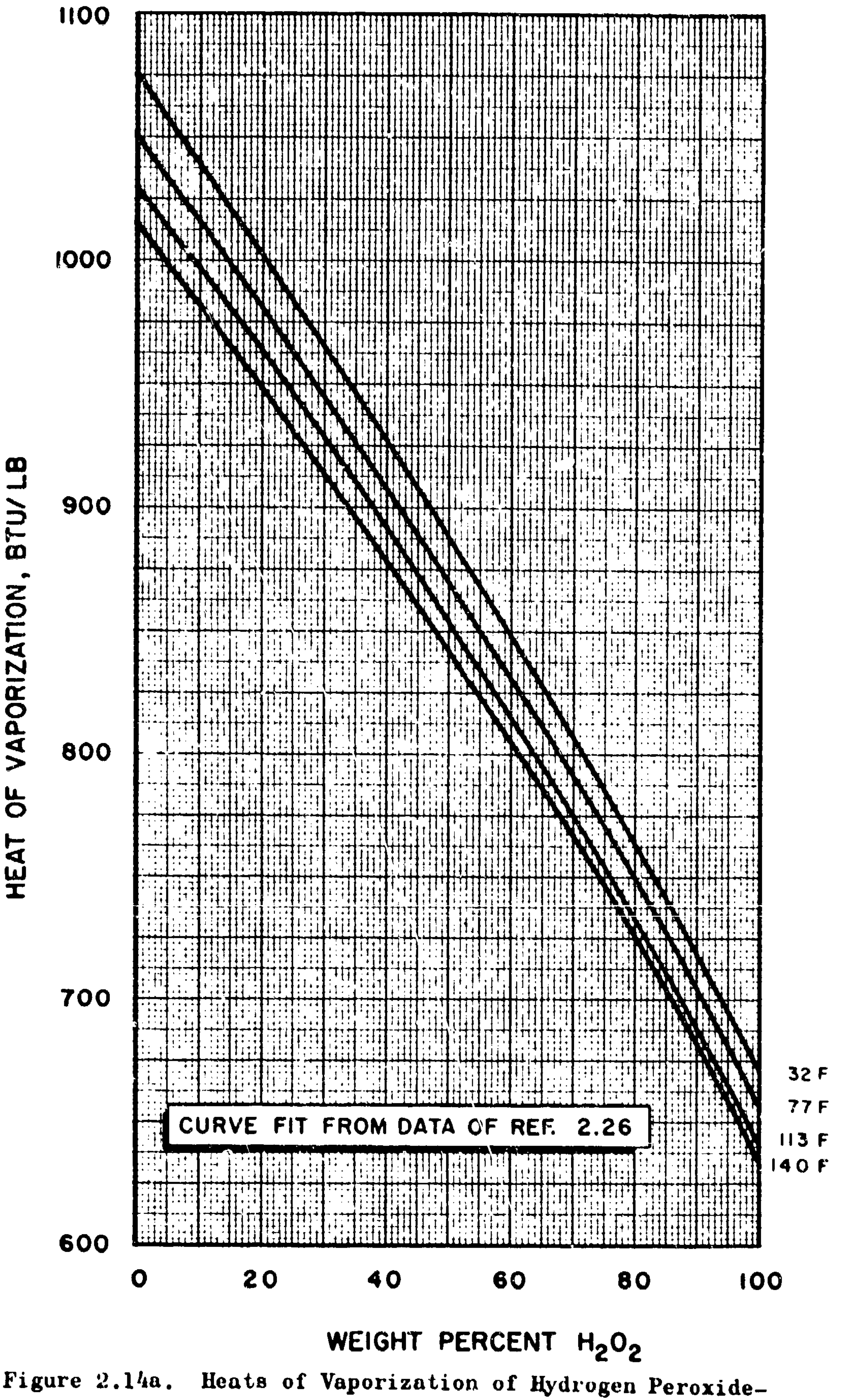


Figure 2.14a. Heats of Vaporization of Hydrogen Peroxide-Water Solutions

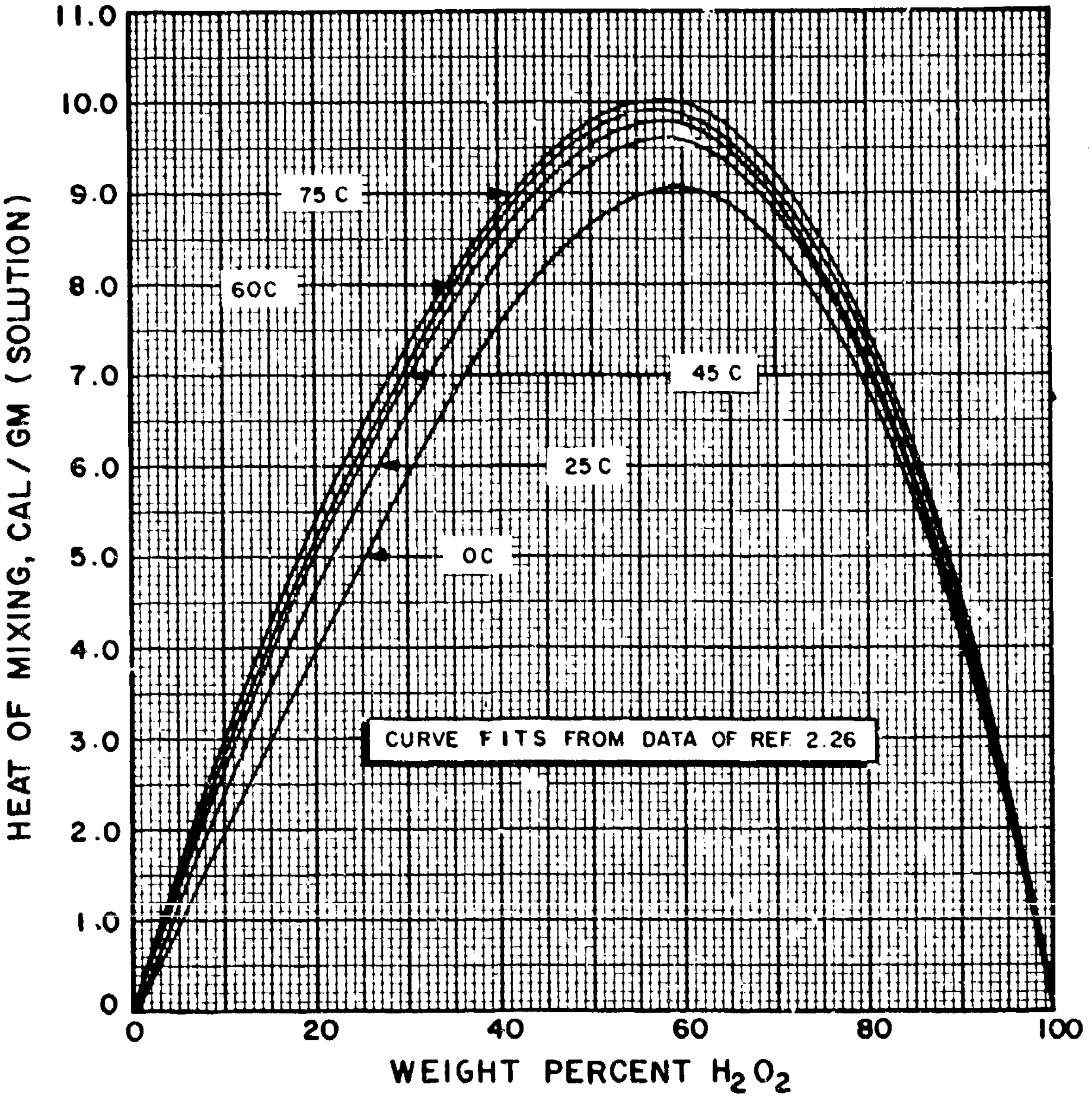


Figure 2.15. Heats of Mixing of Hydrogen Peroxide-Water Solutions

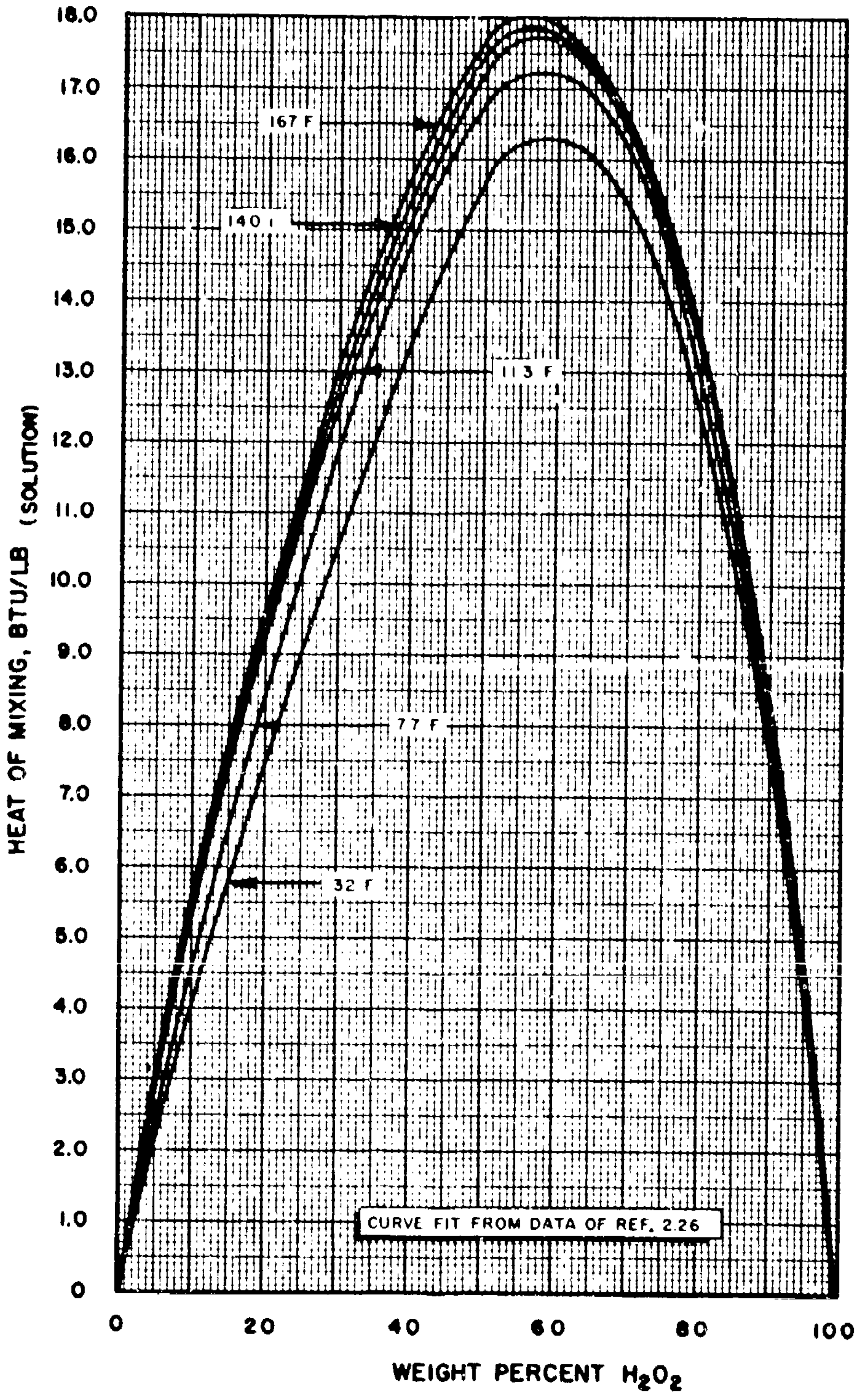


Figure 2.15a. Heats of Mixing of Hydrogen Peroxide-Water Solutions

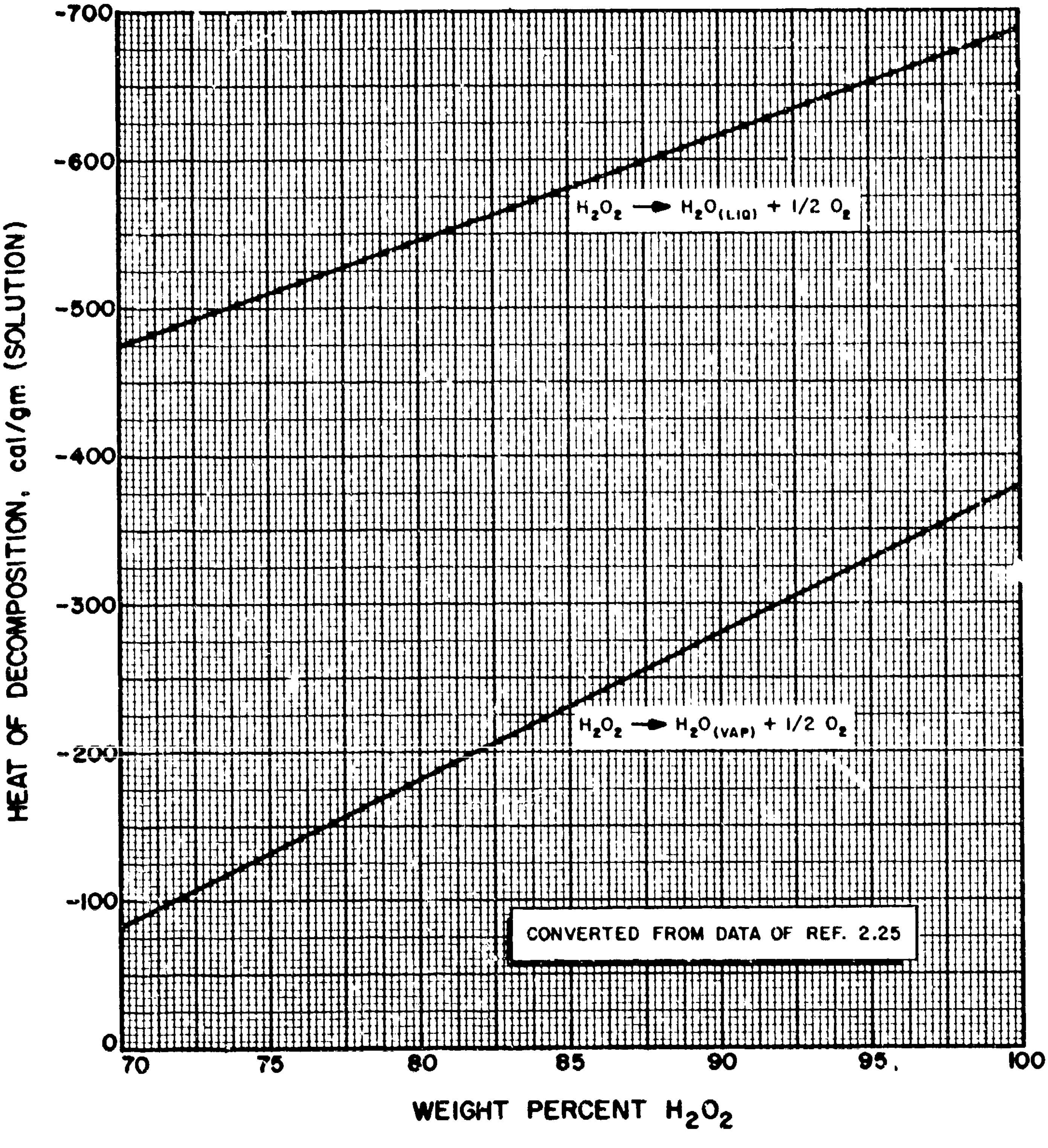


Figure 2.16. Heats of Decomposition of Propellant-Grade Hydrogen Peroxide-Water Solutions at 25 C

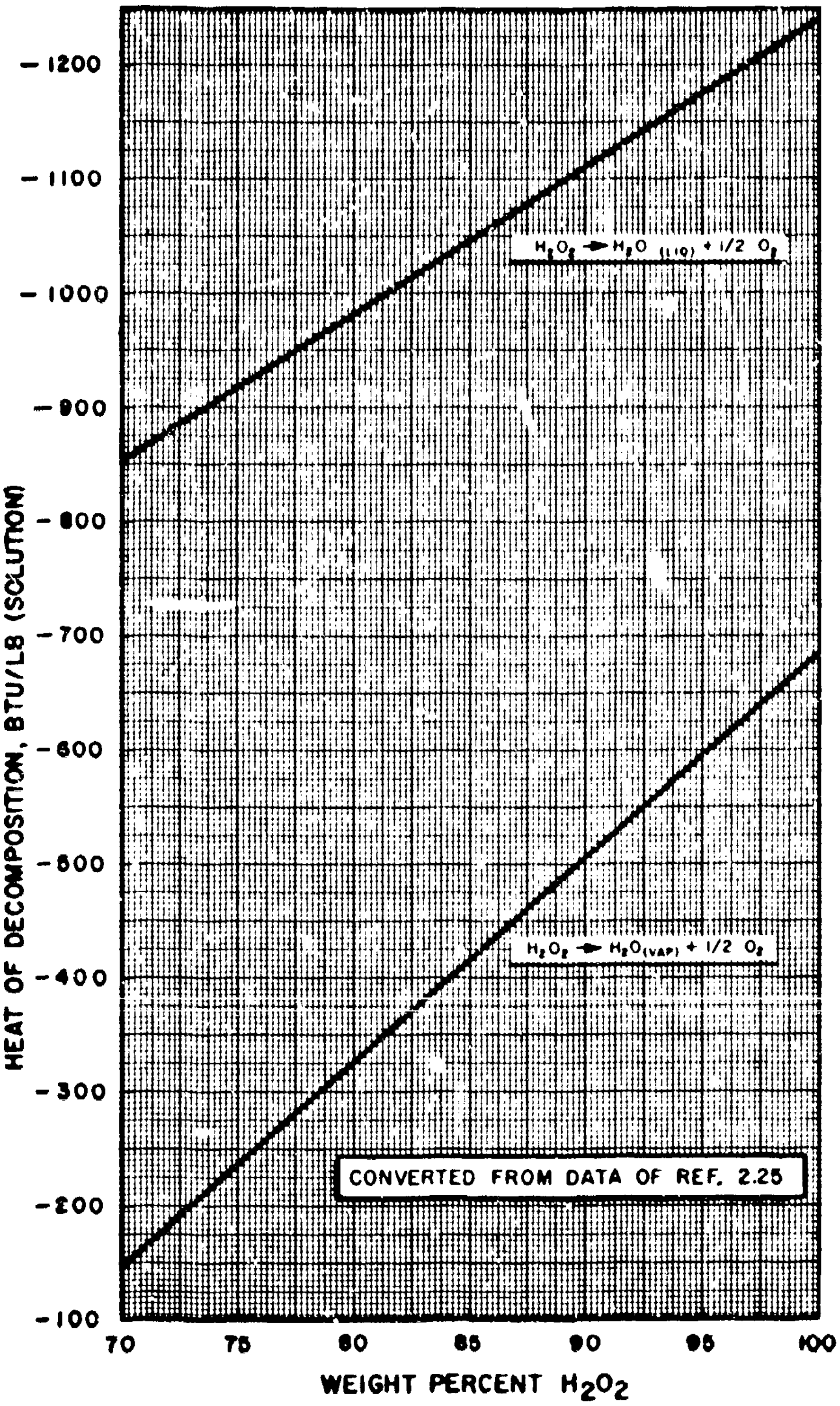


Figure 2.16a. Heats of Decomposition of Propellant-Grade Hydrogen Peroxide-Water Solutions at 77 F

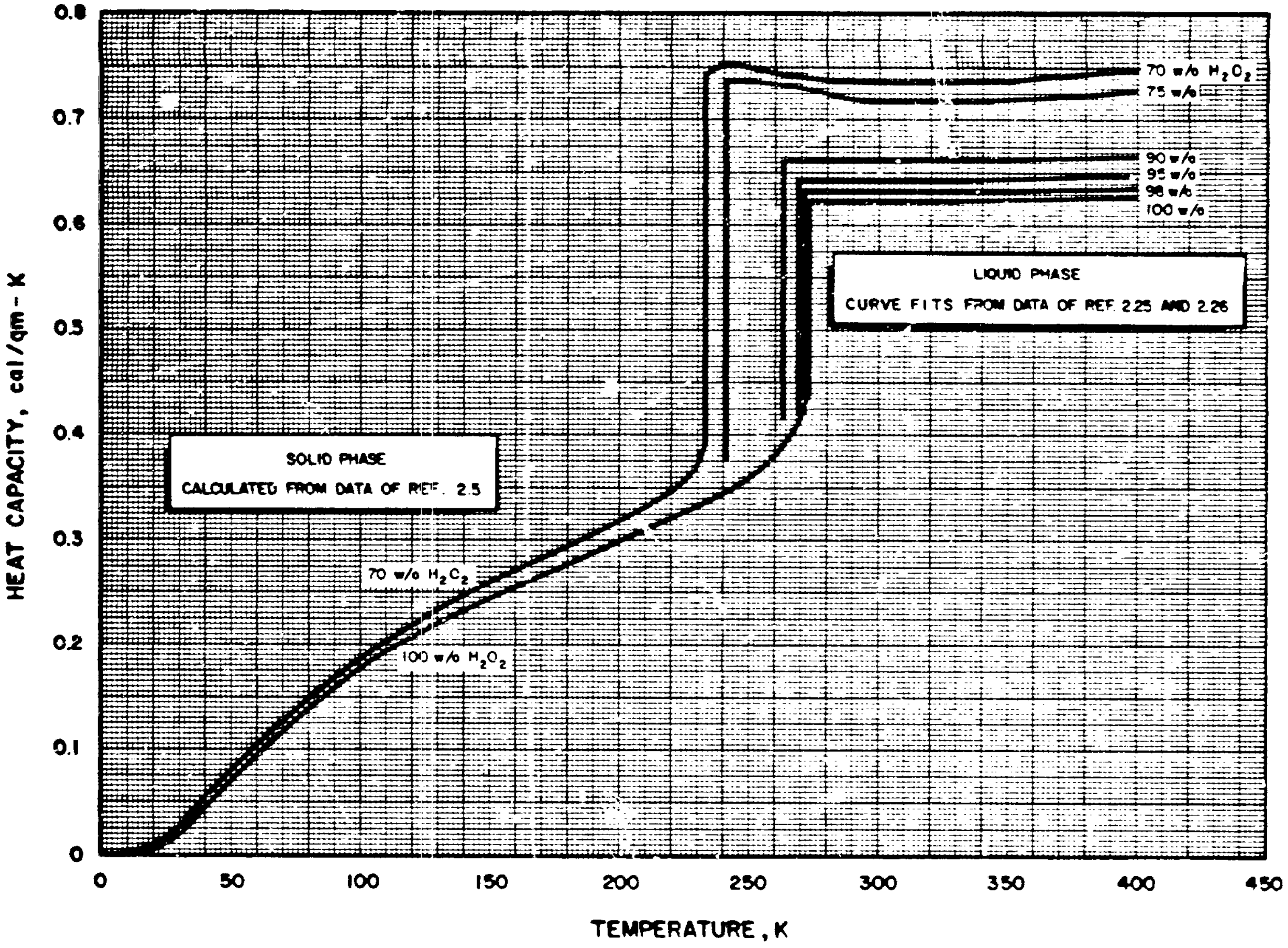


Figure 2.17. Heat Capacities of Propellant-Grade Hydrogen Peroxide-Water Solutions

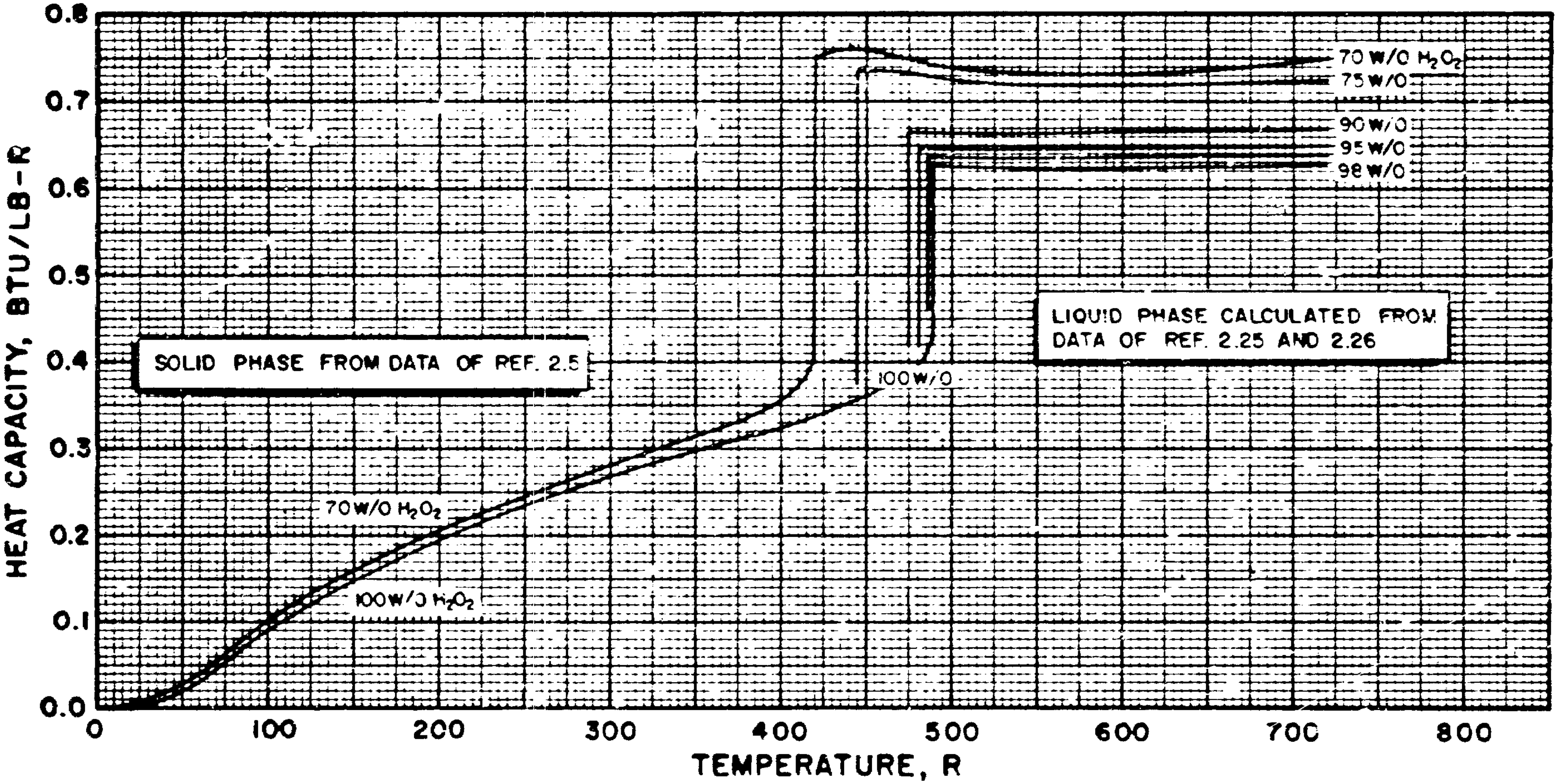


Figure 2.17a. Heat Capacities of Propellant-Grade Hydrogen Peroxide-Water Solutions

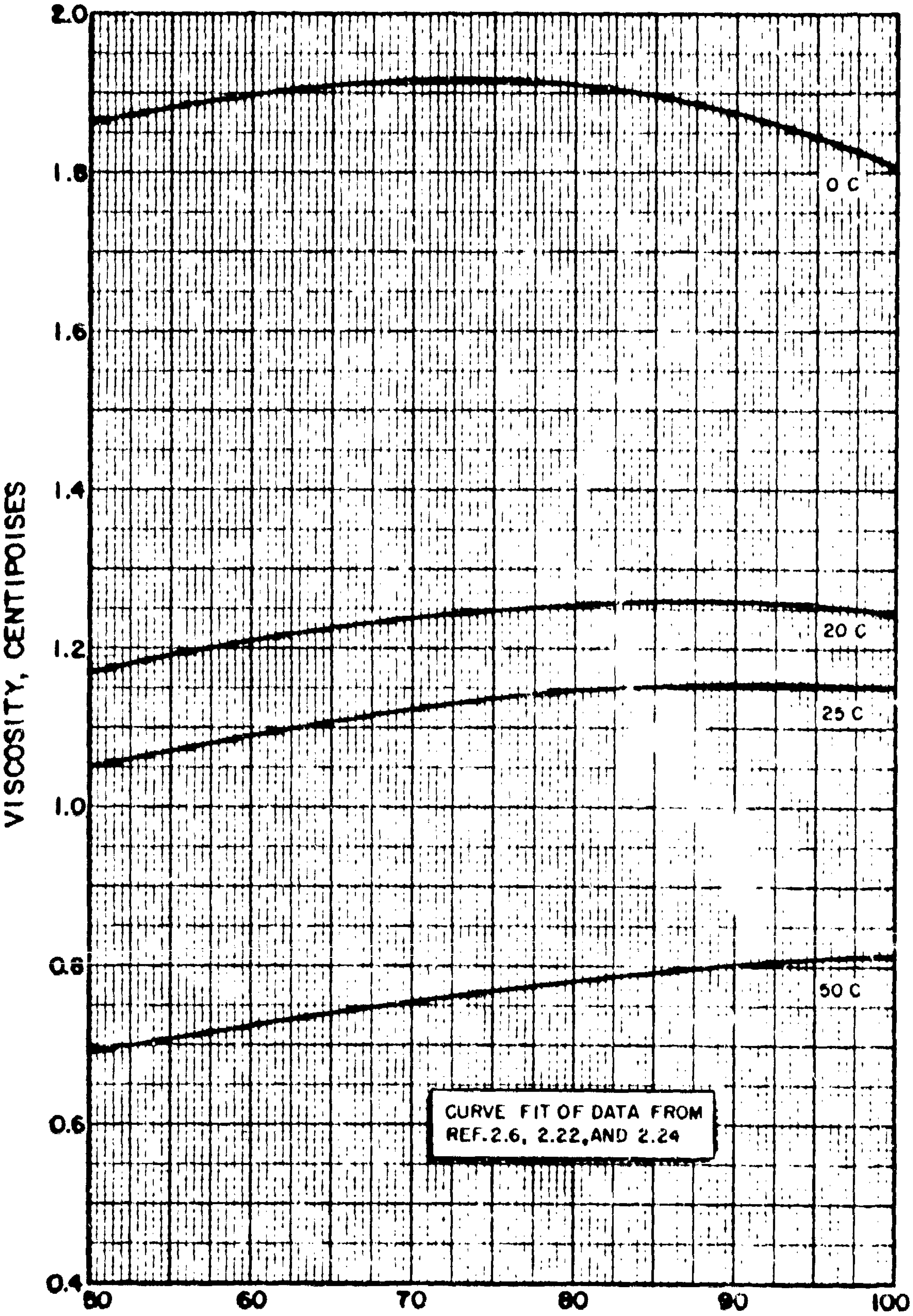


Figure 2.18. Viscosity of Liquid Hydrogen Peroxide-Water Solutions

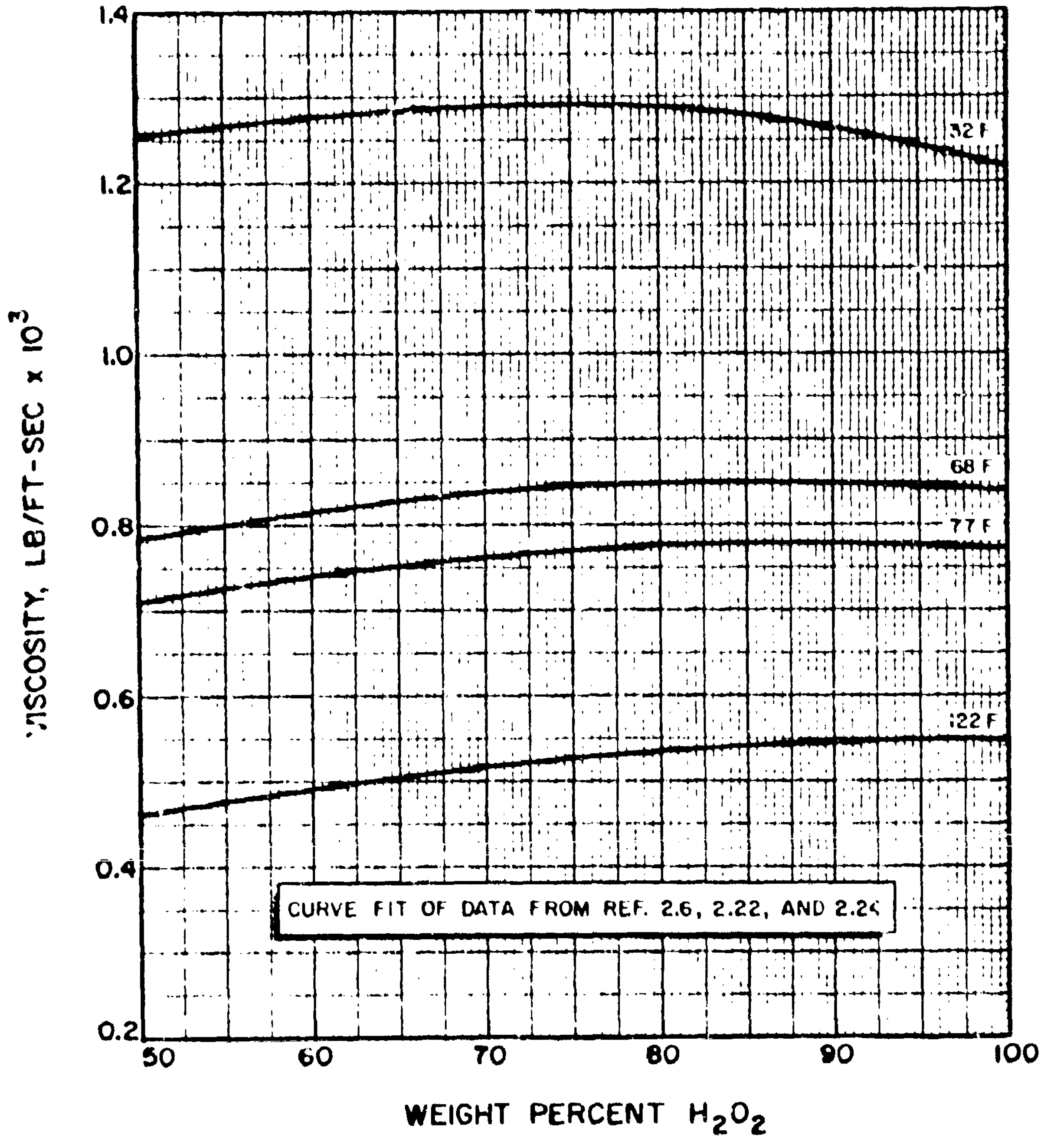


Figure 2.18a. Viscosity of Liquid Hydrogen Peroxide-Water Solutions

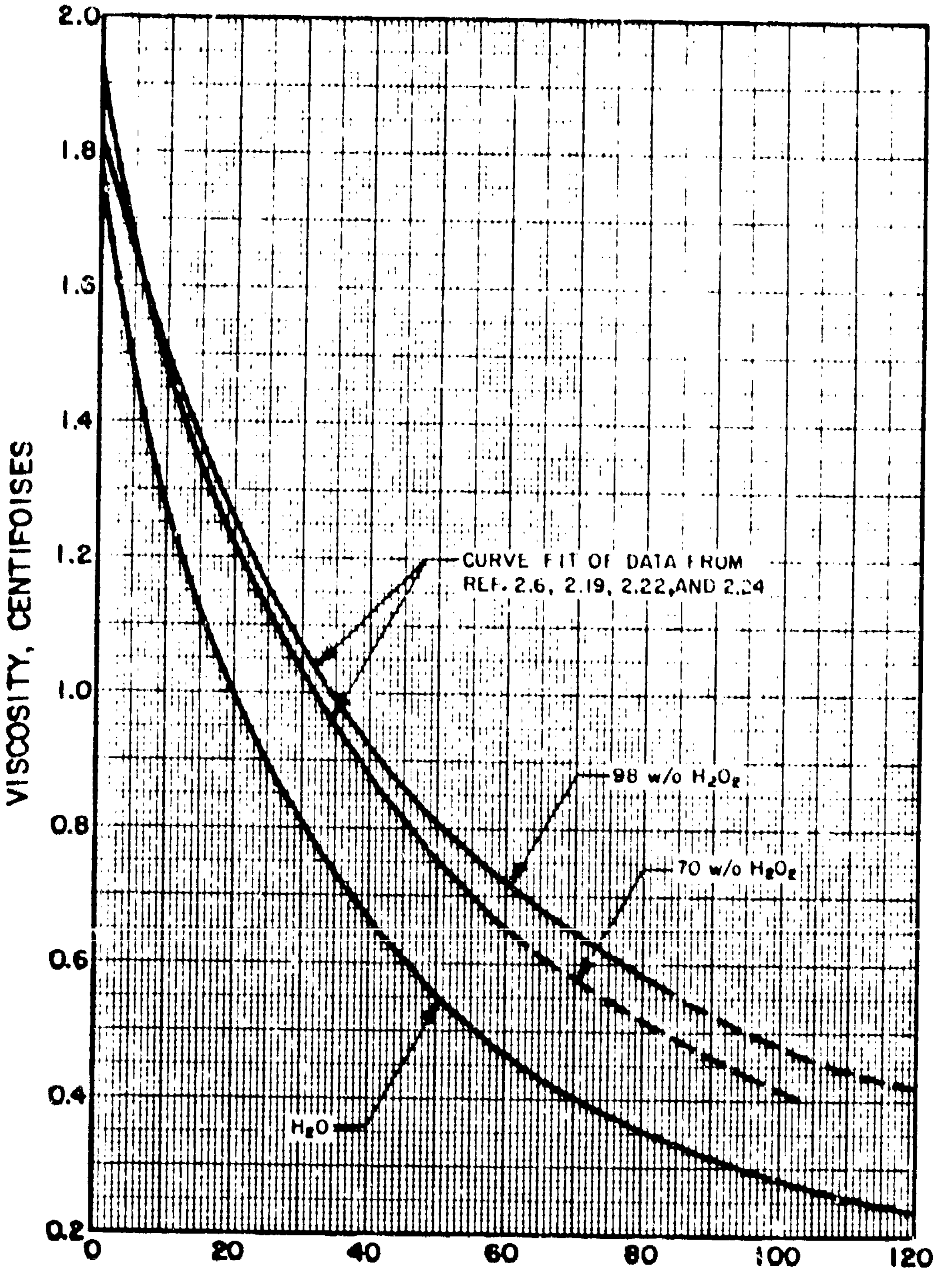


Figure 2.19. Viscosities of 98 w/o Hydrogen Peroxide, 70 w/o Hydrogen Peroxide, and Water

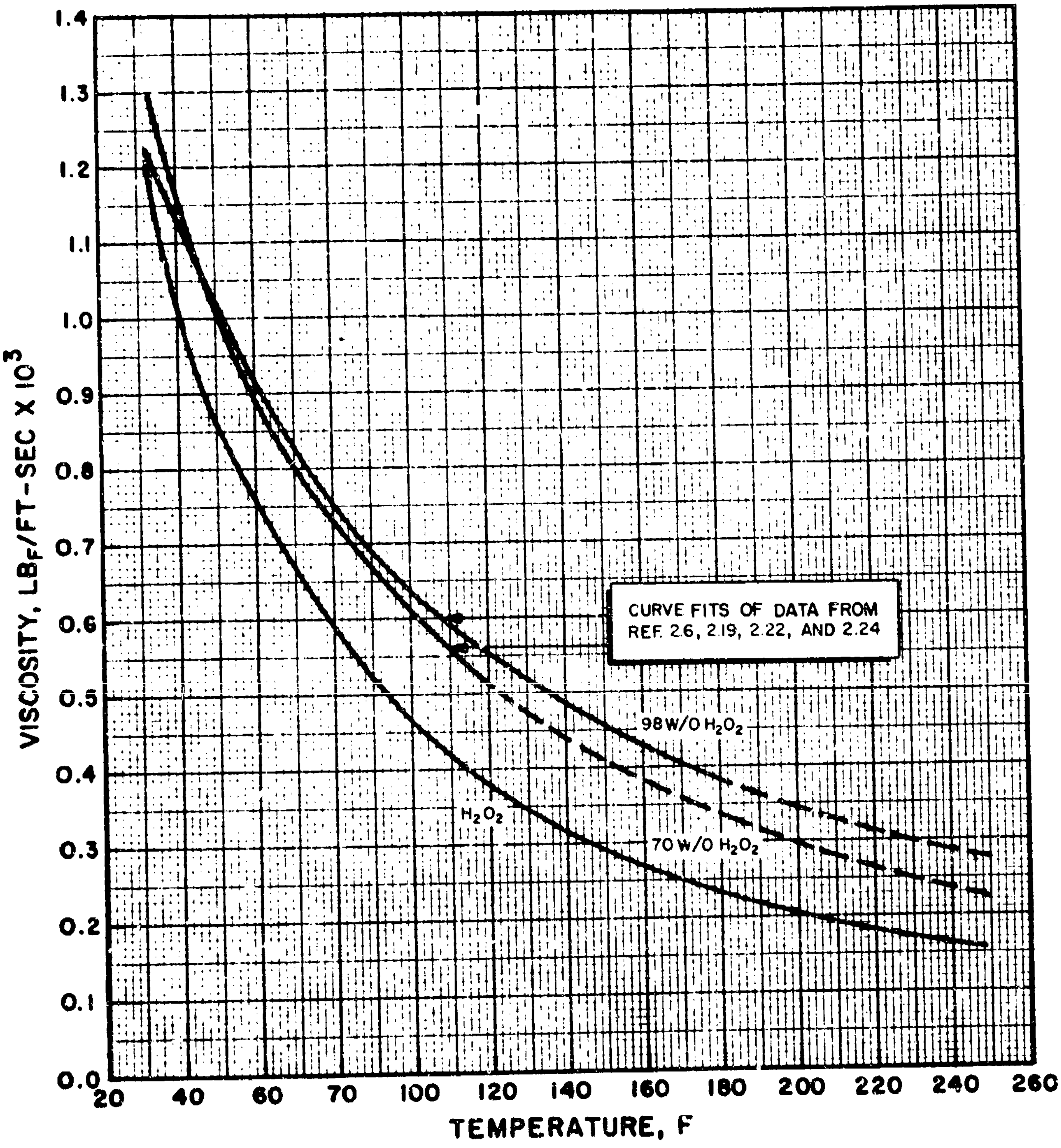


Figure 2.19a. Viscosities of 98 w/o Hydrogen Peroxide, 70 w/o Hydrogen Peroxide, and Water

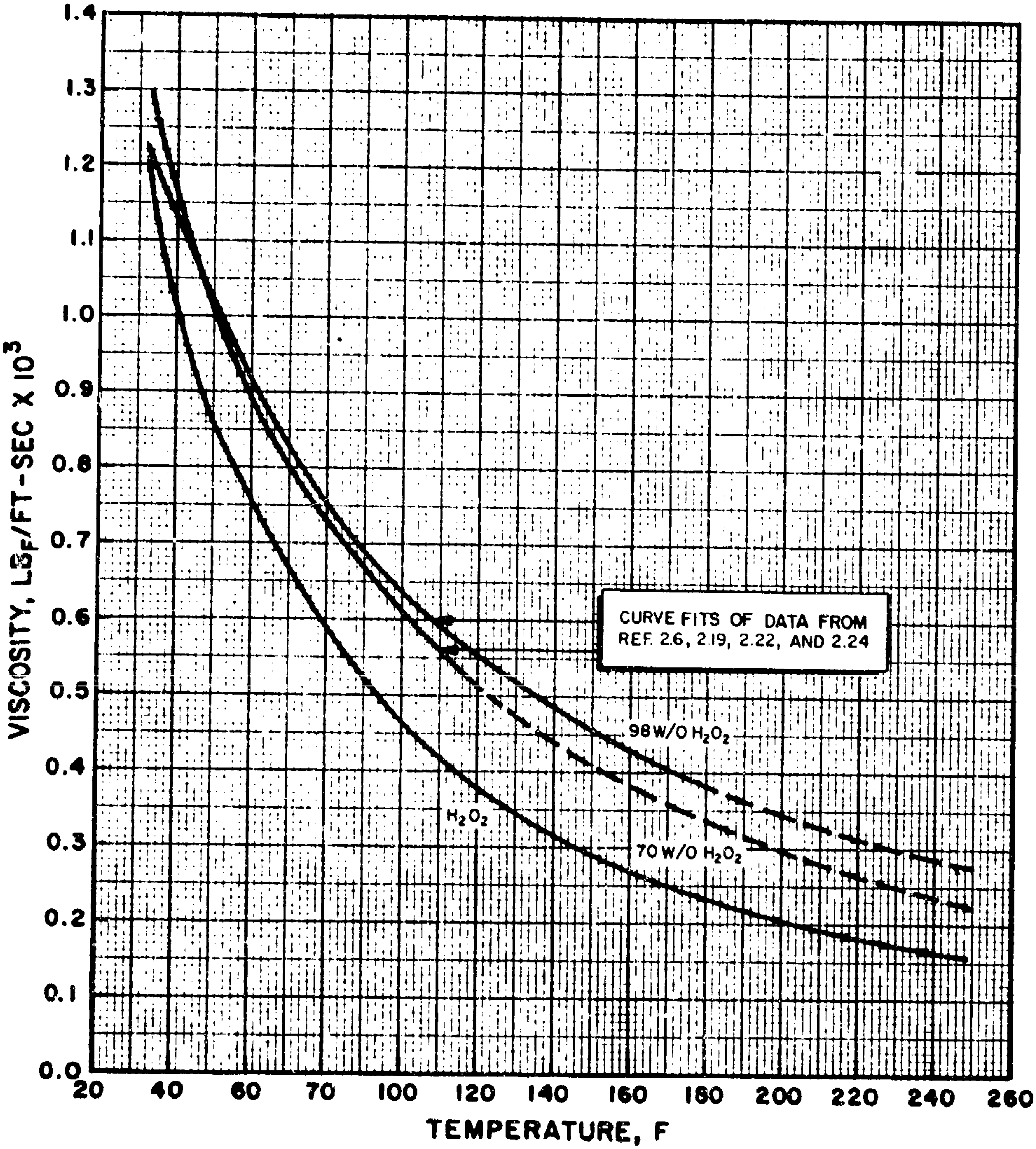


Figure 2.19a. Viscosities of 98 w/o Hydrogen Peroxide, 70 w/o Hydrogen Peroxide, and Water

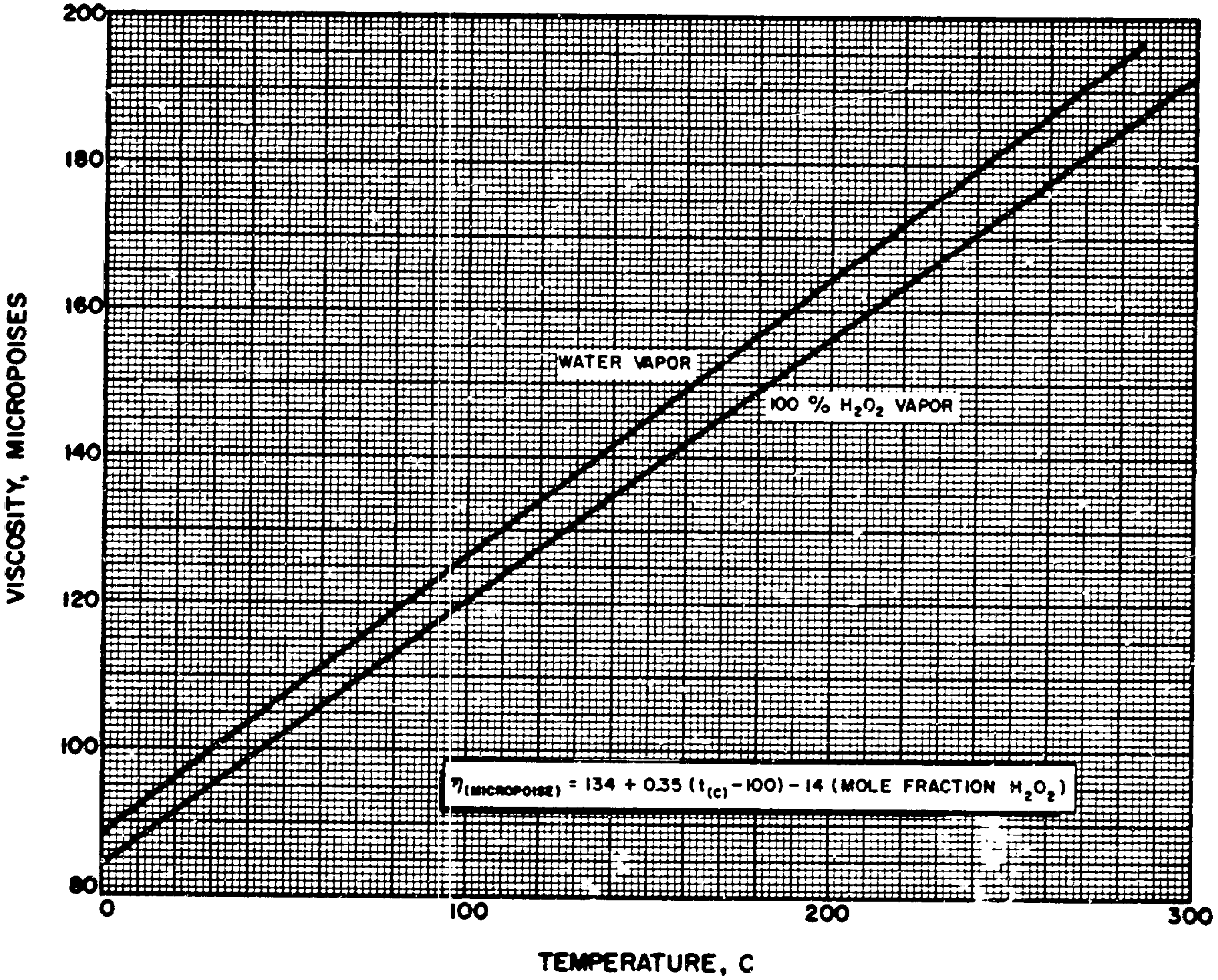


Figure 2.20. Viscosity of Hydrogen Peroxide and Water Vapor

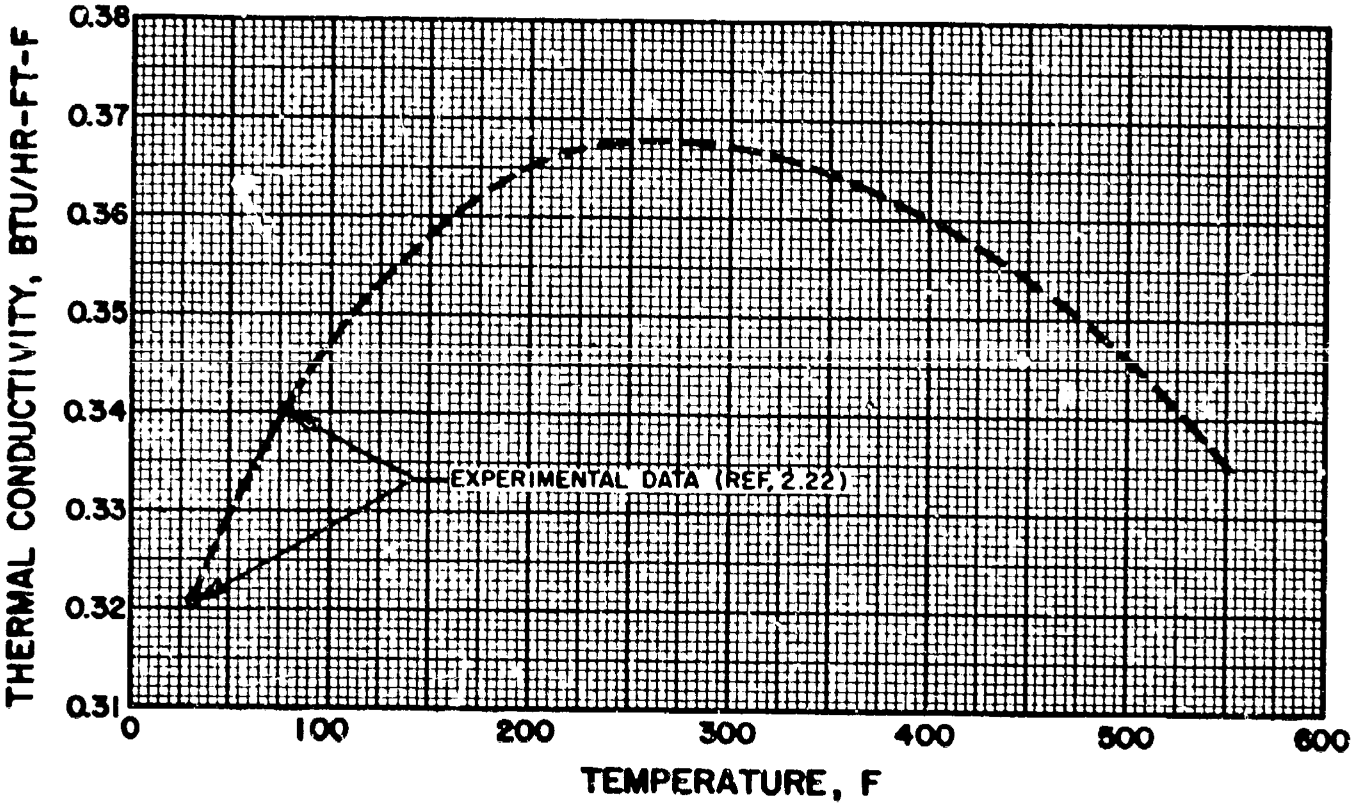


Figure 2.21. Thermal Conductivity of 98.2 w/o Hydrogen Peroxide (Ref. 2.31)

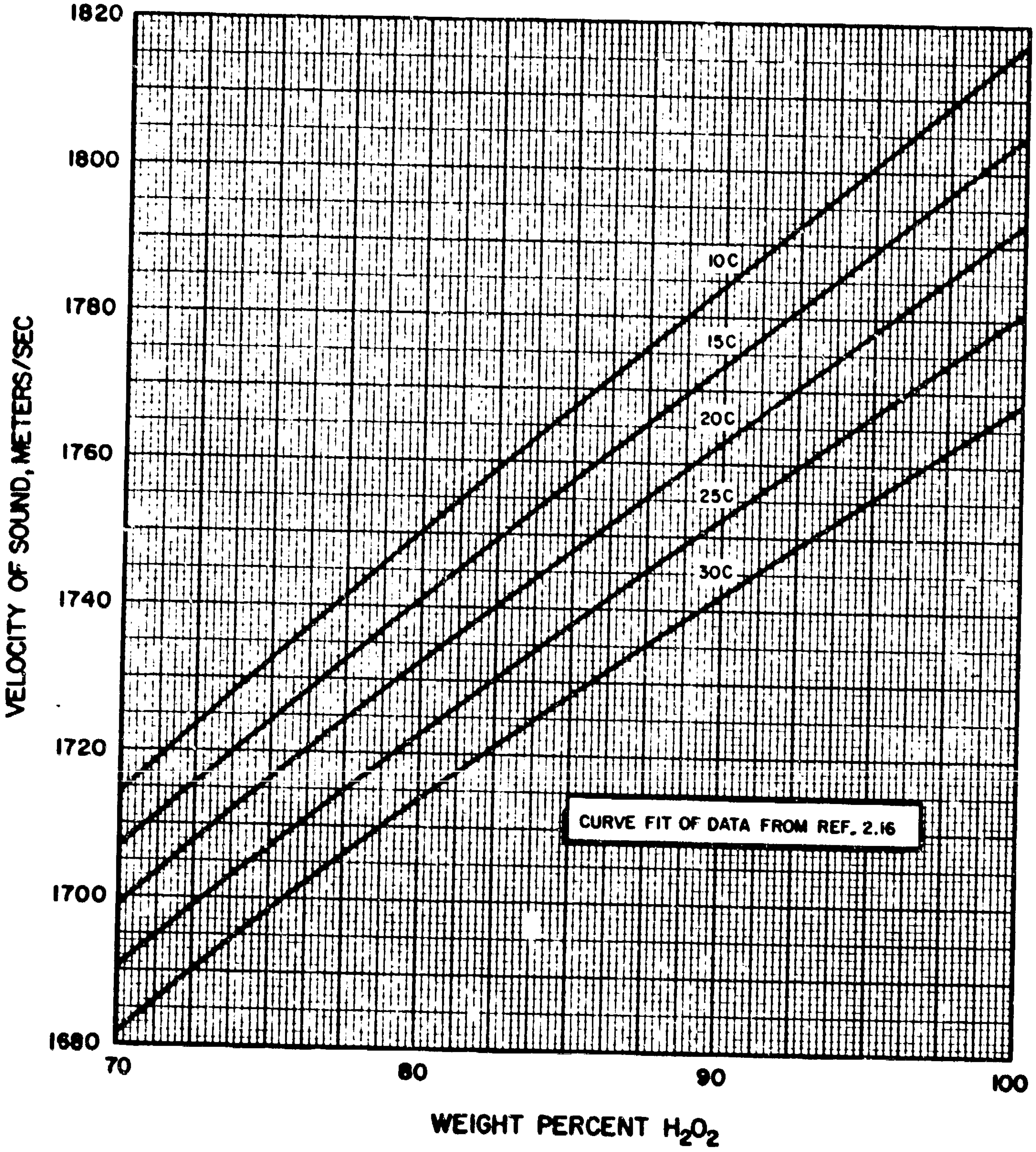


Figure 2.22. Velocity of Sound in Propellant-Grade Hydrogen Peroxide-Water Solutions

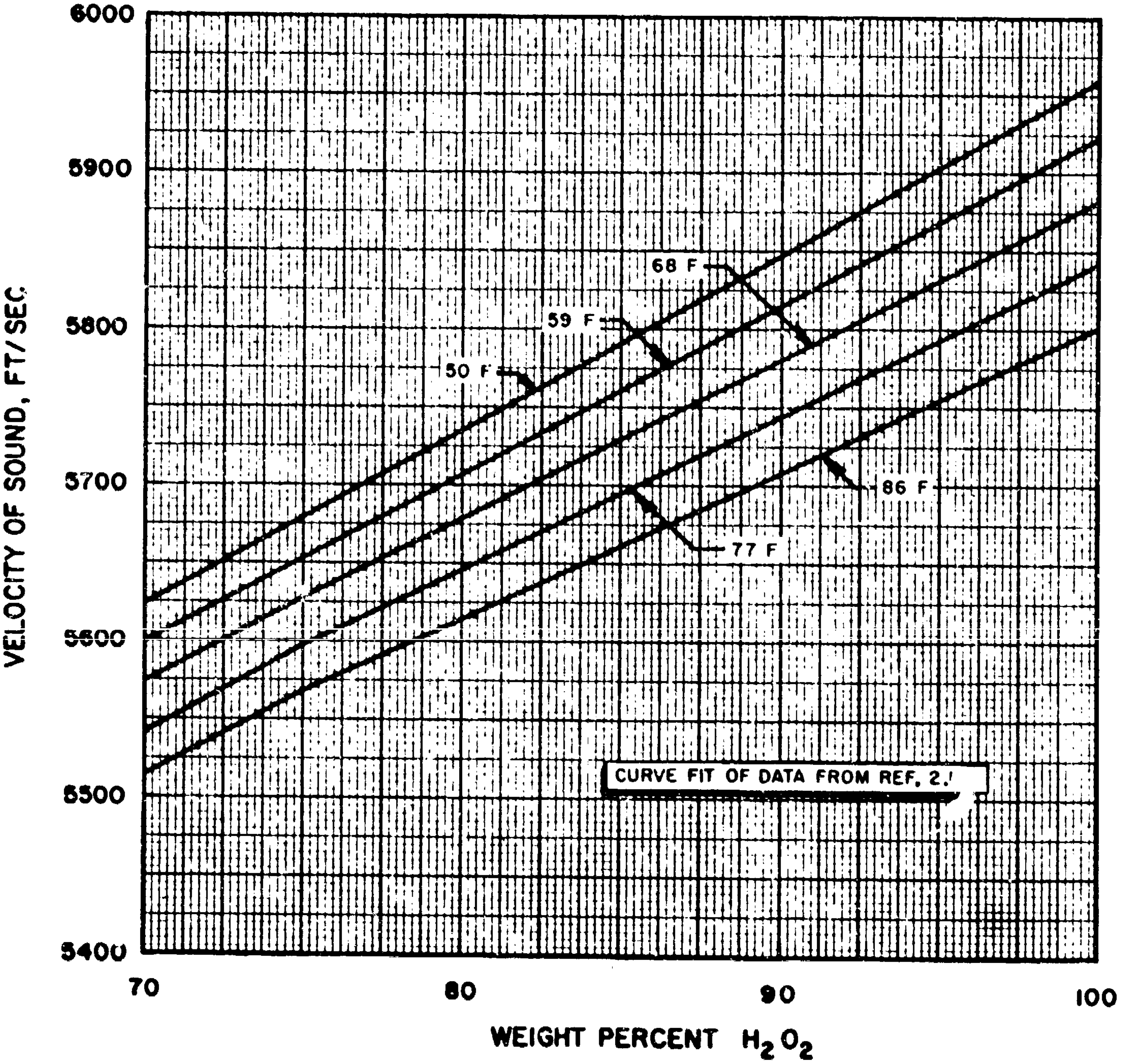


Figure 2.22a. Velocity of Sound in Propellant-Grade Hydrogen Peroxide-Water Solutions

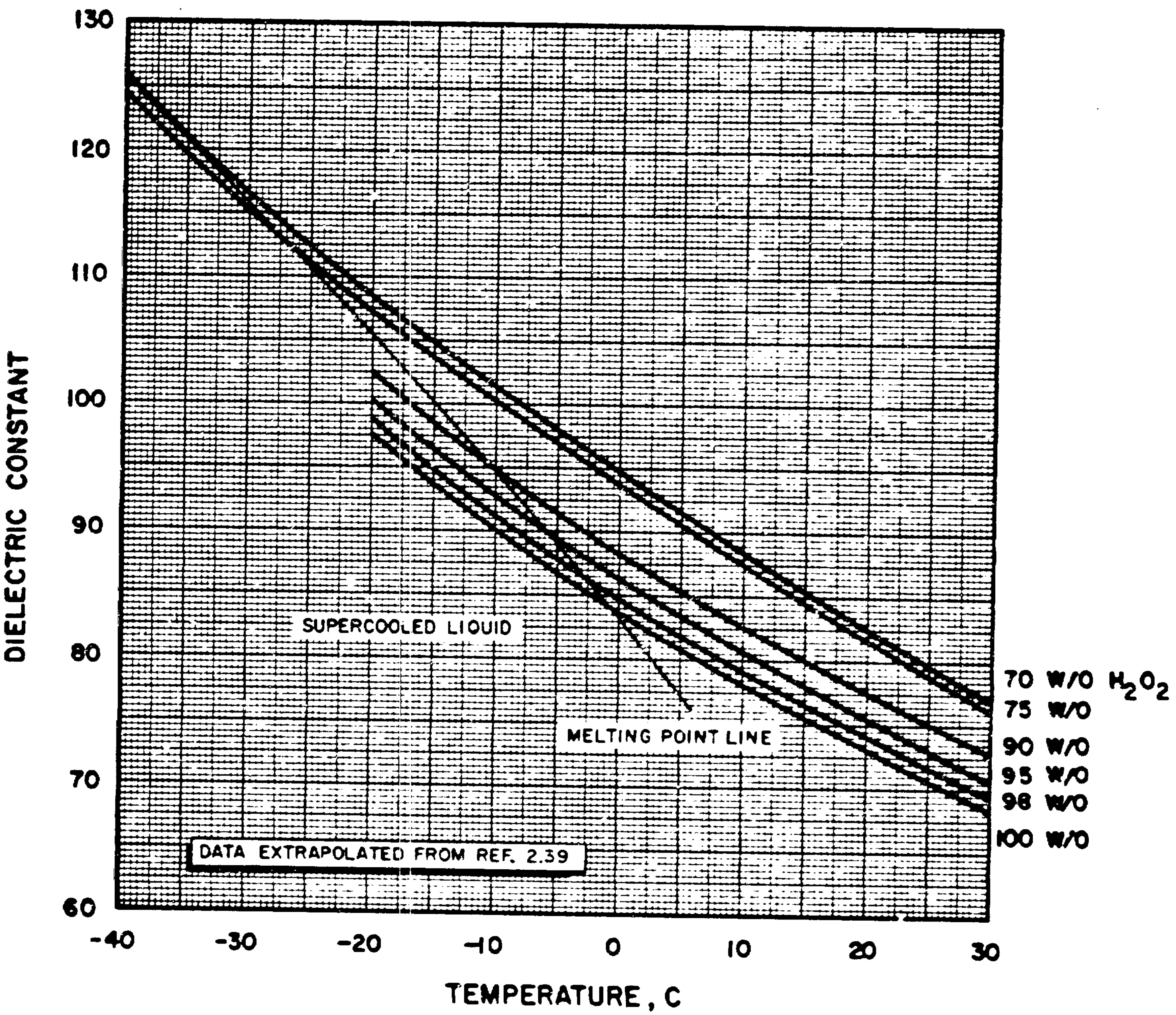


Figure 2.23. Dielectric Constant of Propellant-Grade Hydrogen Peroxide-Water Solutions

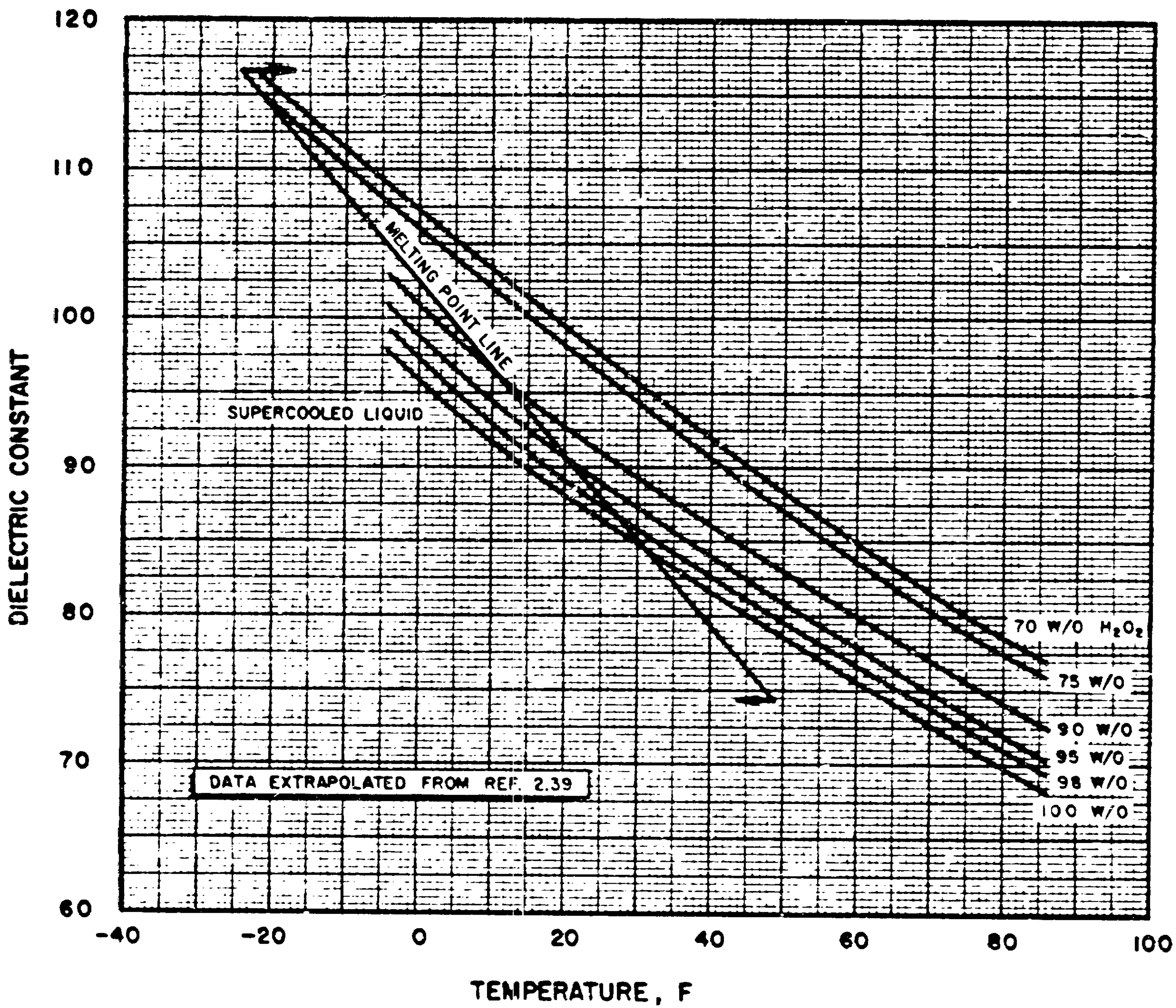


Figure 2.23a. Dielectric Constant of Propellant–Grade Hydrogen Peroxide–Water Solutions

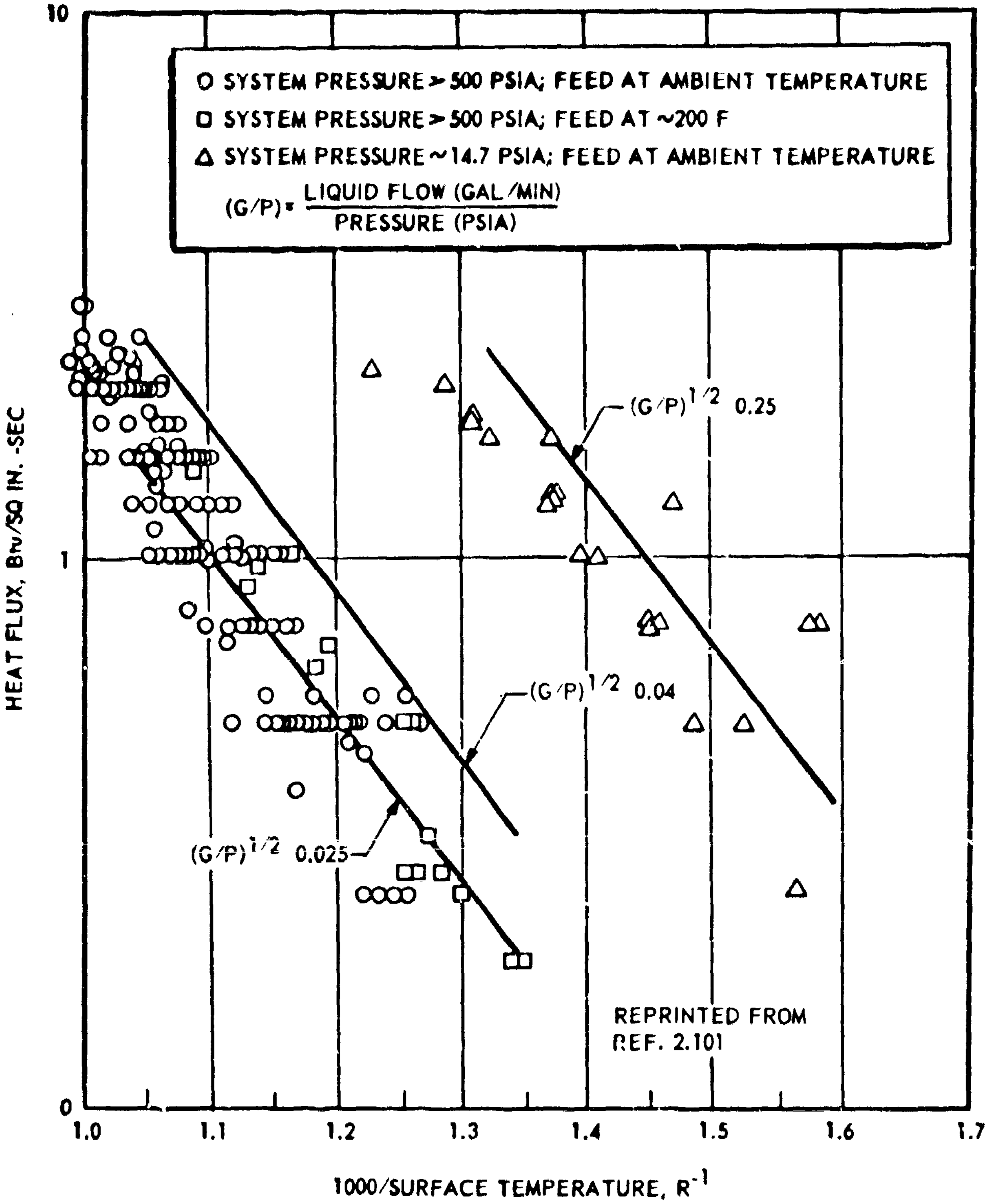


Figure 2.24. Heat Flux From a 347 Stainless-Steel Surface to 90 w/o Hydrogen Peroxide as a Function of Surface Temperature

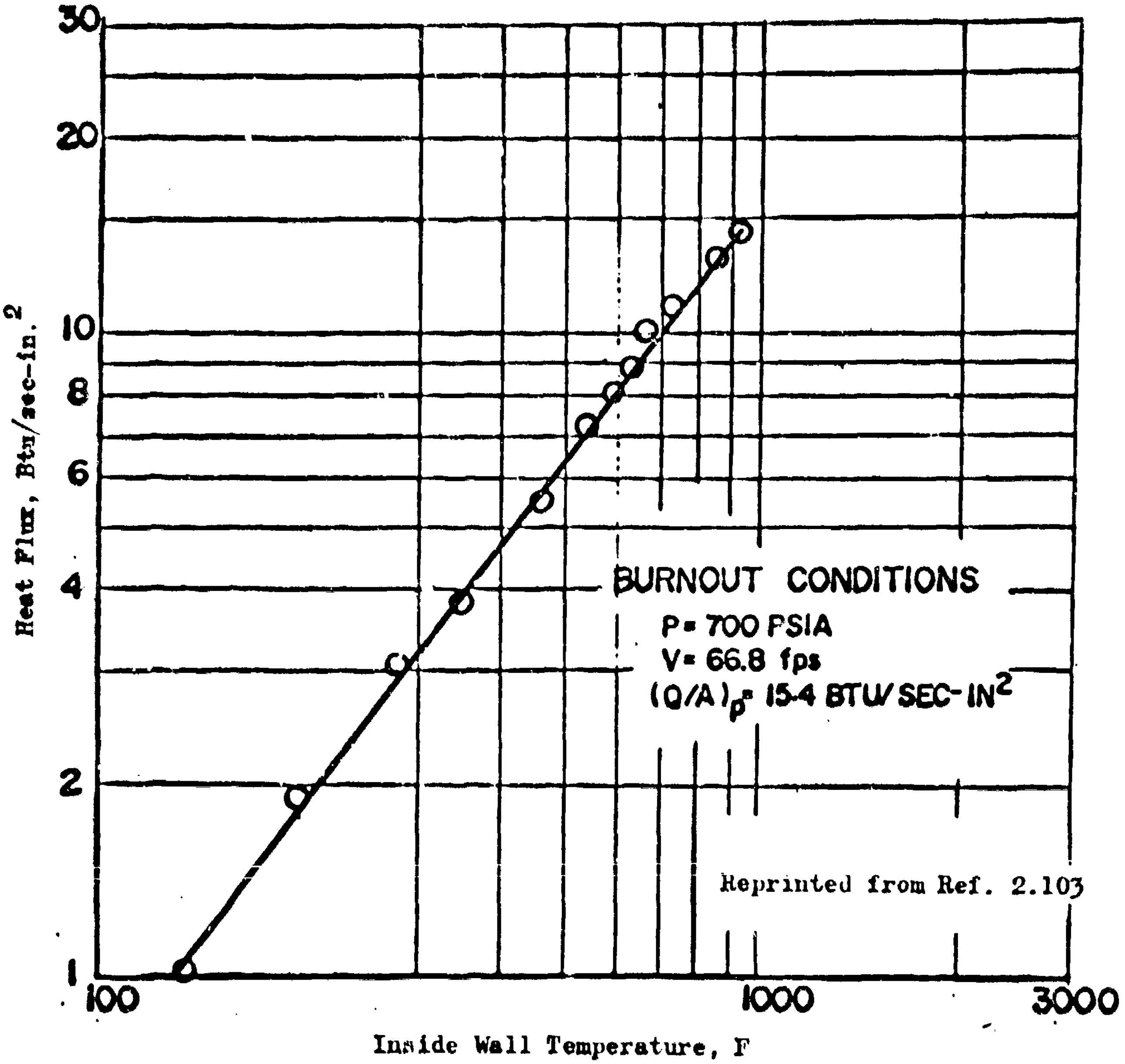


Figure 2.25. Typical Curve of Heat Flux vs Inside Wall Temperature (98 w/o Hydrogen Peroxide 1-1/2 Inches Upstream From Exit of Heated Section)

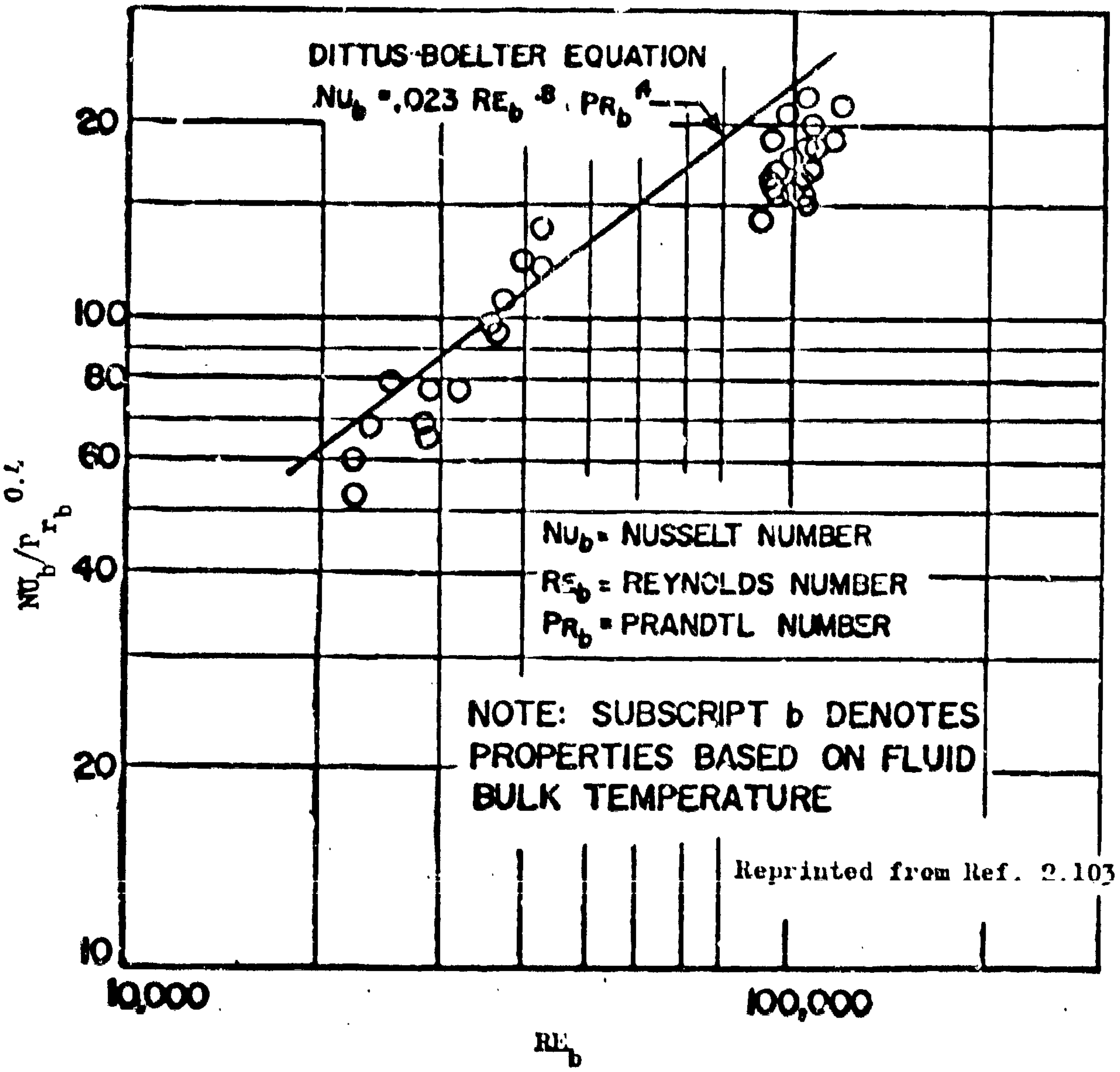


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Figure 2.26. Correlation of Heat Transfer Coefficients of 98 w/o Hydrogen Peroxide With Dittus-Boelter Equation (Convective Region)

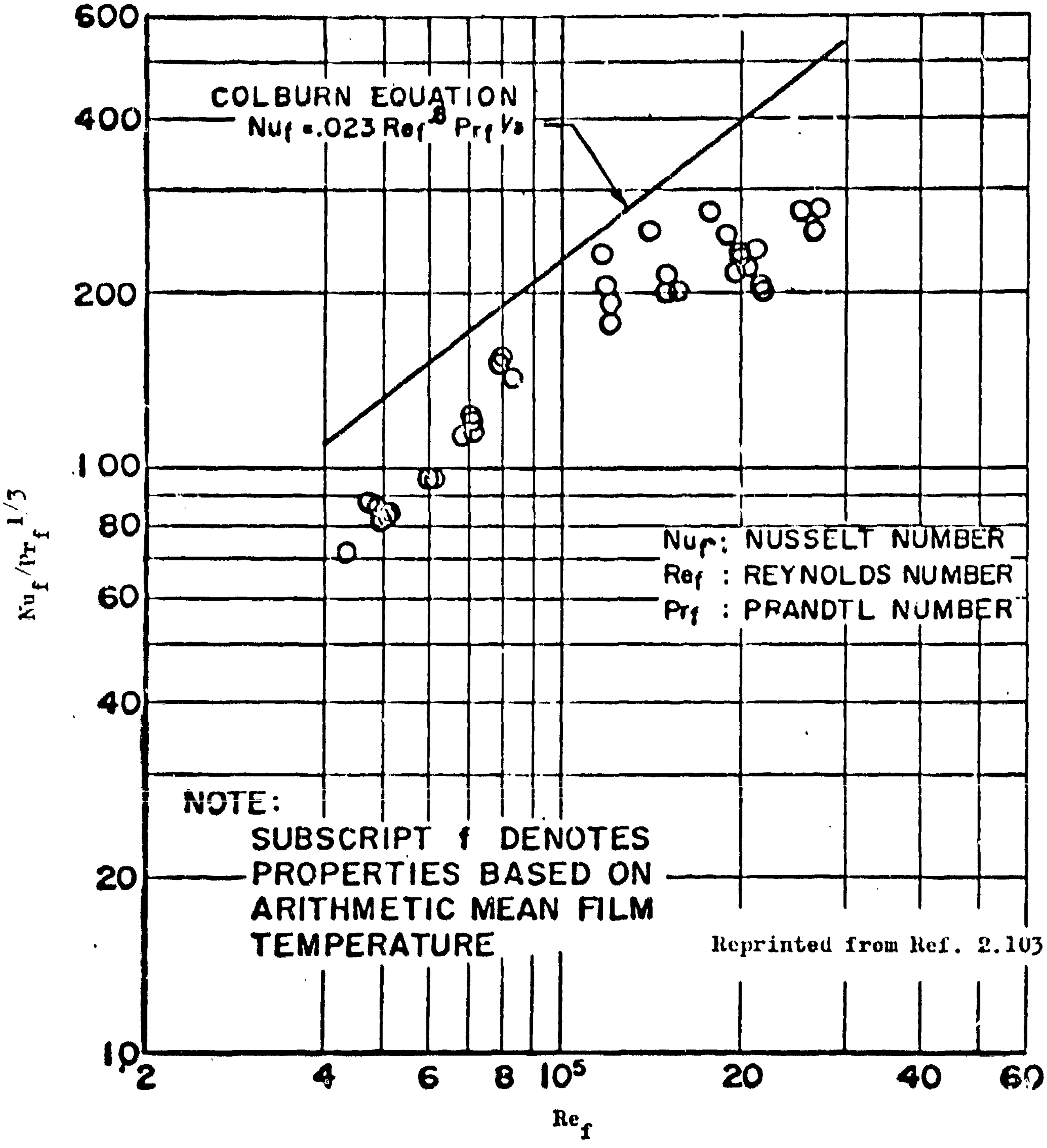

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Figure 2.27. Correlation of Heat Transfer Coefficients of 98 w/o Hydrogen Peroxide With Colburn Equation (Convective Region)

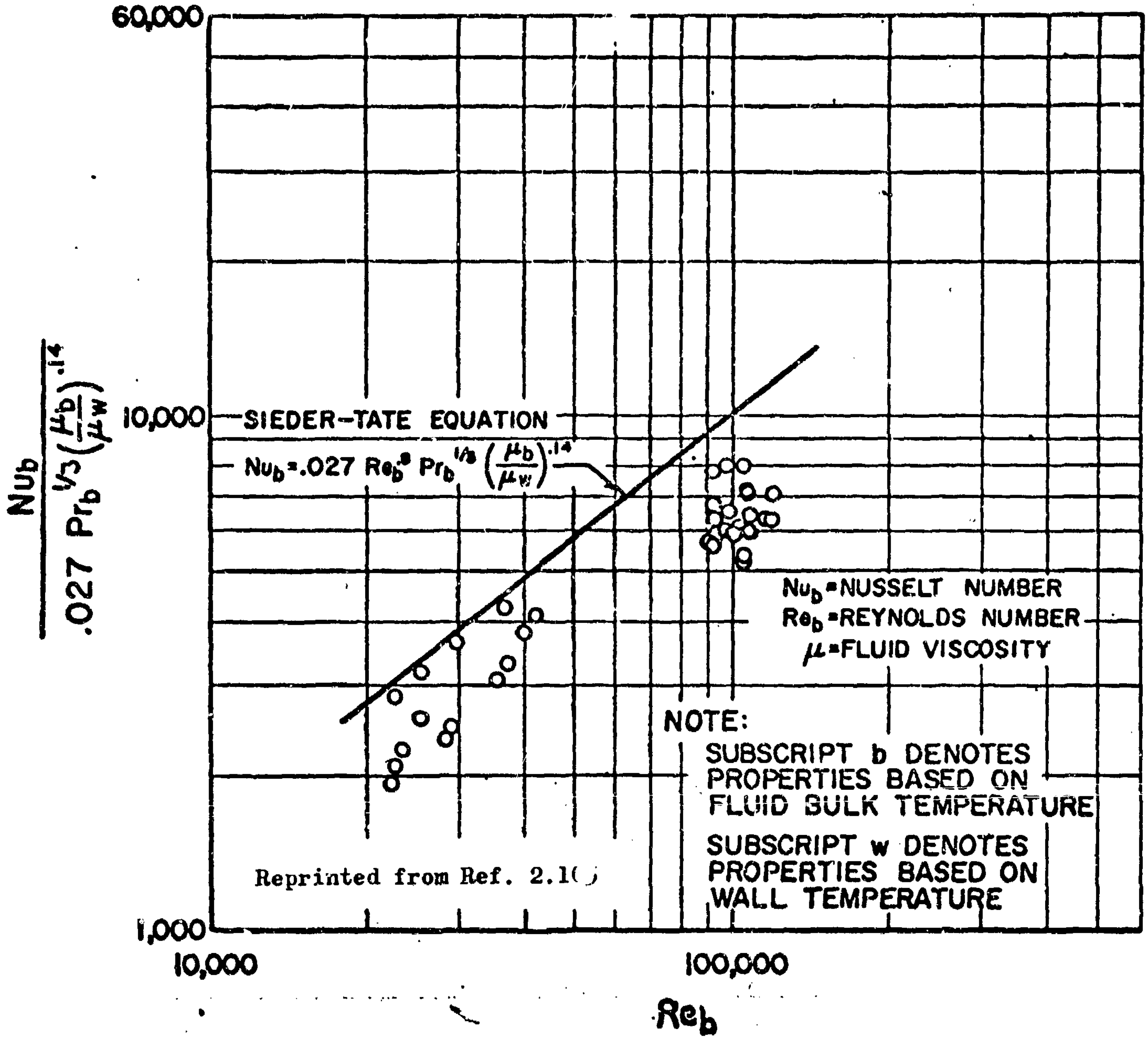


Figure 2.28. Correlation of Heat Transfer Coefficients of 98 w/o Hydrogen Peroxide With Sieder-Tate Equation (Convective Region)

## 3.1 MANUFACTURING TECHNIQUES

### 3.1.1 Preparation

The early laboratory preparation of hydrogen peroxide was based on the technique that Thenard used during the initial preparation of hydrogen peroxide. In this technique, barium nitrate, purified by recrystallization, was decomposed by heating in air in a porcelain retort. The resulting oxide was further oxidized by heating in a stream of oxygen to a dull red heat. The barium peroxide which formed was then dampened, ground, and dissolved in hydrochloric acid (nitric acid was used in Thenard's initial experiments). A slight excess of sulfuric acid was then added to precipitate barium sulfate and regenerate hydrochloric acid. The procedure of barium peroxide solution and sulfate precipitation was repeated several times in the same solution to increase the peroxide concentration (concentrations of up to 33 percent by weight hydrogen peroxide could be achieved in this manner).

The concentrated solution containing water, hydrogen peroxide, and hydrochloric acid, along with accumulated impurities, was cooled with ice and saturated with barium peroxide; iron and manganese impurities in the solution were then precipitated out as phosphates. The hydrochloric acid was removed by the addition of silver sulfate and the sulfate ion was removed by the subsequent addition of barium oxide. Further concentration was accomplished by vacuum distillation until "no further density increase occurs." Thenard reported that 100 w/o hydrogen peroxide (on the basis of density data and the measurement of the volume of oxygen released) could be obtained by this technique.

The first record of commercial production of hydrogen peroxide appeared in the 1865 to 1875 period. The first commercial production in the United States was by the Oakland Chemical Company, Brooklyn, New York, in 1881. Laporte Chemicals Ltd. established a factory in Yorkshire, England, in 1888. With the exception of substitution of fluorosilicic acid for the hydrochloric acid, Thenard's process was used essentially unchanged for the manufacture of hydrogen peroxide until nearly 1900. The formation of hydrogen peroxide in the electrolysis of sulfuric acid was first reported in 1853; later developments made the manufacture of hydrogen peroxide by an electrolytic process possible in 1908. By 1939, only 10 percent of the world's production was by the barium peroxide process.

Currently, hydrogen peroxide is commercially manufactured either by an electrolytic (inorganic) method or one of two organic processes. The electrolytic process (Ref. 3.1) involves the electrochemical formation of either peroxydisulfuric acid or peroxydisulfates (from an ammonium bisulfate solution), their subsequent hydrolysis, and separation of hydrogen peroxide by distillation. The basic equations for these reactions may be summarized as follows:

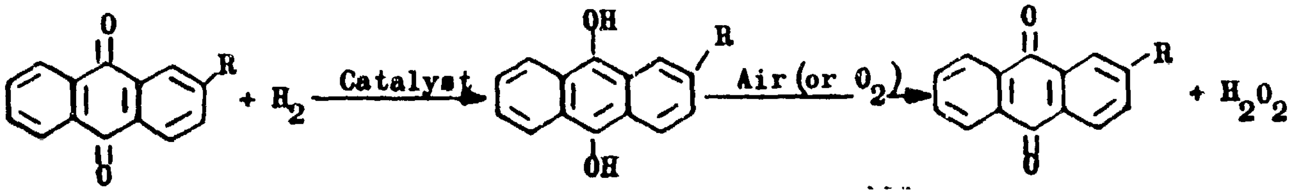
$$2NH_4HSO_4 \xrightarrow{\text{electrolysis}} (NH_4)_2S_2O_8 + H_2$$

$$(NH_4)_2S_2O_8 \xrightarrow{\text{hydrolysis}} 2NH_4HSO_4 + H_2O_2$$

Although sulfuric acid may be used as the starting material, the ammonium bisulfate process is cheaper and has a higher cell efficiency.

The electrolysis is carried out in stoneware tanks with platinum electrodes; conversion of bisulfate to the persulfate takes place at the anode. After hydrolysis of the persulfate (with steam) in an evaporator, the resulting dilute aqueous solution of $H_2O_2$ is separated from the bisulfate and further distilled in a stoneware distillation column. The resulting solution is approximately 30 w/o $H_2O_2$. Both the cathode liquor (after purification) and the bisulfate from the evaporator (and separator) are recycled back to the cells.

One of the organic processes used commercially for the manufacture of hydrogen peroxide involves the catalytic reduction of a substituted anthraquinone and subsequent oxidation back to the quinone structure with the production of $H_2O_2$ (Ref. 3.2). Although the process may vary slightly among the several commercial manufacturers who use it, the basic reactions can be summarized as follows:



where R may be ethyl, t-butyl, etc.

The reduction of the substituted anthraquinone with hydrogen is accomplished from room temperature to 40 C or more and at 1 to 3 atmospheres of pressure in the presence of a Raney nickel, nickel, palladium, or platinum catalyst. The catalyst is separated from the hydroquinone solution and recycled to the hydrogenator. After oxidation of the hydroquinone by either air or oxygen, the resulting quinone solution containing 0.5 to 1 w/o $H_2O_2$ is extracted with water at 25 to 40 C. The aqueous solution of hydrogen peroxide (~ 15 to 35 w/o $H_2O_2$) is cleaned of organic contamination and vacuum distilled to ~ 70 w/o $H_2O_2$. The organic phase from the extractor is evaporated from entrained water, partially dried, cleaned of $H_2O_2$ (by a decomposition catalyst), and recycled as the work solution to the hydrogenator.

The second organic process used in the present commercial manufacture of hydrogen peroxide is based on the oxidation of propane or a propane derivative (such as isopropyl alcohol). Although the actual details of hydrogen peroxide manufacture by these processes are not defined, the basic reactions of the propane oxidation are postulated as follows (Ref. 3.3):

$$C_3H_8 \xrightarrow[O_2]{} C_3H_7\cdot$$

$$C_3H_7\cdot + O_2 \longrightarrow C_3H_7OO\cdot \longrightarrow \text{oxygenated species}$$

$$C_3H_7\cdot + O_2 \longrightarrow C_3H_6 + HO_2\cdot$$

$$C_3H_7\cdot + \cdot H \longrightarrow C_2H_4 + CH_4$$

$$HO_2\cdot + C_3H_8 \longrightarrow C_3H_7\cdot + H_2O_2$$

As noted, the side products in this reaction series are a variety of oxygenated organic species, propylene, methane, and ethylene.

The oxidation of isopropyl alcohol may occur as follows (Ref. 3.3):

$$(CH_3)_2CHOH + O_2 \longrightarrow (CH_3)_2CO + H_2O_2$$

It is reported that the latter reaction can be conducted in either the liquid or vapor phases. Hydrogen peroxide concentrations of 15 to 17 w/o $H_2O_2$ and 25 to 30 w/o $H_2O_2$ are obtained from the propane and isopropyl alcohol oxidations, respectively.

### 3.1.2 Concentration

In most applications outside the propulsion field, only dilute solutions of hydrogen peroxide are required and the product grades normally obtained from the conventional commercial processes are adequate. To meet the demands of propellant-grade hydrogen peroxide, additional concentration is required. Although hydrogen peroxide is normally concentrated commercially by fractional distillation to concentrations $\leq$ 90 w/o $H_2O_2$, other concentration procedures, such as fractional crystallization combined with vacuum distillation, have been frequently used for small-scale purification. The concentration of the 90 w/o $H_2O_2$ solutions to ~ 98 w/o $H_2O_2$ is presently being accomplished commercially (Ref. 3.4) by fractional crystallization. This crystallization process also removes most of the impurities.

The high volatility of water with respect to hydrogen peroxide makes it relatively easy to concentrate peroxide by simple distillation procedures; however, there are several disadvantages to this technique. Concentration of the nonvolatile impurities, which occurs in the hydrogen peroxide during distillation, decreases the stability of the product. In addition, the rate of decomposition increases with temperature rise (2.3 times for each 10 C rise in temperature). Finally, hydrogen peroxide vapors which are in excess of 26 m/o $H_2O_2$ are explosive.

### 3.1.3 Purification

For some purposes, a relatively high impurity and stabilizer content may be innocuous and a lower stability acceptable; however, for most propellant applications it is essential that the impurities be removed or kept to a minimum. This is particularly true when concentrations of 80 w/o or more are desired. High purities in the propellant-grade solutions are obtained by a multiple-stage distillation process in which the hydrogen peroxide is completely vaporized in the first stage, leaving only the nonvolatile impurities. A vacuum distillation is usually performed (Ref. 3.3) to keep the temperature (and subsequently, the decomposition) to a minimum. This technique also decreases the potential explosion hazard.

Theoretically, the removal of impurities by distillation or fractional crystallization should be complete except for impurity pickup from the apparatus itself in either the final process condenser or receiver. However, because of the catalytic impurities acquired during the handling and storage operations, a stannate stabilizer is usually employed in small concentrations to buffer the effects of these impurities. However, the gradual dropout of this stabilizer during storage results in additional emphasis on the importance of impurity removal from hydrogen peroxide solutions.

Although ionic impurities may be removed by applying an electric potential, the use of ion-exchange resins may prove to be a more practical means of purification because this method could be applied easily at the point of final use to remove contamination acquired during transfer operations as well as residual manufacturing impurities. Extensive experimental studies in this area (Ref. 3.5) have indicated that stannic acid seems the most likely choice for an ion-exchange media.

## 3.2 CURRENT PRODUCTION

### 3.2.1 Availability

The principal European manufacturer of hydrogen peroxide is Laporte Chemicals, Ltd. of Luton, Bedfordshire, England. Principal U.S.A. manufacturers are Allied Chemical & Dye, Columbia Southern Chemical Corporation, E. I. duPont de Nemours and Company, Inc., Food Machinery and Chemical Corporation (FMC), and Shell Chemical Company. Of these U.S.A. manufacturers, duPont (anthraquinone process), FMC (electrolytic and anthraquinone processes), and Shell (oxidation of isopropyl alcohol) are the major producers of propellant-grade ($\geq$ 70 w/o $H_2O_2$) hydrogen peroxide. Allied Chemical, which presently produces $H_2O_2$ grades to 70 w/o, has indicated a potential interest in production of higher grades. Presently, FMC is the only commercial manufacturer of > 90 w/o $H_2O_2$ grades. Although hydrogen peroxide concentrations of 99.7 to 99.8 w/o $H_2O_2$ have been produced commercially (Ref. 3.4 and 3.6), the economic- and application-feasibility tradeoff will probably limit commercial manufacture to maximum concentrations of 98 to 99 w/o $H_2O_2$.

The production of hydrogen peroxide was estimated (Ref. 3.7) to be 55,000 short tons (as 100 w/o $H_2O_2$) for the year 1966. This quantity, which includes all grades of hydrogen peroxide, represents an increase over the productions of 52,567, 45,519, and 39,085 short tons which were quoted for the previous 3 years. The present production capacities of the duPont (Memphis, Tenn.), FMC (Buffalo, N.Y., Charleston, W. Va., and Vancouver, B.C.), and Shell (Norco, La.) hydrogen peroxide plants have been quoted as $2.5 \times 10^6$, $3 \times 10^6$, and $> 5 \times 10^6$ pounds hydrogen peroxide (as 100 w/o $H_2O_2$) per year, respectively.

Hydrogen peroxide is available in various quantities up to tank car sizes (4000-, 6000-, or 8000-gallon capacity). The use of 500- and 1300-gallon capacity portable hydrogen peroxide tanks that can be filled at the plant and used as storage vessels at the user's site offers many advantages, particularly for remote, overseas, or temporary sites. Tank trucks with capacities up to 4000 gallons are presently in service or available. Small quantities are normally purchased in 30-gallon drums.

### 3.2.2 Cost

Because hydrogen peroxide sales are of a highly competitive nature, the cost of propellant-grade hydrogen peroxide is flexible. The grade (including concentration, purification, stabilization, etc.), quantity, and present competition are all prime factors in the determination of hydrogen peroxide cost. Thus, all individual manufacturers should be contacted at the time of procurement to determine the exact cost.

For the purpose of estimation, the current price list (Ref. 3.6) of FMC includes the following prices for three different grades of hydrogen peroxide in tank car quantities:

98 w/o $H_2O_2$—$0.60/lb

90 w/o $H_2O_2$—$0.50/lb

70 w/o $H_2O_2$—$0.34/lb

The quoted list prices of the other manufacturers are similar for the 90 and 70 w/o $H_2O_2$ grades. However, the last Air Force procurement (FY 1967) of 90 w/o $H_2O_2$ was based on a cost of $0.23+ (tank car lots) to $0.30/lb (drum lots).

In the procurement of low concentrations of hydrogen peroxide for initial system passivation, pond decontamination, or other applications requiring limited stability, it has been recommended by various manufacturers that higher concentrations be purchased and diluted on site; this technique effects some cost savings in transportation (cost per pound of solution shipped as $H_2O_2$). However, for the high-purity grades or grades requiring special degrees of stabilization, product treatment should be limited to that performed at the manufacturing site.

## 3.3 PROPELLANT SPECIFICATION

Currently, there are two government specifications for the procurement of hydrogen peroxide. These are:

1. MIL-P-16005D, "Propellant, Hydrogen Peroxide," (18 March 1965).
2. MIL-H-22868 (Wep)—"Hydrogen Peroxide - Stabilized, 70% and 90% (for Torpedo Use)," (21 March 1961).

In addition, during the development and utilization of the Redstone Missile System, there was a "purchase description" document, ABMA-PD-H-763, dated 14 August 1958, which was issued by the Army Ballistic Missile Agency for the purpose of procurement of $H_2O_2$ used in this system. Although no longer applicable, this document controlled the previous procurement of 76 w/o $H_2O_2$.

A comparison of the limits and analytical techniques used in these specifications, which have been used in the procurement of 90 w/o propellant-grade, 70 and 90 w/o torpedo-grade, and 76 w/o propellant-grade hydrogen peroxide, respectively, is presented in Table 3.1. It should be noted that many of the users of propellant-grade hydrogen peroxide have company-procurement and use specifications for hydrogen peroxide; however, because of the many variations, these specifications are not discussed in this handbook.

The impurity limits established for torpedo-grade hydrogen peroxide are based on stabilization requirements for maximum storability with respect to torpedo use; thus, the high concentrations of the phosphates, tin, and nitrate ions are required. In the establishment of limits for propellant-grade hydrogen peroxide, minimum stabilization require~~ments had to be met, but impurities that cause $H_2O_2$ catalyst poisoning~~ were strictly controlled. These impurities were identified during an experimental study reported in Ref. 3.8. Phosphate, which acts as a stabilizer by complexing the heavy metal ions which promote $H_2O_2$ decomposition, is a severe catalyst poison; thus, its content in propellant-grade $H_2O_2$ is limited. Tin (as stannous chloride) is added to the peroxide as a stabilizer to offset the effects of residual phosphate; therefore, a minimum limit was established for tin. (The tin content in $H_2O_2$ will gradually decline during storage due to drop-out from the solution). The chloride and sulfate ions are limited because they cause container corrosion (through solution of aluminum). Nitrate has been found to inhibit the effects of chloride and sulfate, and a lower level has been established for this ion to inhibit container corrosion. Although certain carbonaceous materials are known to be catalyst poisons, the effect of carbon is not entirely defined. This effect is discussed further in Section 7.2.1.3.1.

All manufacturers of propellant-grade 90 w/o hydrogen peroxide can presently meet the limits established in MIL-P-16005D. This is illustrated in Table 3.2 with typical analyses of products from three different manufacturers, duPont, FMC, and Shell, compared to the procurement specification requirements.

> NOTE: Although there are some differences in impurity types and levels in the hydrogen peroxide produced by the various manufacturers, the limits criteria established by MIL-P-16005D are adequate to govern the procurement and operational quality of propulsion-grade 90 w/o hydrogen peroxide. Further discussion of this analysis is presented in Section 7.2.1.3.

Currently, there is no government procurement specification for 98 w/o hydrogen peroxide. However, the Air Force Rocket Propulsion Laboratory, which has been assigned primary responsibility for DOD and NASA propellant specification coordination, has indicated (Ref. 3.9) that a procurement specification for 98 w/o $H_2O_2$ will be released in 1967. Present plans are to revise MIL-P-16005D to include the limitations for higher concentrations of $H_2O_2$. The tentative limits on the $H_2O_2$ assay of the higher concentration are 98 w/o minimum and 99 w/o maximum. In addition, the revision will include some changes in the analytical techniques recommended in the present specification. An indication of these changes is given in the following discussion under Chemical Analysis.

## 3.4 CHEMICAL ANALYSIS

The currently recommended procedures and techniques for the complete analysis of propellant-grade hydrogen peroxide are presented in the appropriate procurement specifications. The chemical analysis of other propellant grades, not included in the present procurement specifications, can be conducted with similar techniques. Chemical analysis techniques for hydrogen peroxide also are available from the hydrogen peroxide manufacturers upon request.

Because of the space limitations of this handbook and the ready availability of the analytical procedures, they are not reproduced in this handbook. However, in summation of the analytical techniques recommended by MIL-P-16005D, $H_2O_2$ assay is determined by standard titration with ceric sulfate to a ferroin end point. The Al, Cl, $NH_4$, $NO_3$, $PO_4$, and $SO_4$ ions are all determined spectrophotometrically, and tin is determined polarographically. Carbon content is determined by combusting the sample in a furnace to change the carbon materials to $CO_2$; this is subsequently determined by titration (Ref. 3.9). There are some differences in the analytical techniques recommended by MIL-P-16005D and those recommended by the various manufacturers and used in the industry. The differences in these procedures, which are for the most part minor, are summarized in the following paragraphs. The Air Force Rocket Propulsion Laboratory has recognized these differences and has indicated probable changes in the presently recommended analytical techniques during the next revision of the procurement specification.

### 3.4.1 $H_2O_2$ Assay

Although MIL-P-16005D recommends determination of $H_2O_2$ assay by ceric sulfate titration, a survey of the industry has indicated that most laboratories prefer $H_2O_2$ assay determination by a permanganate titration because of the ease in identification of the end point. However, all laboratories can perform the ceric sulfate titration with equivalent accuracies.

### 3.4.2 Aluminum

In the spectrophotometric procedure specified in MIL-P-16005D for determination of the aluminum ion, an aluminon-gelatin buffer solution is used for color formation. The duPont (Ref. 3.10) and Shell (Ref. 3.11) procedures suggest the use of 8-hydroxyquinoline and extraction with chloroform for color formation. The FMC (Ref. 3.6a) procedure suggests that the sample size be increased from 10 to 25 milliliters and that the buffer solution, prepared by the specification method, may be slightly less stable than the buffer solution preparation detailed in the FMC procedure.

### 3.4.3 Chloride

Shell (Ref. 3.12) suggests determination of the chloride ion by measurement of turbidity with a colorimeter instead of the spectrophotometer specified in MIL-P-16005D. The FMC procedure (Ref. 3.6b) is a colorimetric method using mercuric thiocyanate and ferric ammonium sulfate.

### 3.4.4 Ammonium

In determination of the ammonium ion by spectrophotometry, duPont (Ref. 3.10) separates the ammonia from the other contaminants by distillation before color formation. The FMC (Ref. 3.6) and Shell (Ref. 3.13) procedures essentially agree with MIL-P-16005D except FMC suggests that greater accuracy may be achieved by increasing the sample size from 10 to 50 milliliters.

### 3.4.5 Nitrate

FMC (Ref. 3.6) recommends that the heating step with the phenoldisulfonic acid reagent, employed in the determination of the nitrate ion, be increased to 15 minutes (from 5 minutes) to ensure complete contact and nitration of the sample residue. The Shell procedure (Ref. 3.14) utilizes a larger sample size and increases the heating time to 10 minutes.

### 3.4.6 Phosphate

The duPont procedure for the determination of the phosphate ion is essentially identical to MIL-P-16005D except that the ether extraction is omitted (Ref. 3.10). The Shell (Ref. 3.15) procedure also omits the ether extraction and uses hydrazine instead of stannous chloride to develop the molybdenum blue color. The FMC (Ref. 3.6c) procedure is somewhat different. FMC (Ref. 3.6) reports that attempts to use this procedure (MIL-P-16005D) failed to give valid or comparative results. Although only preliminary investigations have been conducted, studies indicate an error in pH adjustment of the sample solution before extraction with ether. It also appears that the stannous chloride reagent is too acid, as the blue molybdate color is removed by this reagent. Three reagents added to the sample solution (HBr, HCl, and $HNO_3$), are not added in the calibration curve procedure. Thus, the $PO_4$ content of the sample could be enhanced by any $PO_4$ contained in these reagents.

### 3.4.7 Sulfate

For the determination of sulfate, duPont (Ref. 3.10) recommends the use of a preliminary perchloric acid oxidation to measure total sulfur, instead of only sulfate sulfur. Shell (Ref. 3.16) recommends precipitation with barium chloride, stabilization of the suspension by the addition of alcohol and glycerine, and turbidity measurements with a photoelectric colorimeter. FMC (Ref. 3.6d) also suggests the use of a turbidimeter (rather than the spectrophotometer), and a method which converts $SO_4$ to $H_2S$ instead of a caustic addition with $BaSO_4$ precipitation.

### 3.4.8 Tin

Both duPont (Ref. 3.10) and FMC (Ref. 3.6e) suggest the use of a polarographic method for determining tin in contrast to the spectrophotometric technique recommended in MIL-P-16005D. Shell (Ref. 3.17) uses a spectrophotometric technique which is different from that in the MIL-P-16005D; the stannic tin is extracted into an 8-hydroxyquinoline-chloroform solution at a pH of 0.85, and the tin is determined spectrophotometrically in the chloroform extract.

### 3.4.9 Carbon

DuPont (Ref. 3.10) suggests that measurement of change in conductivity of the barium hydroxide scrubbing solution is a more accurate technique for carbon determination than the titration recommended in MIL-P-16005D. FMC (Ref. 3.6) suggests that the MIL-P-16005D procedure is (1) "time consuming and hence expensive to run, and (2) it requires rather elaborate combustion equipment." Instead, FMC suggests the use of a procedure (Ref. 3.6f) where the sample is decomposed by addition of silver nitrate solution and the noncondensable vapors, from boiling of the resulting solution, are passed through a combustion tube packed with copper oxide at 750 C; the resulting gas is passed through a solution of barium hydroxide and potassium persulfate, which is then titrated with standard HCl solution to determine carbon. Shell (Ref. 3.18) uses a combustion technique to convert the carbon to $CO_2$, which is determined in a gas chromatographic column.

### 3.4.10 Residue

DuPont (Ref. 3.10) obtains residue by atmospheric pressure concentration rather than in a vacuum oven.

### 3.4.11 Particulate

The stringency of the particulate limit, 1 mg/liter, established by MIL-P-16005D has been noted (Ref. 3.6) in comparison to that established (10 mg/liter) for other propellants. In addition, duPont (Ref. 3.10) prefers the use of a Teflon polytetrafluorethylene filter instead of a polyethylene filter for reasons of safety.

### 3.4.12 Stability

Most laboratories prefer gas collection techniques for determining stability in contrast to the weight loss technique recommended in MIL-P-16005D.

## 3.5 REFERENCES

3.1 __________, "Current Hydrogen Peroxide," Chem. Eng., 61, 304-307 (1954).

3.2 F.M.C. Corporation, New York, New York, "Hydrogen Peroxide," Hydrocarbon Processing, 44, 225, (1965).

3.3 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, Hydrogen Peroxide, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

3.4 Bloom, Ralph, Jr., and Norris J. Brunsvold, "Anhydrous Hydrogen Peroxide as a Propellant," Chem. Eng. Prog., 53, (11), 541-7 (1957).

3.5 Shell Development Company, Emeryville, California, Storable Concentrated Hydrogen Peroxide, Report No. AFRPL-TR-66-262, Report period: June - August 1966, Contract AF04(611)-11416.

3.6 Private communication, J. C. McCormick, F.M.C. Corporation, Buffalo, New York, to M. T. Constantine, Rocketdyne, Canoga Park, California, December 1966.

3.6a Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-11 (Rev. 0).

3.6b Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-18 (Rev. 0).

3.6c Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-21.

3.6d Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-22B.

3.6e Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-12.

3.6f Ref. 3.6, based on F.M.C. Analytical Procedure SC-55-5 (Rev. 0).

3.7 __________, Chemical and Engineering News, 5 September 1966.

3.8 Naval Research Laboratory, Washington, D.C., *The Role of Inorganic Contaminants in the Catalytic Decomposition of Hydrogen Peroxide*, Report No. 5117, 15 April 1958.

3.9 Forbes, F. S., "Propellant Specification, Quality Control Analysis," Presented at the Sixty-first National Meeting, A.I.Ch.E., Houston, Texas, 19-23 February 1967.

3.10 Private communication, J.C. Snyder, duPont, Memphis, Tennessee, to M. T. Constantine, Rocketdyne, Canoga Park, California, 22 November 1966.

3.11 Shell Development Company, Emeryville, California, *Shell Analytical Methods for Hydrogen Peroxide*, SMS 714/59, 1959.

3.12 Ref. 3.11, SMS 722/59, 1959.

3.13 Ref. 3.11, SMS 708/59, 1959.

3.14 Ref. 3.11, SMS 720/62, 1962.

3.15 Ref. 3.11, SMS 712/59, 1959.

3.16 Ref. 3.11, SMS 725/59, 1959.

3.17 Ref. 3.11, NP-99/63, 1962.

3.18 Ref. 3.11, SMS 749/59 (Rev. 11/13/64), 1959.

## TABLE 3.1

## SUMMARY OF MILITARY SPECIFICATIONS USED IN THE PROCUREMENT OF HYDROGEN PEROXIDE

| Property | MIL-P-16005D |  |  | MIL-H-22868 |  |  | ABMA-PD-H-763 |  |
|---|---|---|---|---|---|---|---|---|
|  | Limits |  | Analytical Technique | Limits |  | Analytical Technique | Limits | Analytical Technique |
|  | Minimum | Maximum |  | Minimum | Maximum |  | Maximum |  |
| Weight Percent $H_2O_2$ | 90.0 | 91.0 | $CeSO_4$ Titration | 69.5 to 71.0 | 89.5 to 91.0 | $KMnO_4$ Titration | 76 ±0.5 | $KMnO_4$ Titration |
| Aluminum, mg/liter |  | 0.5 | Spectrophotometric |  |  |  | 0.6 | Spectrophotometric |
| Chloride, mg/liter |  | 1.0 | Spectrophotometric (turbidimetric) |  | 1.0 | Turbidimetric | 0.5 | Turbidimetric |
| Ammonium, mg/liter |  | 3 0 | Spectrophotometric |  |  |  | 3.5 | Colorimetric |
| Nitrate, mg/liter | 3.0 | 5 0 | Spectrophotometric | 90 | 130 | Colorimetric | 5.0 | Colorimetric |
| Phosphate, mg/liter |  | 0.2 | Spectrophotometric | 25 | 33 | Colorimetric | 0.5 | Colorimetric |
| Sulfate, mg/liter |  | 3.0 | Spectrophotometric (turbidimetric) |  | 10.0 | Turbidimetric | 3.25 | Turbidimetric |
| Tin, mg/liter | 1.0 | 4.0 | Spectrophotometric | 28 | 36 | Polarographic | 3.0*<br>2.5** | Polarographic |
| Carbon, mg/liter |  | 200.0 | Combustion | — | — |  | — |  |
| pH | — | — |  | 1.2 to 1.6 | 0.0 to 0.4 | pH Meter | — |  |
| Surface Tension, $\frac{\text{dynes}}{\text{cm}}$ | — | — |  | 72 | 74 at 20 C | Capillary Rise | — |  |
| Evaporative Residue, mg/liter |  | 20.0 |  |  | 325 |  | 10 |  |
| Stability, percent |  | 5 | (Loss in weight after 24 hours at 100 C) |  | 2 | (Loss in weight after 24 hours at 100 C) | — |  |
| Color | (Clear, colorless) |  |  | (Clear, colorless) |  |  | (Clear, colorless) |  |
| Container Condition | (No defects, leaks or signs of decomposition) |  |  | (No defects, leaks or decomposition) |  |  |  |  |

## TABLE 3.2

## COMPARISON OF TYPICAL ANALYSES FOR PROPELLANT-GRADE 90 w/o HYDROGEN PEROXIDE FROM THREE DIFFERENT COMMERCIAL MANUFACTURERS

| | Military Specification | DuPont | Shell | FMC |
|---|---|---|---|---|
| Percent $H_2O_2$ | 90.0 to 91.0 | 90.7 | 90.7 | 90.8 |
| Percent AOL | 5.0 maximum | 0.9 | 0.3 | 1.1 |
| Carbon, mg/liter | 200 maximum | 11 | 150 | BDL* |
| Residue, mg/liter | 20 maximum | 15 | 15 | 15 |
| $Cl^{-1}$, mg/liter | 1.0 maximum | 0.2 | < 0.1 | 0.2 |
| $PO_4^{-3}$, mg/liter | 0.2 maximum | 0.1 | 0.04 | 0.07 |
| $NO_3^{-1}$, mg/liter | 3.0 to 5.0 | 3 | 3.6 | 3.5 |
| $SO_4^{-2}$, mg/liter | 3.0 maximum | 0.3 | < 3.0 | 0.02 |
| Sn, mg/liter | 1.4 to 4.0 | 1.8 | 1.8 | 1.9 |
| $NH_3$, mg/liter | 3.0 maximum | 0.3 | < 3.0 | 0.03 |
| Al, mg/liter | 0.5 maximum | 0.2 | 0.2 | 0.07 |
| Insolubles, mg/liter | 1.0 maximum | <1.0 | <1.0 | <1.0 |

*Below Detectable Limits

# SECTION 4: STORAGE AND HANDLING

## 4.1 STORABILITY

### 4.1.1 General

The storability (or storage stability) of hydrogen peroxide is usually described in terms of decomposition rate and/or concentration change of the $H_2O_2$ over a period of time. Because storability is directly related to decomposition, it becomes a function of the considerations involved in the decomposition mechanisms. In a simplification of these mechanisms, which are described in detail in Section 7, the basic factors controlling decomposition rate in a storage system are $H_2O_2$ concentration; temperature; impurity types and concentrations in the $H_2O_2$; and the composition, area, and condition of the surface in contact with the $H_2O_2$. Although many of these factors are discussed in other sections of this handbook as a result of studies of materials compatibility, passivation techniques, decomposition mechanisms, etc., they are interrelated and presented in this section in terms of storability.

Until the early 1960's, the generally accepted decomposition rate AOL* of commercial, unstabilized, propellant-grade hydrogen peroxide under normal storage conditions (e.g., in a 30-gallon storage drum at an S/V of 0.38 $in.^{-1}$) was ~1 percent/year at ambient temperatures of 77 to 86 F (Ref. 4.1). This rate is theoretically equivalent to a propellant-grade hydrogen peroxide concentration loss of ~ 0.5 w/o $H_2O_2$/year. Some examples of decomposition rates actually experienced during drum storage (under field handling conditions) of various types of hydrogen peroxide between 1945 and 1963 are shown in Table 4.1 in terms of concentration changes and actual oxygen loss. These results, which are essentially representative of propellant manufactured before 1960 and of storage at the S/V (0.38 $in.^{-1}$) typically found in 30-gallon storage drums, were reported in Ref. 4.2.

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*AOL (active oxygen loss) is defined in Section 4.2.1.1.4.

There are some discrepancies noted in Table 4.1 between the reported oxygen losses and the $H_2O_2$ concentration changes. It would appear that if the magnitudes of the reported $H_2O_2$ concentration changes were entirely attributable to $H_2O_2$ decomposition, the oxygen losses would be much higher. Although it is possible that some of the $H_2O_2$ concentration change during the storage period was due to moisture absorption from the air (during drum "breathing"), the discrepancies do cause some doubt in the validity of the oxygen losses reported. Because the technique for determination of oxygen loss is not reported, and it is assumed that such a measurement would be difficult under the uncontrolled conditions of drum storage, the concentration change appears to be the most indicative factor of decomposition rate during these tests.

From the $H_2O_2$ concentration changes reported in Table 4.1, the decomposition rate of the unstabilized 90 w/o $H_2O_2$ can be estimated as approximately 1-percent AOL/year which corresponds to that rate generally accepted by the industry during this period. The data presented in the table also indicate smaller decomposition rates for both the 98 w/o $H_2O_2$ propulsion grade and the stabilized torpedo grades (90 and 70 w/o $H_2O_2$) under essentially the same storage conditions. These effects are discussed further in Sections 4.1.3.2 and 4.1.3.5.

Recently, improvements have been reported in the storage stability of hydrogen peroxide, particularly, in the 90 w/o grade. The gross result of this improvement is illustrated in Table 4.2 with data from studies conducted in 1947 (Ref. 4.3) and in 1965 (Ref. 4.1 and 4.4) on 90 w/o $H_2O_2$ and studies on 99+ w/o $H_2O_2$ in 1953 (Ref. 4.5). In this table the rate of decomposition of the hydrogen peroxide has been reported as a function of temperature and as a function of contamination for the three different time periods. Although the reasons for the improvement in hydrogen peroxide stability are not defined in Table 4.2, the data are indicative of the progress that has been made in the storability of hydrogen peroxide.

### 4.1.2 Storability Improvement Studies

This recent increase in the storage stability of hydrogen peroxide is a result of a combination of factors including (1) increased purity of the hydrogen perioxide, (2) better selection of the container materials, (3) improved surface treatment and passivation of the container, and (4) development of more effective stabilization techniques. A recent characterization of these factors resulted from three primary studies directed at the improvement of hydrogen peroxide storability. These studies, which were conducted by duPont (Ref. 4.6), FMC (Ref. 4.7), and Shell (Ref. 4.1, 4.8 and 4.9), are summarized in the following paragraphs.

DuPont (Ref. 4.6) conducted studies on (1) the stability of solid and low-temperature (32 F) liquid hydrogen peroxide (90 to 100 w/o $H_2O_2$) in Pyrex; (2) the effect of aluminum, Pyrex, polyethylene, and fluorocarbon polymers on the stability of $H_2O_2$ in the 122 to 158 temperature range; and (3) the reaction mechanisms of hydrogen peroxide decomposition. As a result of this study, the decomposition rate of high-purity or commercially stabilized hydrogen peroxide at -76 to 32 F was found to be less than 0.04 percent per year in Pyrex. In addition, the decomposition rate of 90 w/o $H_2O_2$ in contact with a Teflon FEP fluorocarbon film that had been mildly irradiated in air was less than one-third of the rate involved in contact of the 90 w/o $H_2O_2$ with a passivated aluminum surface and less than one-half the rate with Pyrex.

Sealed storage studies of the commercial and propulsion grades of 90 and 98 w/o $H_2O_2$ in TFE Teflon bladders (contained in mild steel tanks) were conducted at 70 to 72 F (5 months), 120 F (7 days), and 165 F (72 hours) by FMC (Ref. 4.7). Although bleaching and cracking of the bladders were experienced, the tests demonstrated a reduction in $H_2O_2$ decomposition rates through improved surface pretreatment and passivation techniques and use of stabilizers. Extrapolations of the data indicated the oxygen losses of 98 w/o $H_2O_2$ were less than 0.4 percent/year at 70 F in the bladders. Compatibility screening studies indicated that other bladder materials such as NAA Vicone 185, duPont Viton B (805), and 3M Fluorel 2141 were superior to the TFE Teflon material.

In the study conducted by Shell (Ref. 4.1), experimental investigations were directed into three major areas: (1) improvement of $H_2O_2$ purity, (2) development of an improved liquid decomposition inhibition system, and (3) assessment of container materials of construction for long-term storage. Storage decomposition rates for 90 w/o $H_2O_2$ were reduced to 0.04 percent/year at ambient temperature as a result of $H_2O_2$ stabilization and careful selection and preparation of the storage container material (Pyrex). It was also indicated that the use of other materials such as ACLAR-33C and Kel-F plastics, 1260 aluminum, and electrolytic tin plate (special preparation) in large storage tanks [minimum surface-to-volume ratio (S/V)] could reduce overall decomposition rates under normal storage conditions to 0.1 percent/year. Various means of purification such as distillation, recrystallization, and ion exchange on insoluble inorganic exchangers have also been effective in reducing the decomposition rate; it was also indicated that decomposition rates of 99 w/o $H_2O_2$ were slightly lower than those of 90 w/o $H_2O_2$ under the same environmental conditions (including the degree of contamination).

Shell has continued the investigation of hydrogen peroxide purification and stabilization techniques and the passivation of container materials to determine the feasibility of sealed hydrogen peroxide storage for periods of 5 years (Ref. 4.8 and 4.9). In this study, which was scheduled to be concluded in January 1968, $\beta$-stannic acid was determined to be the most effective ion-exchange purification medium for increasing the stability of hydrogen peroxide in storage; decomposition rates of 90 w/o $H_2O_2$ treated with this technique were approximately one-third the rates of untreated 90 w/o $H_2O_2$ after storage in aluminum for periods of 1 year. It was also determined that the minimum decomposition rate of hydrogen peroxide in contact with aluminum surfaces was achieved when the aluminum was subjected to a caustic-nitric acid-hot (212 F) 90 w/o $H_2O_2$ pretreatment sequence prior to testing; however, only minor changes in stability resulted from various types of chemical pretreatment of stainless-steel surfaces (Tables 4.31 and 4.31a and Section 4.2.2.12). The decomposition rate of 90 w/o $H_2O_2$ in contact with tin-plated (electroplated) aluminum was greater than that observed with either the best tin surface or the best passivated aluminum surface.

### 4.1.3 Factors Affecting Storability

As noted throughout the various studies of storability, decomposition, passivation, materials compatibility, propellant purification, etc., reported in various sections of this handbook, storage stability of hydrogen peroxide is dependent on a variety of factors. Because it is difficult, however, to separate the influence of each contributing factor under actual storage conditions, many of these studies have been conducted under ideal or isolated environments. Although, for this reason, the translation of the data from these tests into gross storability in terms of particular rates are difficult, the general degree of influence can be fairly accurately predicted and established. Thus, the general effect of factors such as concentration, purity, temperature, container material, container surface pretreatment, and passivation, S/V container ratio, and propellant stabilization system on storability are discussed briefly in the following paragraphs.

4.1.3.1 Concentration. Under equivalent storage conditions, it has been determined that the storage stability of hydrogen peroxide is increased with its concentration (Ref. 4.1 and 4.2). This is generally attributed to the decrease in impurities and ionization with the loss in water content, and to the decrease in container contact area with decrease in surface tension. This effect is illustrated as a function of concentration from 90 to 98 w/o in Fig. 4.1; comparisons of other decomposition rates between 90 and 98 w/o $H_2O_2$ are shown at two other conditions in Fig. 4.2 and 4.3.

4.1.3.2 Purification. As the various inorganic and organic contaminants are removed from hydrogen peroxide-water solutions, storage stability will approach that of high concentration (98 w/o) hydrogen peroxide; however, because of the various effects (described in Section 4.1.3.1) resulting from water elimination, the storability of the more aqueous solutions will never equal the stability of 98 w/o $H_2O_2$ assuming the same degree of impurities (Ref. 4.1). Current studies (Ref. 4.8 and 4.9) have demonstrated that various types of purification techniques will produce hydrogen peroxide with homogeneous decomposition rates on the order of 0.03 to 0.07 percent AOL/year at 77 F.

4.1.3.3 Temperature. In general, the decomposition rate of hydrogen peroxide has been found to increase 2.3 times for each 10 C (18 F) rise in temperature; this effect is illustrated in Fig. 4.4 which was reprinted from Ref. 4.1. Other data on this effect have been reported in Ref. 4.5.

4.1.3.4 Container Surfaces. The effect of the storage container on the storability of hydrogen peroxide is essentially a function of the type of material, the surface treatment and passivation, and the S/V of the material in contact with the liquid volume.

4.1.3.4.1 Container Material. The effect of various materials in contact with the hydrogen peroxide is described and compared in the Materials Compatibility Section (Section 4.2.2). However, for comparison purposes, decomposition rates resulting from the effect of selected materials in combination with other effects are shown in Fig. 4.4 (Ref. 4.1) and 4.5 (Ref. 4.1 and 4.10) for 90 w/o $H_2O_2$.

4.1.3.4.2 Surface Treatment and Passivation. Several studies (i.e., Ref. 4.1, 4.7 to 4.9, and 4.11 to 4.18) have established the importance and effect of surface pretreatment and passivation on the decomposition rate and the stability of hydrogen peroxide. Detailed data in this area are presented in Section 4.2.2.12 and Tables 4.21 through 4.31a as part of the Materials Compatibility Section. An example of the effect of surface pretreatment in terms of storability of hydrogen peroxide is shown in Fig. 4.6.

4.1.3.4.3 Surface to Volume Ratio. The effect of the storage container surface on the decomposition rate of the hydrogen peroxide is usually illustrated in terms of S/V. This ratio is generally defined as the immersed surface area (that area in contact with the liquid hydrogen peroxide)/liquid volume of the hydrogen peroxide. The relationship between these two factors has been found to be an effective means of expressing the contribution of the heterogeneous decomposition rate of the liquid to the overall decomposition rate of the hydrogen peroxide.

In determination and comparison of the compatibility of various materials, the S/V is usually kept constant. For most of the studies illustrated in Section 4.2.2, a sample size of 1-1/2 by 1/2 by 1/16 inch has been immersed in 75 milliliters of hydrogen peroxide, thus establishing a S/V value of 0.38 $in.^2/in.^3$ ($0.38\ in.^{-1}$). This number generally corresponds to the conditions found in the storage of hydrogen peroxide in a standard 30-gallon storage drum.

It is obvious that as the surface in contact with the liquid is reduced (S/V → 0), the heterogeneous decomposition rate is reduced. Thus hydrogen peroxide stored in large storage tanks should have a minimum decomposition rate, assuming the equivalency of the other factors. This is illustrated in Fig. 4.5a in which experimental studies (Ref. 4.1) were used to predict the decomposition rates shown in the figure; as S/V is reduced, the overall decomposition rate of the hydrogen peroxide approaches that of the homogeneous decomposition rate. Further, it was indicated in this study that "decomposition rates of the order 0.1 percent AOL/year at ambient temperature appear to be readily attainable by use of highest quality (90 w/o $H_2O_2$) stabilized with sodium stannate and stored in vessels of low surface activity and low S/V ratio.

Other experimental studies (Ref. 4.5 and 4.10) of the effect of S/V on hydrogen peroxide storability are illustrated in Fig. 4.5b, 4.5c, and 4.7. Figure 4.5a, 4.5b, and 4.5c also indicate the effect of S/V as a function of different materials. Figure 4.7 represents work (Ref. 4.5) that attempted to limit the homogeneous decomposition rate through the use of high purity (99+ w/o) hydrogen peroxide and limit the catalytic effect of the container surface by using carefully pretreated glass. It was concluded from the latter study that "the whole inside surface of the container plays a part in the decomposition, but per unit area the immersed surface is more effective than the nonimmersed surface."

4.1.3.5 **Stabilization**. The use of stabilizers to improve hydrogen peroxide storage stability is essentially based on the premise that they will inhibit decomposition by contamination incurred during storage and handling operations. If the hydrogen peroxide could be protected against contact with soluble and insoluble contaminants, stabilization would not be required. In addition to the contamination of the hydrogen peroxide by the system fabrication materials, $H_2O_2$ contamination may result from improper storage and/or handling system, cleaning and passivation techniques. The incomplete removal of organic solvents, acids, detergents, chromic acid cleaning solutions, etc., by inadequate rinsing or the use of rinse waters which contain various impurities can readily cause contamination of hydrogen peroxide by the storage or handling system. For the preceding reasons, and because the normally manufactured hydrogen peroxide does contain traces of impurities that will cause $H_2O_2$ decomposition, some degree of stabilization has been effected in most of the commercially manufactured hydrogen peroxide. The degree and type of stabilization has depended on the planned use of the $H_2O_2$.

There is no single stabilizing agent which may be designated as the most effective or the most desirable. The selection of a stabilizer must be made with regard to the conditions under which the hydrogen peroxide ultimately is to be used, to the type of contamination likely to be encountered, and to such considerations as the required storage period and the probable prevailing temperature during that storage period. If the storage period is to be relatively brief, an organic stabilizer may be satisfactory; however, over a long period of time, slow oxidation may destroy the effectiveness of an organic component. However, limitations may be placed upon the choice of an inorganic stabilizer because of the quantity of undesirable residues which may remain after a large quantity of hydrogen peroxide has been decomposed. It is also apparent that a large proportion of stabilizer is unsatisfactory.

An extensive number of stabilizers, both inorganic and organic have been tested (i.e., Ref. 4.1, 4.5, 4.8, and 4.9) with both dilute and concentrated hydrogen peroxide solutions. Among these substances, the most notable success was obtained, especially in the case of the highly concentrated hydrogen peroxide solutions (Ref. 4.5), with sodium stannate or 8-hydroxyquinoline ("oxine") in the presence of a soluble pyrophosphate, or a phosphate-pyrophosphate mixture. A detailed discussion of hydrogen peroxide stabilizers is presented in Ref. 4.19 and 4.20.

Recently, the effect of the contaminants most commonly encountered in propellant-grade hydrogen peroxide on the stability of hydrogen peroxide was characterized (Ref. 4.21). Separate 90 w/o hydrogen peroxide solutions were contaminated with various concentrations of selected ions ($Cr^{+3}$, $Fe^{+3}$, $Cu^{+2}$, $Ni^{+2}$, $PO_4^{-3}$, $SO_4^{-2}$, $NO_3^{-1}$, $Cl^{-1}$) to determine their influence upon the stability of the hydrogen peroxide. Copper was found to exhibit the greatest effect (toward decreasing the stability) followed by iron, nickel, and chromium (Table 4.2). The anions exhibited no detectable influence in the concentration ranges studied when stability was measured by standard weight loss technique.

4.1.3.5.1 Stabilization Effects. The total effectiveness of hydrogen peroxide stabilization depends largely on the type and quantity of stabilizer used, the initial $H_2O_2$ concentration and purity, and the container material type and surface pretreatment. Recent studies by Shell (Ref. 4.5) on storage in 5-gallon drums has demonstrated that commercially available 90 w/o hydrogen peroxide can be stabilized and stored in properly prepared vessels with a decomposition rate as low as 0.04 percent/year at ambient temperatures. The evolved gas at such rates can be contained in the vessel with relatively low ullage and at reasonable pressures for several years. The decomposition rate depends to an appreciable extent upon the container material and the surface finish. Pyrex effects the lowest decomposition rate. However, with the proper passivation and surface treatment, containers of ACLAR, Kel-F, 1260 aluminum and electrolytic tin having low S/V demonstrated decomposition rates as low as 0.1 percent/year. The rates predicted for these materials as a function of S/V are shown in Fig. 4.5a.

Other examples of the end results of stabilization are illustrated in Fig. 4.1, 4.8, and 4.9. Figure 4.1 (Ref. 4.2) compares oxygen loss over a 24-hour period between commercially stabilized and unstabilized hydrogen peroxide as a function of concentration at 212 F. Figure 4.8 (Ref. 4.7) illustrates the reduction in AOL by commercial stabilization of 98 w/o hydrogen peroxide as a function of temperature. The effect of stabilizer quantity is illustrated in Fig. 4.9 (Ref. 4.8); the stabilizer used in this illustration was sodium stannate, which was added in varying amounts to hydrogen peroxide obtained from three different manufacturers.

4.1.3.5.2 Stabilization Requirements. The requirement for hydrogen peroxide stabilization is based on the end use to which the hydrogen peroxide will be applied. Generally, stabilizers are added to extend the storage life of the propellant, and as such, would appear to be desirable for all situations. However, when the end use of the propellant depends on its decomposition in a fixed catalyst bed chamber, the use of stabilization is severely limited by the poisoning effect of the stabilizer on the catalyst (Section 7). This is reflected in the two primary propellant specifications presently in use. The torpedo-grade propellant specification, MIL-H-22868, which requires long-term sealed storage propellant not subject to decomposition in a fixed-bed catalyst, specifies a large amount of stabilizers. MIL-P-16005D, which is the procurement specification for propulsion-grade hydrogen peroxide, limits the total stabilizer content to a few mg/liter because of the usual application of this hydrogen peroxide grade in fixed catalyst beds. Hydrogen peroxide used in the chemical pretreatment and passivation of hydrogen peroxide systems is sometimes

(Ref. 4.2) heavily stabilized to provide enough ions to complex all of the potential catalytic sites. Therefore, the quantity and type of hydrogen peroxide stabilization is dictated by the end use of the material.

Stabilization is usually effected by the hydrogen peroxide manufacturer as a condition of the procurement. The individual requirements should be discussed with the manufacturer and his assistance sought in determining the need for and type and amount of stabilization required. All hydrogen peroxide manufacturers indicate that conventional stabilization should be accomplished at the manufacturing site.

4.1.3.5.3 Emergency Stabilization. Stabilization of hydrogen peroxide at storage sites has been utilized under "emergency conditions." The conditions, which necessitate this corrective action, are usually associated with self-heating of hydrogen peroxide storage systems due to excessive decomposition caused by unanticipated contamination of the system. One source (Ref. 4.22) has recommended such corrective action when the temperature of the hydrogen peroxide (without external heating) rises to a level 20 F greater than that of the surroundings. The rate of temperature rise also determines the urgency of the corrective measures. Another source (Ref. 4.3) considers it desirable to maintain time-temperature records of all storage units and recommends taking corrective action when the bulk temperature achieves a 2 to 3 F increase in temperature over the maximum ambient temperature. Corrective action is also recommended if the rate of temperature increase is greater than 0.5 F/hour. The more conservative methods limitations of Ref. 4.3 should result in fewer "incidents" and provide additional time to consider appropriate action.

In estimating the necessity of corrective action based on AOL, Ref. 4.23 states that for a 30-gallon drum, a rate of more than 2 percent AOL/year (or 0.0054 percent AOL/day) is abnormal;

for a 500-gallon tank, a rate greater than 1 percent AOL/year or 0.0027 percent AOL/day is excessive and for flow systems a decomposition rate of 0.05 percent AOL/hour is the maximum permissible rate concurrent with a temperature rise of approximately 5 F above ambient conditions.

In the early stages of storage system self-heating, temperature rises may be counteracted by the use of water spray on the storage container. If adequate pure water is available, if container free space is available, and if moderate dilution is not critical to the end use, the most rapid cooling may be achieved by the addition of water directly to the hydrogen peroxide in the storage container. This cooling period allows greater flexibility and additional time for analysis, procurement, or preparation of stabilizer, but does not eliminate the need for further action.

When attempting to control a self-heating tank, a careful record of the temperature vs time should be maintained to help evaluate the effectiveness of the control technique. In projecting a time-temperature curve from previous experience, several assumptions must be made. Most of the approximations will overestimate the hazard and underestimate the time before eruption from the storage container. There are two major factors which may result in decomposition rate accelerations with time: (1) excessive temperature rise may result from the decomposition of the stabilizer, and (2) decomposition at the container walls may result in the formation of a gas blanket which prevents adequate heat transfer through the container wall causing additional temperature increase of the solution and increased decomposition. In the latter case, a temperature-indicating device on the outside wall of the tank will not indicate the temperature increase in the liquid but will indicate a lower temperature. Because heat transfer under these conditions may be somewhat erratic, this temperature is a poor indication of true liquid conditions.

The hydrogen peroxide bulk temperature will lag changes in air temperature depending on the container size. A large tank which has been warmed during the day will require some time to cool because of the volume of solution. For a tank to be warmer than air temperature at night is normal and no cause for alarm. For the tank temperature to be gradually increasing toward an increased air temperature is normal. For the temperature of a tank not exposed to direct rays of the sun to be increasing in temperature when the air temperature is decreasing is abnormal. For the tank temperature to be consistently higher than ambient air temperature is not normal.

In making a decision to stabilize a "hot system," the advice of the hydrogen peroxide manufacturer should be sought if at all possible. If the conditions are so critical that this contact cannot be accomplished, the guide of Paragraph 1.6.6 in "The Handling and Storage of Liquid Propellants - Hydrogen Peroxide" (Ref. 4.24) can be used:

> 1.6.6 Emergency Stabilization: The decomposition of hydrogen peroxide at an accelerating rate, as evidenced by increasing gas evolution and temperature may be brought under control by the following emergency stabilization procedure: add 1 pound of 85 percent phosphoric acid solution (in water) for each 100 gallons of hydrogen peroxide solution. Mixing is not necessary because the turbulence will disperse the stabilizer. After being thus stabilized and if the decomposition subsides, hydrogen peroxide may be stored in aluminum containers until consumed or otherwise disposed of. This solution must not be used in applications involving catalytic decomposition chambers, because the stabilizer will poison the catalyst.

4.1.3.5.4 Effective Life of Stabilizers. Storage in metal containers slowly destroys the stabilizing effect of stannate by precipatation out of the solution. This normally takes approximately 4 months for aluminum containers; in Pyrex containers the stabilizer is approximately 45 percent depleted in 4 months; however, in polyethylene, no loss of stabilizer was detectable (Ref. 4.20). The analysis of hydrogen peroxide solutions for tin will also reveal varying concentrations depending upon the age of the solution when tested. Comparison of analytical reports from separate laboratories on the same solution must allow for this variation.

Hydrogen peroxide used by the Germans during World War II was usually 85 percent by weight $H_2O_2$ and was stabilized with 8-hydroxyquinoline in the form of the pyrophosphate or mixed with sodium pyrophosphate. This stabilizer slowly oxidized and in approximately 6 months had effectively disappeared. This organic stabilizer is normally considered superior to stannate in protection against iron.

## 4.2 MATERIALS OF CONSTRUCTION

Initial selection of materials for application in hydrogen peroxide storage and handling systems is based on a series of materials compatibility tests. These tests may range from an evaluation of a material sample under a set of general test conditions to the definition of the specific limitations of various pieces of hardware fabricated from a number of different materials. Although the compatibility of materials with a propellant is usually based primarily on the ability of the material to withstand chemical attack by the propellant (as expressed by corrosion rate), the emphasis in the evaluation of materials compatibility with hydrogen peroxide is placed on the effect of the material on hydrogen peroxide stability (as expressed by decomposition rate). Because hydrogen peroxide decomposition is a function of several variables, including material type, surface area, contamination, temperature, etc., it is essential that the selection of a material represent an evaluation of all of these potential effects.

The available technology on materials compatibility testing with hydrogen peroxide is summarized in this section. A description of the compatibility studies that have been conducted and the criteria established by these results are used to provide a basis for the selection of materials of construction for hydrogen peroxide service. The final evaluation of a material and its suitability for an application involving contact with $H_2O_2$ is based on experience resulting from that application. In general, the recommendations of materials classification for $H_2O_2$ service contained herein are based on both the results of laboratory tests and on practical experience. In a few instances, practical experience has revealed results different from those of laboratory tests. Whenever this is the case, the greater consideration has been given to practical experience and conclusions are drawn accordingly. Criteria established for laboratory tests are based as far as possible on correlations with experience resulting from placing the materials in service.

> NOTE: The user of this handbook should be cautioned that the materials compatibility data presented herein should only serve as a basis for selection of materials for hydrogen peroxide service. Careful consideration should be given to the conditions of testing; the use of the material under a different set of conditions may have an entirely different effect. Materials which are not suitable for use at high temperatures may be acceptable for uses at lower temperatures. Different fabrication procedures and passivation techniques may result in variation in compatibility classification. Even different lots of the same parts fabricated from "compatible" materials by the same manufacturer using the same manufacturing techniques have revealed variations in compatibility. Thus, it must be emphasized that any material used in hydrogen peroxide service be thoroughly tested and qualified under the conditions of its intended use before it is placed in service.

### 4.2.1 Compatibility Studies

Compatibility studies that have been conducted with hydrogen peroxide are described in terms of standard test procedures, standard compatibility classification definitions, and standard rating criteria. Although the illustrated procedures and classifications do not necessarily reflect the most desirable methods for all purposes, they do represent the most typical (as noted in Ref. 4.25) of the general tests, classifications, and rating criteria presently employed.

4.2.1.1 Compatibility Test Procedure. The compatibility test procedure normally consists of three basic tests. An initial screening test is performed to eliminate all materials that cause gross decomposition of the hydrogen peroxide. The compatibility of the preselected materials with hydrogen peroxide is then determined by measuring a rate of $H_2O_2$ decomposition (as percent AOL) during an immersion of the materials in hydrogen peroxide (of a selected composition) for a stated temperature and time interval. The final evaluation in the compatibility test procedure is the determination of the stability of the hydrogen peroxide after contact with the material.

4.2.1.1.1 Screening. Prior to quantitative testing, a new or untried material should be immersed (after chemical pretreatment) in 75 milliliters of hydrogen peroxide in a passivated container at room temperature for 24 hours. Special attention should be directed to possible violent decomposition, combustion, solution, dimensional distortion, etc. If no unusual action occurs, the sample should be subjected to a further screening at 150 F for 24 hours. If no gross reaction occurs under these preliminary conditions, the material is further tested using the following technique.

4.2.1.1.2 Sample Size. In determinations of the compatibility of solid materials, a sample strip, 3 by 1/2 by 1/16 inches, is normally used for evaluation of both the liquid and vapor phases. For those materials that will be used in a continuously wetted condition, a sample strip, 1-1/2 by 1/2 by 1/16 inches, is usually immersed in 75 milliliters of the hydrogen peroxide solution. This test condition simulates an apparent sample surface area of 1 sq in. per 42.8 milliliters of hydrogen peroxide (which approximates the 0.33 in.$^2$/in.$^3$ S/V of the wetted surface of a standard drum containing 250 pounds of $H_2O_2$). If it is necessary to test a differently sized sample, retention of this apparent S/V will aid in comparison of the results with those of previous studies. In evaluating materials for specific applications, the S/V of the application should be duplicated if possible. In testing the compatibility of liquids with $H_2O_2$, a 5-milliliter sample size is normally used; evaluations of greases are usually conducted with samples of 5-milliliter size which have been smeared on the inside of the test flask. It is important to record and report surface area of the test sample and the liquid volume of the $H_2O_2$ used. Vapor space or ullage should be minimized or held constant in comparison of different materials.

4.2.1.1.3 Cleaning and Passivation of the Test Container and Specimens. Prior to use, all glassware (the test container) should be immersed in a 10-percent sodium hydroxide solution for 1 hour at room temperature, rinsed with water, immersed in a 10-percent $HNO_3$ solution (3-hour minimum), and finally rinsed with distilled water. The use of chromic acid cleaning solutions should be avoided, and passivation with hot concentrated (70+ percent) hydrogen peroxide is recommended.

Aluminum samples should be scrubbed with a warm detergent solution, immersed in 0.26 w/o (N/15) sodium hydroxide at room temperature for 15 to 20 minutes, washed, immersed in 45-percent nitric acid for 45 minutes to 1 hour at room temperature, and finally washed with distilled water. The samples should then be pretreated with 35 w/o $H_2O_2$ at 68 to 72 F for 8 to 24 hours.

Stainless-steel samples should be degreased by scrubbing with trichloroethylene, rinsed with water, allowed to drip dry, and immersed in 70-percent nitric acid for 4 to 5 hours at room temperature. Then, the samples should be washed with clean water, washed with distilled water, and finally pretreated with 35 w/o $H_2O_2$. In instances where the stainless-steel specimens do not respond well to the preceding passivation technique (as noted by decomposition activity in the 35 w/o $H_2O_2$), stainless-steel specimens may be passivated by the following alternate procedure which has been utilized successfully in the past:

1. Degrease by scrubbing with trichloroethylene and allow to drip dry.
2. Immerse the specimen in 2-percent $Na_2Cr_2O_7$ solution, wash twice with $H_2O$, and immerse in a 20-percent $HNO_3$ solution for 1/2 hour at 120 to 130 F. (This procedure has been questioned because contamination with chromate ions is possible.)
3. Flush with potable water.
4. Flush with distilled water and pretreat with 35 w/o $H_2O_2$.

In the case of rusted stainless-steel surfaces and stainless-steel welds, an acid pickling is required before satisfactory passivation can be achieved. The procedure for this treatment is as follows:

1. Immerse in a 3-percent hydrofluoric acid-10-percent nitric acid solution for 30 minutes at 100 F, or 2 to 3 hours at 65 to 70 F.
2. Flush with potable water and scrub with a stiff brush to remove welding scale and rust.

3. Passivate by immersion in 70-percent nitric acid for 4 to 5 hours at room temperature, rinse with clean potable water, and finally rinse with distilled water. Expose the specimen to 35 w/o $H_2O_2$ at 68 to 72 F for 8 to 24 hours.

Plastics and elastomer samples should be thoroughly scrubbed in an 0.5-percent solution of a synthetic detergent, rinsed with distilled water, and immersed in a 10-percent $HNO_3$-water solution at 68 to 72 F for 1 hour. The samples should then be pretreated with 35 w/o $H_2O_2$.

During the final rinsing of all passivated specimens, the samples should not be touched with bare fingers; at this point only gloves or tongs should be used in sample handling. It is usually convenient to wash sample strips on a Pyrex funnel (as a handling medium), taking care to wash all areas. The strip should be dried between two sheets of filter paper at room temperature or in a 122 F oven and then placed in a test flask which is immediately capped with aluminum foil to eliminate possible contamination by dust, dirt, etc.

4.2.1.1.4 <u>AOL Determination by Weight Loss</u>. The specimen, prepared as described in the preceding paragraph, is placed in a passivated 100-milliliter Kjeldahl flask that has been rinsed with a small volume of hydrogen peroxide of the required strength. The flask is weighed to 0.01 gram and the desired quantity (usually 75 milliliters) of hydrogen peroxide of the desired strength is added to the flask. The flask is reweighed and the initial weight of hydrogen peroxide solution is recorded as the difference between these weights. At conclusion of the desired test, the flask and its contents are removed from the constant-temperature bath, cooled to room temperature and weighed. As a minimum requirement, these tests should be conducted in duplicate.

The percent of active oxygen lost is calculated as follows:

$$\text{Percent Active Oxygen Loss} = \frac{W_1 - W_2}{CW_1 \times 0.470} \times 100$$

where

$W_1$ = initial net weight of hydrogen peroxide

$W_2$ = final net weight of hydrogen peroxide

$C_1$ = initial weight fraction of hydrogen peroxide, $\frac{(\text{percent concentration})}{100}$

The results of some compatibility tests (Ref. 4.10 through 4.16 and 4.18) have been based on $H_2O_2$ concentration determinations before and after the tests. During these tests the active oxygen loss is determined by the expression

$$\text{Percent AOL} = \frac{(W_1C_1 - W_2C_2)}{W_1C_1} \times 100$$

where

$W_1$, $W_2$, and $C_1$ are as defined previously and $C_2$ is the final concentration of hydrogen peroxide.

> NOTE: The term 0.47 in the first equation represents the weight fraction of available oxygen in 100 w/o $H_2O_2$.

Qualitative observations are also recorded on such effects as discoloration of the hydrogen peroxide and apparent changes in the physical properties of the test material. The latter includes: (1) for metals--corrosion, staining, and any surface change during or after testing; (2) for plastics and elastomers--blistering, swelling, distortion, changes in flexibility, color, transparency, tensile strength, and tear resistance; and (3) for fabrics—changes in color, tensile strength, burning, and tear resistance.

4.2.1.1.5 AOL Determination by Gas Evolution. During compatibility tests where the AOL is small, probably the most accurate method of measurement is by gas evolution. This technique, which is described in detail in Ref. 4.26, involves the collection of the gas evolved during the test period in a small gas measuring buret. The long neck on the special test flask acts as an air-cooled condenser to reduce loss of the hydrogen peroxide vapor. The neck is connected by means of small bore tubing to nozzles submerged under a few centimeters of water in a trough. Burets are inverted over the nozzles to collect the gas. A multiple arrangement of differently sized burets with appropriate valving is used to permit selection of the proper size and additional volume without loss of any gas. The volume of gas collected is converted to weight of oxygen evolved by use of the relationships expressed in the perfect gas laws. The percent AOL is then computed from the following expression:

$$\text{Percent AOL} = 100 \text{ x weight of oxygen evolved}/0.47 \text{ x } C_1 \text{ x } W_1$$

where $C_1$ and $W_1$ refer to the original concentration of hydrogen peroxide in the test sample expressed as weight fraction and $W_1$ is the original weight of the test sample.

4.2.1.1.6 Stability Determination. The recommended procedure for stability determinations on the resultant hydrogen peroxide is the same as presented in the MIL-P-16005D procurement specification (Ref. 4.27). The stability of the $H_2O_2$, which is obtained from the compatibility test flasks, is measured by determining the active oxygen loss (by either weight loss or gas evolution techniques) over a 24-hour period at 212 F.

In MIL-P-16005D the stability is expressed in percent AOL, although most procedures essentially express stability as (100-AOL) percent.

4.2.1.1.7 Special Compatibility Test Methods. A suggested procedure (Ref. 4.25) for determining the compatibility of protective clothing is performed on 4 by 4 inch clean test samples of "as received" material. The $H_2O_2$ is permitted to drop on the cloth sample at a rate of 4 milliliters per minute for ~ 1 hour. Results are evaluated by visual observation of any changes in the material during this period. To simulate "soiled cloth," a swatch of the material is soaked in a 0.005 N $KMnO_4$ solution for 30 seconds and dried at 230 F for 1 hour. The test is then performed with the procedure used with the "as received" material.

Sealing compounds are tested (Ref. 4.25) initially for impact sensitivity while immersed in $H_2O_2$. Qualified (nonimpact sensitive) materials are then applied to the male threads of a plug and a nipple, which are assembled into a coupling and tightened with a torque wrench (using a 1200 in. lb torque on stainless-steel assemblies and a 600 in. lb torque on aluminum assemblies). After drying at room temperature for 24 hours to set the sealing compound, the assemblies are tested for leakage by charging them with nitrogen and immersing them in water. A maximum of 1200-psig nitrogen pressure is applied to a stainless-steel assembly and 500-psig pressure is applied to an aluminum assembly. The pressure at which leakage, if any, occurs is noted. The torque required for disassembly should be noted. The sealing compound may also be tested by coating 1-1/2 by 1/2 by 1/16 inch, clean, passivated metal strips of 1060 aluminum and 316 stainless steel on one side. After drying at room temperature for 24 hours, the strips are subjected to the normal strip compatibility test described in Section 4.2.1.1

Protective coating materials are usually evaluated in accordance with standard compatibility procedures. The coating is applied according to the manufacturers' specifications to standard test strips and is tested as generally described in Section 4.2.1.1. (It is important to differentiate between compatitiblity of the coating material and the effectiveness or covering ability of the coating on the base metal.) The percent AOL is determined, and visual observations of any physical changes in the coating are noted. Other variations of this coating test involve filling a coated steel cup with $H_2O_2$, inverting a second coated cup on top of the cup containing the liquid, and maintaining two such sets at 86 and 150 F for 1 year and 1 week, respectively. A final laboratory test involves the half-filling of a coated 5-gallon container with $H_2O_2$ and allowing the test container to stand at room temperature in the laboratory or in a controlled temperature room. Containers with a 12-inch ID and 12 inches high with a 2-inch vented opening in the top are recommended for a 12-month test duration. Hydrogen peroxide concentration is determined initially and bimonthly thereafter for both the cup tests and the container test. Prior inspection of the coating for blisters or pinholes should be made before the tests are initiated.

A method for determining the compatibility of bladder materials has been suggested in Ref. 4.28. In this procedure, the bladder is immersed in concentrated $HNO_3$ for 10 days at the maximum potential application temperature (110 F, Ref. 4.28). At the conclusion of the immersion test, the bladder is removed and the $HNO_3$ is evaporated to dryness. The "residue" is treated with the test $H_2O_2$ at 140 F; acceptance of the bladder material depends on the resultant nonreaction between the "residues" and the test $H_2O_2$.

### 4.2.1.2 Hydrogen Peroxide Materials Compatibility Classifications.

The results of the various laboratory materials compatibility evaluations and of application experience have shown that materials can be classified into various categories based on their contemplated types of use in hydrogen peroxide service. All materials need not be suitable for indefinite storage because in applications requiring only short-time contact with $H_2O_2$, materials of a lesser degree of compatibility can be employed. To facilitate selection on this basis, materials have been generally classified according to the types of applications for which they are suited.

A system of four classes has generally been adopted (Ref. 4.25, 4.29, and 4.30) for materials for hydrogen peroxide service. These classes are arbitrary but they do provide a standard for rating materials compatibility with $H_2O_2$. These classes are:

Class 1: Materials Satisfactory for Unrestricted Use with $H_2O_2$. Such service includes long-time contact with the $H_2O_2$. Typical use is for storage containers.

Class 2: Materials Satisfactory for Repeated Short-Time Contact with $H_2O_2$. Such materials are used for transient contact with the $H_2O_2$ prior to storage of the $H_2O_2$, or limited contact with the $H_2O_2$ prior to use. Such contact is not to exceed 4 hours at 72 C (160 F) or 1 week at 22 C (70 F). Typical uses are for valves and pumps in $H_2O_2$ transfer lines and feed tanks.

Class 3: Materials Which Should be Used Only for Short-Time Contact with $H_2O_2$. These materials should be used only where neither a Class 1 nor Class 2 material would suffice. These materials can be used for repeated contact, but a single use period should not exceed 1 minute at

160 F or 1 hour at 70 F. An example of a Class 3 application is materials for use in a flow system. The hydrogen peroxide should be consumed in the application or disposed of after the test because contamination of hydrogen peroxide solutions with Class 3 material is usually sufficient to render it unsuitable for storage. Many Class 3 materials indicate satisfactory room temperature service; however, the material should be checked prior to use.

Class 4: Materials not Recommended for Use with $H_2O_2$. These materials (1) cause excessive decomposition of $H_2O_2$ even on short-time contact, (2) are attacked or deteriorate on contact, (3) yield corrosion or deterioration products which cause excessive decomposition of $H_2O_2$ on subsequent contact, or (4) form impact-sensitive mixtures with concentrated $H_2O_2$.

Other Classifications: Clothing materials are classified as "suitable" or "unsuitable". Within the classification of "suitable," choices are made on the basis of resistance of the material to deterioration in contact with the $H_2O_2$.

4.2.1.3 Test Evaluation Criteria. An explanation of typical (Ref. 4.25) criteria used to evaluate the materials compatibility tests described in Section 4.2.1.1 (as well as results from application experience), and to rate the results in the appropriate classifications per Section 4.2.1.2 is illustrated in Table 4.3. Because the illustrated classification system is general for all types of materials of construction that may be used in hydrogen peroxide storage and handling systems, and the classification limits were selected arbitrarily, more precise limits should be established for specific applications. The application of the criteria of Table 4.3 to results from compatibility tests are usually subjected to the following modifying considerations (Ref. 4.25):

1. If there is any doubt as to whether a material should be in a given category, e.g., Class 1 or 2, the material is placed in the lower category, e.g., No. 2.
2. If the results of practical experience are at variance with the results of laboratory tests, then the greater weight is given to the practical experience in selecting the classification.
3. The main distinction between Class 2 and 3 is the possible effect on the stability of the $H_2O_2$. If there is any doubt as to whether the stability might be affected, the material is placed in Class 3. Slight deterioration of the materials causing foreign matter to enter the $H_2O_2$ might cause decreased stability of the $H_2O_2$.
4. Numerical limits for the various classes are approximate. Class 1 materials would fall within rather narrow limits, while Class 2 materials have much broader limits. In general, the higher the active oxygen loss for a particular material, the less reproducible are the results.

The AOL reported during $H_2O_2$ materials compatibility tests has numerous meanings in the study of hydrogen peroxide solutions. This report uses the expression "Active Oxygen Loss" (AOL) or percent AOL as defined in the government procurement specifications for hydrogen peroxide; this definition may be simply explained by the following mathematical expression:

$$\text{Percent AOL} = 100\ (H_2O_2 \text{ weight loss during testing}) / \text{initial } H_2O_2 \text{ weight} \times 0.470$$

The weight loss is measured over a specific period of time at a controlled (and known) temperature. The generally accepted criteria for AOL vs compatibility rating are presented in Table 4.3.

Hydrogen peroxide stability, which is usually reported as percent stability, is the test used to determine the relative homogeneous decomposition reaction rate of hydrogen peroxide solutions. As applied in the materials compatibility tests, it is essentially a measure of the degree of contamination of the solution by the test material. This is determined by essentially measuring the AOL of the $H_2O_2$ during a 212 F exposure for 24 hours. The stability is then expressed as (100-AOL) percent.

Another rating criteria for $H_2O_2$ materials compatibility is that of impact sensitivity. Liquid and powdered materials, including solids which might yield finely divided particles in service such as a carbon bearing ring, must be evaluated for possible sensitivity to impact when in intimate contact with hydrogen peroxide solutions. This impact sensitivity is determined by subjecting varying proportions of the material and $H_2O_2$ to the impact of a weight dropped from a specified height. Illustrations of some impact sensitivity results are presented in Table 4.14; however, no weight-distance data were reported for many of the positive results. Because there are appreciable variations in impact results with various machines, operators, and facilities, these data are not quanitative, but simply indicate that under some conditions sensitive situations are possible with the noted materials. In some impact test procedures, a small amount of wetting agent is added to the $H_2O_2$ to simulate the intimate contact which might be created by mechanical load (such as might be found in pump packings or bearings). This practice, however, is not employed consistently. Any material which is impact sensitive when in contact with $H_2O_2$ in any proportion is considered a Class 4 material. The criteria of impact sensitivity of a material in contact with the $H_2O_2$ is the incidence of any positive detonation on the basis of a minimum of 10 trials. A mixture which gives negative results during the initial 10 valid tests is tentatively considered to be non-impact sensitive unless later tests produce a positive result.

During tests of protective coating materials, special care is necessary (and perhaps additional criteria are necessary) if the test is to determine the compatibility of the coating material and not its efficiency or covering power. Ideally, coating materials should first be tested alone or as coatings on known Class 1 base metals; after these tests are completed, the materials should be tested as coatings on the particular base metal contemplated for end use in the composite assembly. Criteria (Ref. 4.25, 4.29 used in expressing the results of coating tests will depend on the type of service contemplated; the coating must yield the class of compatibility required for the application and must continue to tightly adhere to the metal during the standard compatibility tests. Exact criteria for these coating tests have not been established; but it is believed that the coating should show no blisters or deterioration in contact with either the liquid phase or vapor phase for a period of 1 year at 86 F or 1 week at 150 F (or at the desired service temperature). Splash resistance coatings to be used as protection for surfaces in $H_2O_2$ installations should not react violently with the $H_2O_2$ and should not blister during a period of 24 hours at room temperature.

Clothing materials are normally classified (Ref. 4.25) according to recommendations for their use. Criteria for such classification are as follows:

<u>First Choice</u>: The material does not burn on immersion or during drip tests in the "as received" or "soiled"

condition; the material fibers are not appreciably weakened after immersion for 1 month in $H_2O_2$.

Second Choice: The material does not burn on immersion or during drop tests in the "as received" stage; however, the material may show some tendency toward burning in the "soiled" state and its fibers may be significantly weakened.

Not Suitable: The material either causes excessive decomposition of the $H_2O_2$, burns, dissolves, and/or disintegrates in either the "as received" or "soiled" state.

Selection of materials for use as joint sealing compounds with $H_2O_2$ is based primarily on the impact sensitivity of the compound with the appropriate concentration of hydrogen peroxide. The impact tests should show no positive results with a 3 kg-meter impact at room temperature. Decomposition of the $H_2O_2$ in contact with the compound is of secondary importance; however, the compound must not act as a strong $H_2O_2$ decomposition catalyst and the compound should not be a Class 4 material. These compounds should also show zero leakage during the tests described in Section 4.2.1.1.7.

### 4.2.2 Materials Compatibility

A large number of laboratory hydrogen peroxide materials compatibility tests and the experience provided by a number of years of $H_2O_2$ usage have resulted in a comprehensive knowledge of the effects of certain materials on hydrogen peroxide. These materials compatibility data are summarized in Tables 4.4 through 4.31a. Although the most extensive compilation of materials compatibility data was taken from Ref. 4.25, the most recent data are those of Ref. 4.10 through 4.18.

In general, the compatibility data reported in these tables are tests for usage with 90 w/o $H_2O_2$; but it has been found that materials suitable for $\geq$90 w/o $H_2O_2$ service are usually suitable for use with lower concentrations. In a few instances, materials that are unsuitable for $\geq$ 90 w/o $H_2O_2$ service have been found suitable for service at lower concentrations. However, it is uncertain as to whether materials suitable for 90 w/o $H_2O_2$ service will be suitable for use in higher concentrations. Therefore, some compatibility data have been generated (Ref. 4.9, 4.25, 4.29) on a selected number of materials with 98 w/o $H_2O_2$ and are presented in Tables 4.4, 4.5, 4.8, 4.19, and 4.31.

The results presented in these tables indicate that, in general, the materials suitable for 90 w/o $H_2O_2$ service are suitable for 98 w/o $H_2O_2$ service. Some plastics are attacked more severely by the more concentrated $H_2O_2$ solutions. With metals, 98 w/o $H_2O_2$ generally showed less active oxygen loss than did 90 w/o $H_2O_2$. This apparent greater stability of 98 w/o hydrogen peroxide in the presence of metals was found to result in increased storage stability in the pure aluminum shipping drums which are used for all hydrogen peroxide shipments. The data in Tables 4.4 through 4.18 are presented and classified according to the criteria of Section 4.2.1.2. Materials compatibility presented in Tables 14a, and 4.19 through 4.31a are results of studies conducted under special and specific conditions. These results are presented only in terms of measured values and no attempt has been made to classify the results to meet a specific set of standards.

The results presented herein are based on the conditions noted. Different conditions (i.e., temperatures, passivations, fabrication techniques, etc.) can result in significantly different results. The data should be used as a basis for materials selection; however, all systems after construction or fabrication should be tested for compatibility prior to actual use.

The materials compatibility data presented in Tables 4.4 through 4.31a are summarized with respect to various types of materials in Sections 4.2.2.1 through 4.2.2.10, and various controlling effects in Sections 4.2.2.11 through 4.2.2.14.

4.2.2.1 Aluminum and Aluminum Alloys. The results of a large number of compatibility tests of aluminum alloys with 90 and 98 w/o are summarized in Tables 4.4, 4.20, 4.21, and 4.31. These results indicate that several aluminum alloys meet the stringent requirements of Class 1 materials. Of these, aluminum alloys with low copper content such as 1060, 1160, 1260, 5254, and 5652 have shown excellent service. Minimum corrosion has been experienced with 1060 alloy, and this alloy is the one most frequently used in storage containers. The higher strength 5254 and 5652 aluminum alloys have shown excellent service in shipping drums, tank trucks, and tank car fabrication materials. The 5254 alloy, in various grades of temper, has been used successfully in several missile applications.

Aluminum 1060 has been used extensively for standard piping despite its low tensile strength and ultimate yield. Where pressures may be involved which are too great for standard pipe, the use of schedule 90 pipe of 1060 aluminum is recommended. Alternate choices of piping material are 5254 and 5652 aluminum.

Other aluminum alloys with low copper content, such as 6061 and 6063, have shown Class 2 compatibility. The high strength structural alloys such as 2014, 2017, and 2024 are unsuitable for service with $H_2O_2$ because of corrosion and a high rate of decomposition of the $H_2O_2$ in contact with them.

Aluminum casting alloys 43 and 356 have been employed successfully for pump and valve bodies for many years although some corrosion generally does occur. The low copper casting alloy

B-356 has indicated Class 1 compatibility during laboratory tests with $H_2O_2$, and satisfactory service experience has resulted with various $H_2O_2$ concentrations.

Some testing has been conducted on hard-coat aluminum. The laboratory results from tests of 10-, 20-, and 30-minute penetration on aluminum alloy 6061 indicated Class 3 compatibility with $H_2O_2$. Use experience is very limited, but it may be desirable to apply hard-coat aluminum in place of 300 series stainless steel in equipment that is fabricated predominantly of aluminum. Experience is needed to determine the resistance of hard-coat aluminum to corrosion in service with intermittent wetting.

Most cases of aluminum corrosion in $H_2O_2$ systems result in localized pitting (cell effect) because of the presence of foreign materials, and hydrated aluminum oxide formed during wetting and drying cycles. The presence of chloride ion in hydrogen peroxide results in aluminum pitting; however, if a 7:1 ratio of nitrate ion to chloride ion is present, almost complete elimination of corrosive action is obtained (Ref. 4.25). Therefore, the nitrate ion is added to $H_2O_2$ to counteract the possibility of chloride damage to aluminum.

4.2.2.2 **Stainless-Steel Alloys**. The compatibility of stainless-steel alloys with 90 and 98 w/o $H_2O_2$ is presented in Tables 4.5, 4.19, 4.22, 4.23, 4.24, 4.25, 4.31 and 4.31a. Although there are no Class 1 stainless steels, several Class 2 stainless-steel alloys are known. In general, the wrought or forged AISI 300 series stainless-steel alloys with proper passivation are suitable for Class 2 service with hydrogen peroxide. Cast stainless steel is generally unsatisfactory for $H_2O_2$ service unless special casting techniques are followed.

It has been reported that some formulas of the type 303 free machining alloy are not suitable for use with $H_2O_2$. Therefore, prior to use of this alloy, it is suggested that a sample of the lot to be used be evaluated for compatibility with the pertinent $H_2O_2$ grade.

Cryogenically prestrained 301 stainless steel offers high yield (260,000 psi) strength and a 280,000 tensile strength. The test data in Table 4.5 reveal that this treatment results in a material that has a borderline Class 1/Class 2 compatibility with 90 or 98 w/o $H_2O_2$.

Experience with use of the wrought 300 series stainless steel for seamless tubing, seamless pipe, fabricated equipment for piping systems, and welded tanks has been satisfactory. The use of 300 series stainless steel is recommended for high-pressure flow systems and applications where the presence of aluminum oxide, which is difficult to avoid in $H_2O_2$ handled in aluminum, cannot be tolerated.

Usually hydrogen peroxide test tanks have been fabricated of 347 stainless steel which contains niobium (columbium) as a welding stabilizer. More than 15 years of satisfactory service have been achieved at FMC with these tanks in the handling of 90 and 98 w/o $H_2O_2$. Although 321 stainless steel has been used in some systems, the titanium welding stabilizers have a slight catalytic effect upon the $H_2O_2$. The extra-low carbon 304 stainless steel has been shown to be an excellent $H_2O_2$ tank material. This material demonstrates good compatibility with $H_2O_2$ at room and elevated temperatures.

An extensive amount of testing has been conducted on precipitation-hardening stainless-steel alloys such as AM-350 and 17-7 PH alloys. The AM-350 material has given excellent service in flight vehicles; however, the material hardness must be less than 42 Rc (Rockwell Hardness Scale C), or there is an increase in $H_2O_2$ decomposition and development of metal rusting. The [illegible] 7 PH material has proved very successful with 70 w/o $H_2O_2$ and moderately successful with 90 w/o $H_2O_2$; however, a special passivation treatment (Ref. 4.31) is required to achieve a Class 2 rating for this material. Surface finishing of the sample with 120-grit abrasive compound was found to be effective in improving the compatibility of this alloy.

The AISI 400 series stainless steels, whether annealed or in the heat-treated form, 40 to 58 Rc, will rust if the surface finish is greater than 10 rms. This type of corrosion phenomenon indicates that it is necessary to examine samples from compatibility tests after the actual test has been completed. It is suggested that this examination should be made at 24-hour and 1-week intervals of exposure to air after the sample is dried. It has been found that immersion of a sample in distilled water for 24 hours following the compatibility test will tend to induce this type of stainless-steel corrosion.

In general, stainless steels suitable for $H_2O_2$ service, i.e., AISI 300 series and precipitation-hardening alloys, are nonmagnetic or only weakly magnetic. Therefore, any metals that are magnetic should be suspected of incompatibility with $H_2O_2$. For example, iron, mild steel, and AISI 400 series stainless steels are magnetic and are not suitable for $H_2O_2$ service. Any unknown material that is magnetic is of questionable compatibility with $H_2O_2$ until completely tested.

It has been determined experimentally that, in general, the smoother the material finish of $H_2O_2$ system components, the better the compatibility. Finishes should not exceed 32 rms, and should be smoother if possible. This is especially important in stainless-steel storage and handling systems; a rough spot in a tank, for example, will cause $H_2O_2$ decomposition. This condition can be avoided with proper design and system fabrication. In addition, it has been noted (Ref. 4.32) that stainless-steel alloys require cleaning and repassivation after extended service in $H_2O_2$ to limit the gradual buildup of decomposition activity.

4.2.2.3 Pure Metals and Other Metal Alloys. The compatibility of pure metals and various other metal alloys with 90 w/o hydrogen peroxide is presented in Tables 4.6 and 4.7, respectively. Many metals other than the aluminum and stainless-steel alloys have been evaluated, but few have been found suitable for $H_2O_2$ service. Silicon, tantalum, tin, and zirconium are exceptions. Of these, tin has been utilized to the greatest extent, i.e., for gaskets and as a solder for stainless steel.

Most other metallic elements exhibit catalytic action in contact with $H_2O_2$. This is especially true of silver, lead, cobalt, and platinum. Iron oxide causes rapid catalytic decomposition of $H_2O_2$. Titanium and zinc are severely attacked by the $H_2O_2$.

A few alloys have shown suitability for Class 3 service and might, with other passivation techniques, be made suitable for Class 2 service; however, additional research would be required in this area. Unfortunately, none of the extreme hardness metals tested have shown suitability for even Class 3 service, except the 10 rms finish 440C stainless steel (56 to 58 Rc) and hard-bearing chrome plating (58 to 70 Rc).

4.2.2.4 Plastics and Rubber Compounds. An excellent summary of the results of compatibility tests with various plastic and rubber compounds, presented in Tables 4.8 through 4.12 and 4.26 through 4.30, was presented in Ref. 4.25. Because plastics and rubber compounds are organic in nature, the compatibility with hydrogen peroxide varies considerably. Even those materials which have shown excellent compatibility with 90 w/o $H_2O_2$, both in the laboratory and in use, may be suspect when new conditions are met which have not been encountered or simulated previously. Conditions which may lead to reaction between a plastic material and $H_2O_2$ are extremely varied and difficult to predict or to evaluate in the laboratory. However, the following one generalization must always be considered: the combination of high-strength hydrogen peroxide, organic materials, and heat from either an external source or from $H_2O_2$ decomposition may lead to an explosive reaction.

The compatibility of plastics often is not determined by the chemical nature or composition of the polymer itself but is determined by the impurities present in it. Contamination of molding materials during handling and storage with dirt, dust, and other organic materials as well as inclusion of metal chips or granules can cause noticeable decomposition reactions. A surface speck of foreign material originating in the mold may initiate a reaction with hydrogen peroxide with sufficient heat release to initiate reactions with the polymer. Laminated plastics or compression molded materials which contain minute pores or air pockets may be incompatible because of the accumulation of organic material in these voids. This is usually the result of some cleaning or rinsing process involving organic materials.

For these reasons, there may be differences in the compatibility of plastics from different manufacturers and even lot-to-lot variations in a given polymer material from the same manufacturer. Lot-to-lot variations are usually much less noticeable than differences caused by various processing and handling techniques. Compatibility of plastic and other polymeric or composite materials are therefore usually associated with a manufacturer's name.

Clean polyethylene has been safely utilized during laboratory work, and polyethylene has proved to be a satisfactory material for use with 27.5 through 50 w/o $H_2O_2$. However, polyethylene at its melting temperature has ignited on contact with concentrated hydrogen peroxide and is therefore not recommended for concentrations in excess of 70 w/o $H_2O_2$. Although no information has been obtained, this possibility should also be considered in the use of other combustible polymers for service at temperatures approaching their melting point or thermal decomposition temperature.

High-temperature service materials such as Kel-F and Teflon have not demonstrated any indication of reaction with hydrogen peroxide over the entire concentration range at ambient temperature conditions. These materials were also found to be compatible with 90 w/o $H_2O_2$ up to 270 F. There is no known reason to avoid using those materials in any $H_2O_2$ service where the $H_2O_2$ will remain below its normal atmospheric boiling point. However, mixtures of these materials with other materials must always be evaluated because reactions are varied and the compatibility of any added ingredient must always be considered. Glass-filled Teflon is acceptable, carbon-filled Teflon may be acceptable, and asbestos-filled-Teflon is not acceptable. Kel-F, Aclar, and "virgin" Teflon are the most compatible plastic materials at high operating temperatures and should be utilized wherever the physical properties are suitable. It is especially recommended that these materials, which have exceptionally low coefficients of friction, be applied in $H_2O_2$ service as dynamic bearings and seals without lubricants wherever possible because of the limitations of the available lubricants. Special high-pressure, 2-hour compatibility tests at 132 C (270 F) and 1000 psig with 90 w/o $H_2O_2$ demonstrated that Teflon and Kel-F are not adversely affected. The AOL for these 2-hour periods is comparable to the percent AOL experienced at 66 C (151 F) in 7 days. Filled plastics such as Kel-F elastomers, 9711 Silicone, and Vitons show swelling at the high test temperatures.

Kel-F elastomeric compounds are generally inferior to Kel-F itself in compatibility with $H_2O_2$, and most of these materials tested have met the Class 2 criteria.

Aclar, Mylar, and Dacron plastics have demonstrated excellent compatibility with $H_2O_2$ in the laboratory. Dacron has been used fairly extensively as cloth for protective clothing and reinforcement of other plastics which contact $H_2O_2$. Mylar film has been used very little because it does not heat seal, and a compatible adhesive has not been found. Aclar is heat sealable and is being used in some applications. Use of these materials, particularly Aclar 33C film, as bag liners for storage containers is currently under study (Ref. 4.9).

There are many plastic materials that break down upon extended exposure (> 7 days) to 90 and 98 w/o $H_2O_2$ at elevated temperatures (151 to 165 F) but exhibit no effect upon 24-hour exposure. The majority of Viton A, Viton B, Fluorel 2141, and Fluorel 4121 compounds show this effect. However, most service applications are at ambient temperature conditions 10 to 50 C (50 to 120 F) and these same plastics and rubbers demonstrate excellent service at these temperatures.

Viton A and Fluorel materials demonstrate Class 1 ratings in 10 to 49 C (50 to 120 F) service. Viton A 271-7, produced by Parker Hannefin Corporation, has demonstrated excellent service as O-rings in 90 and 98 w/o $H_2O_2$ solenoid valves and for component seals. Seals Eastern Corporation's Fluorel 2141 and Fluorel 4121 O-rings, seals, and bladders have proved satisfactory in the moderate temperature range. David Clark Company's Omni (Viton A) has proved useful as O-rings and when used to impregnate glass or Teflon cloth, produces a material which is satisfactory for use as an $H_2O_2$ splash cloth or curtain (Table 4.8).

Polyvinylchloride-based materials vary in their reaction with $H_2O_2$ because of the plasticizer content and because other additives such as fillers and pigments are used. It is generally true that such additives reduce the compatibility of the compound with $H_2O_2$. Koroseal 700 (molded) has been extensively used as a gasketing material in low-pressure service. The formula for this material was developed specifically for $H_2O_2$ service. Koroseal 116 and 117 (molded) are both inferior to Koroseal 700 (molded) for $H_2O_2$ service. Calendered Koroseal is unsuitable because the $H_2O_2$ penetrates into the sheet and develops gas pockets which separate the layers of material. Calendered materials which do not exhibit this condition can only be fabricated of materials which are absolutely impermeable to $H_2O_2$.

Polyvinylchloride plastics are generally permeated by 90 w/o $H_2O_2$. This has been determined for both molded and plastisol types of polyvinylchloride. The absorption of $H_2O_2$ is indicated by the fact that the materials which are generally clear or translucent turn an opaque white after a period of contact with the $H_2O_2$. The polyvinylchloride material containing absorbed $H_2O_2$ may be shock sensitive although no adverse experience of this nature has ever been encountered. Polyvinylchloride plastics will also leach chloride ion into the $H_2O_2$ which will cause corrosion of aluminum even when present in minute quantities.

Silicone rubber elastomers also vary considerably in compatibility with hydrogen peroxide because of the use of pigments and fillers in some compounds. However, there are a number of these compounds, mostly unpigmented, which indicated Class 2 compatibility with $H_2O_2$. Of these, Silastic 9711 has demonstrated the most satisfactory compatibility with 90 w/o $H_2O_2$. Silastic 9711 is used in various applications as an O-ring, gasket, hose, and bladder material. Although silicone rubbers are not subject to heat sealing, welding techniques have been developed and Silastic 9711 welded with Silastic 2200 indicated satisfactory compatibility with $H_2O_2$.

The compatibility of several possible bladder materials is reported in Tables 4.26 through 4.28. Compatibility tests of 90 w/o $H_2O_2$ at 110 F for 10 days with Silastic 9711 (surgical grade), Fluorel 2141, and Aclar 22C (Ref. 4.17) revealed Aclar to be the most compatible material. A similar study involved the use of Vicone 185, alone and as part of a composite structure with aluminum in addition to the preceding materials. Vicone 185 was not quite as satisfactory as Aclar in the pure state. In the composite structures, Vicone 185 with aluminum exhibited the highest decomposition rate while Fluorel with aluminum exhibited the most stable combination. Following compatibility tests conducted at 160 F, both Silastic and Fluorel were badly blistered (Ref. 4.12 and 4.15 through 4.17). These results are in slight conflict with Ref. 4.25 which reported the most compatible bladder material readily available for 90 w/o $H_2O_2$ is North

American Aviation's Vicone 185 (Table 4.26). Other satisfactory bladders are the B. F. Goodrich Company's 9711 high purity silicone material, and duPont's thin film FEP Teflon (heat sealed). There are other materials that show promise as bladder materials, such as Viton A and B.

Some adhesive agents for bonding silicone rubber Silastic 9711 to aluminum 6061 were evaluated in the form of finished washers. Chemloc 607 appeared to be most suitable and DCA 4094 is only slightly inferior to it. With the adhesive present, compatibility results were reported to be poorer than would be expected for the silicone rubber and aluminum alone; however, a control test was not run for comparison.

Silicone rubbers that indicate Class 2 results for $H_2O_2$ service are considered to be superior to polyvinylchloride materials because the possibility of chloride leaching is eliminated and, in general, the flexibility of silicone rubbers varies much less over a wide temperature range. Permeability studies of silicone rubber to $H_2O_2$ indicate slow seepage and layer separation because of oxygen evolution in the pores. Because of the permeability of silicone rubber to hydrogen peroxide, prolonged contact even at atmospheric pressure may make the silicone rubber susceptible to rapid oxidation should a flame be encountered.

Most of the plastic materials discussed can be utilized as gaskets in the proper type of flanges. However, there are two reinforced Teflon gasketing materials which have exhibited satisfactory compatibility, and should find application. Korda-flex, a Teflon-coated glass fabric, has indicated Class 1 results and Duroid 5600 yielded Class 2 results. Actual use experience has not yet been gained with either of these materials.

Several tests have been made of built-up diaphragms, usually a plastic and cloth sandwich type construction using Dacron or glass fabric. The compatibility of these diaphragms with 90 w/o $H_2O_2$ has been satisfactory when using Omni (Viton A) impregnated glass, Teflon, or Dacron cloth. Polyethylene and Kel-F sheet diaphragms have been utilized successfully in pressure transducers with water on the pressure gage side. Stainless-steel diaphragms have also been utilized satisfactorily. In designing equipment for $H_2O_2$ service, it is best to avoid diaphragms if possible. If a diaphragm must be used, there should be adequate testing of diaphragm materials with $H_2O_2$ before the materials for its construction are chosen.

4.2.2.5 Porous Materials. The results of compatibility tests of 90 w/o hydrogen peroxide with porous materials, presented in Table 4.13, are summarized in Ref. 4.25. In this summary, it was indicated that porous materials are generally of interest for use in the filtration of hydrogen peroxide to collect any solid foreign material which accidentally enters into the $H_2O_2$. Whereas a minor amount of catalytic dirt might be tolerated in a large tank of $H_2O_2$, collection of this dirt on a filter in a relatively small quantity of $H_2O_2$ could cause considerable decomposition. Therefore, care must be exercised to keep the use of filters to a minimum and to select filtering media that will not readily react with decomposing $H_2O_2$. Therefore, for concentrations of $H_2O_2$ above 50 w/o, low melting materials such as Dacron are not recommended for filter elements (Ref. 4.25).

Some porous porcelain bacteriological filters have exhibited good serive in $H_2O_2$ power system refueling operations. Tests indicate that porous Teflon and Kel-F may be suitable for use as filter media.

Stainless-steel filters fabricated of wire, either wrapped or woven, yield Class 2 or 3 results. When using these materials for filter elements, welding should be kept to a minimum. Filters made of 316 stainless steel have been used successfully in various $H_2O_2$ operations, such as fueling operations involving flight vehicles. Porous stainless-steel elements formed by sintering powdered metal have not proved satisfactory for $H_2O_2$ service.

Filtros C has been used extensively for filtering all concentrations of $H_2O_2$ and for filters on storage and shipping tank vents, but it is fragile and difficult to back-wash. Replacement of this material for both uses is being investigated. It is not recommended for power-system use.

When using filters for $H_2O_2$ service, it is important to keep them clean and to examine them frequently. When dirt on a filter is allowed to dry, oxidation may occur which may cause increased catalytic action. Therefore, it is a good policy to flush a filter before use, and to back-wash an $H_2O_2$ filter immediately after use with distilled or clean water.

4.2.2.6 <u>Lubricants</u>. The compatibility of various lubricants (Ref. 4.25 and 4.33) with 90 w/o $H_2O_2$ is presented in Tables 4.14 and 4.14a. The test results indicate that only the fluorinated hydrocarbons are sufficiently compatible with 90 w/o $H_2O_2$ to be considered. Even these materials can probably react with the 90 w/o $H_2O_2$ if there is sufficient force or heat applied to the mixture. However, the use of fluorinated hydrocarbons has been satisfactory in transfer pump packing glands in use with 300 series stainless-steel shafts.

The present fluorinated hydrocarbons do not possess good lubricating qualities, and their viscosities vary widely with temperature. Some lubricity additives were evaluated several years ago, but none was completely satisfactory because of the difficulty of attaining stable emulsions. In addition, use of fluorinated hydrocarbons as lubricants for aluminum threads or in conjunction with aluminum with a high surface area in applications where heat may be created (which is a natural condition in all applications requiring lubricants) may lead to detonating reactions without any $H_2O_2$ present. Two instances of such an occurrence, one during a thread cutting on aluminum pipe using Fluorolube as a cutting lubricant and the other when fluorinated hydrocarbon was used as a thread compound on the aluminum head bolts of a decomposition chamber, have been reported. This reaction was reproduced in the laboratory by dropping a fluorinated hydrocarbon on heated aluminum in powder form.

There also is some indication that presence of a fluorinated hydrocarbon in intimate contact with an organic material and 90 w/o $H_2O_2$ may cause increased sensitivity. Although this phenomenon has not been adequately evaluated, it appears that the use of fluorinated hydrocarbons in conjunction with organic materials in concentrated $H_2O_2$ service should be avoided unless the specific system to be used has been adequately tested. The best practice if possible, is to eliminate the need for lubricants.

In evaluating lubricants for $H_2O_2$ service, the results of the impact test are of greatest significance. However, there is no standard impact tester, and the reproducibility of most testers is marginal. The modified Bureau of Mines Impact Tester used for the results reported in Table 4.14 is simple to use and has been proved to be generally reliable; but it is subject to variations in results with different operators, and the condition of the anvil plunger or weight is another variable. Despite the practice of regular calibration of the tester with a "known" mixture of ethyl alcohol and 90 w/o $H_2O_2$ in equal-volume proportions, poor reproducibility has been experienced. Because of this situation, it is thought that any positive detonation should be sufficient to place a lubricant in Class 4 for $H_2O_2$ service. Thus, even though a lubricant or grease may pass all tests with negative results and then give a positive result during a later check test, it will be classed as unsuitable for $H_2O_2$ service.

Pump packing lubrication is one problem which can be overcome by the use of mechanical seals which require no lubrication. Seals fabricated of 300 series stainless steel with ceramic and glass-filled Teflon mating surfaces and cooled with the liquid $H_2O_2$ being pumped have been successfully applied to centrifugal transfer pumps for several years.

4.2.2.7 Ceramic and Refractory Materials. A summation of the results of compatibility tests of 90 w/o hydrogen peroxide with ceramic and refractory materials, which are presented in Table 4.16, has been taken from Ref. 4.25. Testing of materials in this category has been limited because applications are often limited by fragileness where shock impact may be experienced. Most of these materials have been considered for applications where hardness is important or as filter elements contained in a stainless-steel housing. Coors Ceramic AB-2 has been utilized successfully in conjunction with glass-filled Teflon for mechanical seals on $H_2O_2$ transfer pumps, which use $H_2O_2$ as a coolant for the seal. Coors Ceramic AB-2 and AI-200 have been utilized for plunger pump parts, but no experience has been obtained with $H_2O_2$.

Selas porous porcelain microbiological filters have shown satisfactory service with 90 w/o and 98 w/o $H_2O_2$ and may be used to filter high-strength $H_2O_2$.

Aluminum oxide coating materials were evaluated and found to be unsatisfactory. The poor results may be due to the method of coating, added agents, or the roughness of the coating.

Laboratory glassware is used extensively for carrying out compatibility and stability tests as well as general laboratory handling. Pyrex glass is superior to soft glass and is used extensively as piping in the $H_2O_2$ manufacturing facilities. Glass linings have been evaluated to a limited extent; the more common glass used for lining contains cobalt, which demonstrates poor compatibility with $H_2O_2$. Some glass formulas do, however, show excellent compatibility with $H_2O_2$, but there is no use experience available with these linings.

Synthetic sapphire has not been applied extensively despite its excellent compatibility with $H_2O_2$. Rotameter floats are probably the only present application.

4.2.2.8 Protective Coating Materials. The compatibility of protective coatings (Ref. 2.25 and 4.29) with 90 w/o $H_2O_2$ is presented in Table 4.17. Protective coatings are not recommended for $H_2O_2$ storage tank service, but may be of value for special purpose tanks and to protect incompatible materials from $H_2O_2$ splash. Of the protective coatings evaluated for service with 90 w/o $H_2O_2$, only Teflon, Kel-F, and hot air-sprayed polyethylene have indicated suitability for more than splash contact at temperatures to 71 C (160 F) for Teflon and Kel-F, and temperatures of 49 C (120 F) for polyehtylene; however, there has been no experience with such coatings in actual service. The application of such coatings or paints is recommended for surfaces of materials subject to corrosion. Prevention of rust in $H_2O_2$ handling and storage areas is a safety measure because the possibility of contaminating the $H_2O_2$ is reduced.

Kanegin-coated (electroless nickel) mild steel has shown good compatibility with 90 w/o $H_2O_2$. Tin-plating, followed by a heat treatment at 215 C (420 F) to seal the pores, has proved to be an effective coating for $H_2O_2$ service.

It is believed that protective liners may be used to advantage in $H_2O_2$ service for prevention of corrosion of aluminum surfaces and for special cases of high-pressure feed tanks to allow fabrication from metals which possess high strength-to-weight ratios but are not sufficiently compatible with the $H_2O_2$ to allow a practical holding time.

In general, platings, such as tinplate, strip off when exposed to 90 w/o $H_2O_2$ unless special precautions are taken to prevent this. Apparently, the $H_2O_2$ seeps through pinholes in the plate or under the edge and then decomposes when it contacts the undersurface, liberating oxygen gas. The gas then forms a blister which eventually breaks and allows more $H_2O_2$ to contact the undersurface.

4.2.2.9 Protective Clothing Materials. The results of compatibility tests of protective clothing materials with 90 w/o hydrogen peroxide, summarized in Tables 4.18 and 418a, are discussed in Ref. 4.25. The study of materials for protective clothing was directed primarily at finding materials which would not ignite if 90 w/o $H_2O_2$ was spilled on them when they were soiled with catalytic dirt. The chief hazard encountered when concentrated hydrogen peroxide is accidentally splashed on a worker is the possibility that the worker's clothing will ignite. The materials were also evaluated for resistance to deterioration by the action of concentrated hydrogen peroxide.

As a result of this study, it was found that in both the clean and soiled condition,"virgin"Dacron in all forms, Saran-monofilament, and 55 percent Dacron-45 percent wool cloth resisted ignition. Dynel and Saran stable fiber resisted ignition in the clean condition and ignited only with difficulty when soiled. Dacron was unaffected by 90 w/o $H_2O_2$, and Dacron-wool and Dynel were only slight detiorated. It must be noted that some treated and dyed Dacrons in the "soiled" condition will ignite with 90 w/o $H_2O_2$, and all samples must be tested before use.

Based on this study, sources were developed for permeable and impermeable clothing; a recommended protective clothing and necessary accessories list for $H_2O_2$ handling is presented in Section 6.4. This list includes safety clothing and equipment such as goggles, gloves, aprons, and shoe coverings which are made from plastics or rubbers acceptable for the purpose. Dacron and Dynel work clothing have been utilized to a considerable extent with satisfactory service.

It must be pointed out that even protective clothing MUST BE KEPT CLEAN and particularly free of ordinary greases and catalysts such as potassium permanganate. Grease-soiled samples of Dacron, Dynel, and 55 percent Dacron-45 percent wool fabrics have been found to ignite and burn vigorously when wetted with 90 w/o $H_2O_2$. When laundering or cleaning Dynel fabrics, special techniques must be employed because of Dynel's low softening and embrittling points. Dacron may be laundered without special precautions. Thus, Dacron is preferred for this reason in addition to its better resistance to the $H_2O_2$.

4.2.2.10 Joint Sealing Compounds. The results of physical and chemical tests of joint sealing compounds with 90 w/o hydrogen peroxide are summarized in Ref. 4.25 and Table 4.15. Most commerical pipe joint sealing compounds were found to be unsuitable for high-strength hydrogen peroxide service. In systems for concentrations of less than 52 w/o $H_2O_2$, Aviation Grade Permatex No. 3 and equivalent have been used satisfactorily. There are two thread compounds that have shown good service in 52 through 98 w/o $H_2O_2$ systems. These are T Film, a Teflon water-dispersion paste for small pipe threads and Teflon tape for 1/4- through 4-inch-size pipe thread. Fluorinated hydrocarbon-based materials react violently with hot powdered aluminum. Therefore, these compounds must not be used on hot aluminum threads and must never be used as a thread cutting lubricant.

Applications of even the approved joint sealing compounds to threads for an $H_2O_2$ flow system must be made so that no compound will enter the system. The compound should be used sparingly, only on the male part and not on the first two threads. Thus, the surplus amount will press out of the threads, not into the system. Pipe threads should be avoided in $H_2O_2$ systems; flanges and 37-degree flare connections are recommended.

4.2.2.11 Temperature Effects. The effect of high temperatures, in the 212 to 270 F region, on materials compatibility with 98 w/o $H_2O_2$ is shown in Table 4.19. This effect is of particular interest in selection of materials for use in $H_2O_2$ regeneratively cooled thrust chambers (Ref. 4.29).

The effect of high-temperature storage conditions (151 F) on materials compatibilities with $H_2O_2$ is shown in Tables 4.21, 4.22, and 4.24 through 4.30. The appropriate references to this work are given in each of the corresponding tables.

4.2.2.12 **Evaluation of Passivation or Surface Preparation Techniques.** Laboratory tests (Ref. 4.13) have been conducted to: (1) determine the effectiveness of selected passivation methods upon 321 stainless steel, 6061-T6 aluminum (bare and anodized), and Silastic 9711, (2) determine the influence of cyclic exposure of passivated surfaces to hydrogen peroxide; and (3) investigate the effects of various storage conditions upon passivity of materials used in hydrogen peroxide service. The passivation methods employed in these studies are given in the following references:

CVA-10-62a (Ref. 4.34)
NAA LA 0110-003 (Ref. 4.35)
Walter Kidde 520007 (Ref. 4.36)
FMC Bulletin 104 (Ref. 4.25)
McDonnell A/C 13002 (Ref. 4.37)
LTV 308 - 20-3 (Ref. 4.38)
CVA 10-64a (Ref. 4.39)

The results of these tests are given in Tables 4.21, 4.24, and 4.27.

The preferred passivation method for 321 stainless steel was found to be CVA 10-62a with posttreatment with 35 w/o commercial hydrogen peroxide. For 6061-T6 aluminum (bare and anodized), the best passivation technique was according to North American Aviation Specification LA-0110-003. All passivation methods investigated were found to give about the same results with Silastic 9711. The ease in passivation of all materials was found to improve with each exposure to concentrated hydrogen peroxide. Environmental exposure tests revealed that 321 stainless steel can be stored best in clean air with relative humidities up to 100 percent; anodized 6061-T6 aluminum remains more passive in a dry nitrogen atmosphere. Silastic 9711 appears to retain its passivation best in a relative humidity of 100 percent.

The loss of oxygen in 90 w/o $H_2O_2$ solutions in contact with 316L and 321 annealed stainless-steel tubing for 3, 5, 7, and 10 days at a constant temperature of 110 F was determined as a function of two different passivation techniques. One-half of the tubing specimens was passivated by CVA Specification 10-62a with a posttreatment of 35 w/o hydrogen peroxide inhibited with a 0.03-percent $H_3PO_4$ solution; the other half was passivated by Walter Kidde Co. Specification No. 520007. The stability of the $H_2O_2$ solution was also determined after each test. In general, 321 stainless steel produced less hydrogen peroxide decomposition than the 316L material. The best passivation method, as indicated by the AOL results for both the 316L and the 321 stainless, was found to be CVA Specification 10-62a plus posttreatment (Ref. 4.18). These data are summarized in Tables 4.23 and 4.24.

In another study (Ref. 4.9), the effect of surface treatment on the compatibility of various materials was determined and expressed in heterogeneous reaction rates ($k_2$), as shown in Tables 4.31 and 4.31a.

4.2.2.13 Effect of Surface Finish. The effect of surface finish on materials compatibility with $H_2O_2$, summarized in Ref. 4.14, is shown in Tables 4.21 through 4.25. Five different surface finishes applied to 304 stainless steel and aluminum alloy 6061-T6 (both bare and anodized) were evaluated in contact with 90 w/o hydrogen peroxide to determine the influence of surface finish on the stability of the peroxide. The stainless-steel specimens were passivated according to CVA Specification 10-62a with posttreatment in 35 w/o inhibited (0.03 percent $H_3PO_4$) hydrogen peroxide. The aluminum specimens were passivated according to North American Specification LA 0110-003. Although inconsistent correlations were obtained between the surface finish and AOL with the 304 stainless steel and the bare 6061-T6 aluminum specimens, the active oxygen loss resulting from the anodized aluminum in contact with the hydrogen peroxide indicated an increase in AOL values with surface roughness. (Surface roughness may simply be considered as a surface area factor; the rougher the surface the higher the actual surface area compared to the apparent surface obtained through measurements of the linear dimensions of the sample.)

This investigation has strongly indicated (Ref. 4.14) that the Industry Standard AOL test is not an adequate tool for highly selective screening of materials for hydrogen peroxide service. The AOL test is considered insufficiently sensitive to the detection (with any degree of accuracy) of the catalytic decomposition influence exhibited by small variations in surface roughness or materials in contact with concentrated hydrogen peroxide.

4.2.2.14 <u>Effects of Dissimilar Metals.</u> The results of an experimental investigation of dissimilar metal couples compatibility in $H_2O_2$ (Ref. 4.11) are shown in Table 4.30. In this study, the decomposition rate of 90 w/o hydrogen peroxide was measured with the following couples: 1060 Al + 6061-T6 Al; 6061-T6 Al + 321 stainless steel; 6061-T6 Al + 316L stainless steel; 321 stainless steel + 316L stainless steel. The AOL and $H_2O_2$ stability was determined during an exposure of 10 days at 110 F and 7 days at 151 F. The tests at 110 F revealed no significant influence of the dissimilar metal upon the hydrogen peroxide; however, the 151 F test revealed that the catalytic decomposition of the hydrogen peroxide was greater for the dissimilar metal couples than for either of the single-metal alloys.

## 4.3 MATERIALS TREATMENT AND PASSIVATION

### 4.3.1 General

All material surfaces that come in contact with propellant-grade hydrogen peroxide must be specially cleaned and treated prior to their use to minimize hydrogen peroxide decomposition and material corrosion. The general terminology applied to this process, which is designed to provide an inactive surface and eliminate potential contamination sites, is passivation. This section provides a detailed outline of the passivation procedures normally used for materials in hydrogen peroxide service.

The passivation procedure essentially consists of three primary steps prior to the material contact with propellant-grade hydrogen peroxide. The initial step is a chemical and physical cleaning procedure designed to remove oxides, scale, dirt, weld (and heat treat) slag, oil, grease, and other foreign material from the base material. The second step is usually the treatment ("basic passivation") of the material with an alkaline or acid solution to form a film (probably a complex oxide) on the surface to minimize chemical or catalytic activity between the surface and propellant. Finally, the material is subjected to propellant conditioning to check the completeness of the chemical treatment and to eliminate, through further oxidation and chemical complexing, all remaining active sites. Normally, propellant conditioning is conducted in 35 w/o $H_2O_2$, although many organizations prefer additional propellant conditioning of materials at the conditions ($H_2O_2$ concentration and temperature) that will be experienced in final application of the material.

The material surfaces should be subjected to passivation after part fabrication and before component or system assembly.

Basically, items such as valves, pumps, actuators, system piping, etc., cannot be cleaned properly in the assembled state, because the solvent, cleaning solution, residual contamination, etc., may be trapped in inaccessible areas. The cleaning should be conducted immediately before component or system assembly, unless provisions are made for packaging the passivated part to protect against re-contamination until ready for assembly. After assembly, components, such as valves, should be packaged until they are utilized in the final system assembly. It is also standard procedure to check all passivated items with propulsion-grade hydrogen peroxide prior to assembly in the system.

All cleaning, passivating, and rinse solutions should be applied by immersing, spraying, wiping, circulating, or other manner so that all surfaces to be cleaned will be completely wetted and flushed with the solutions. Any section of the item to be cleaned that can trap or retain any liquid should be drained or emptied between the applications of each different solution or chemical mixture. The item should be rinsed until it is chemically neutral between each operation. Surfaces should not be allowed to dry off between the cleaning and the "basic passivation" steps. The water grade used, depending upon the passivation stage, should be distilled, deionized, or potable tap water (which has been filtered through a 40-micron nominal filter). Unless otherwise specified, all chemicals should be C.P. (chemically pure) grade or better.

### 4.3.2 Passivation Facilities

The passivation of materials for hydrogen peroxide service should be conducted in an area designed only for that purpose. The area must be kept clean and free of combustible material. Equipment to be used in the passivation procedures should be large enough to accommodate all items to be placed in the intended system and provide a method of complete wetting (with all solutions) of the surfaces requiring passivation.

Procedures for handling hydrogen peroxide and the various passivation solutions should be well established and observed. Some of the more important requirements are discussed in the following paragraphs.

4.3.2.1 Personnel Education. All personnel operating in the area should be well informed of all operating procedures, potential hazards, safety precautions, procedures, etc. (see Section 6.0).

4.3.2.2 Area Cleanliness. The area must be protected from dust and dirt to prevent contamination of the cleaned parts. Although a clean room atmosphere is not essential, it is recommended, particularly, for passivation of flight hardware.

4.3.2.3 Drainage. An adequate water supply and drain must be available for flushing away spilled acid and hydrogen peroxide. All spillage or dump of chemicals must be heavily diluted before passage into a drainage system; protected open trough drainage is recommended.

4.3.2.4 Safety Showers. An adequate number of deluge safety showers must be provided for area personnel. The locations of these showers should be such that they can be reached within a few steps from any location.

4.3.2.5 Eye Wash Fountains. An adequate number of eye wash fountains should be provided in easily accessible locations.

4.3.2.6 Ventilation. Adequate ventilation must be provided to maintain a minimum concentration of solvent and acid fumes. Hoods with suction fans should be installed and used wherever possible.

4.3.2.7 Warning Signs. Safety and warning signs should be placed where they can be seen and should be appropriate to the hazards created by the cleaning, passivating, and hydrogen peroxide solutions.

4.3.2.8 Personnel Protection. Personnel, when handling the various passivating solutions, should be dressed in suitable protective clothing. The minimum garb should consist of a face shield or goggles, rubber (acid-resistant) gloves, rubbers, and an apron. (For additional information, see Section 6.0).

4.3.2.9 Minor Equipment. Various-sized polyethylene beakers should be provided for the treatment of small parts. These beakers are resistant to all reagents normally recommended and used in the passivation procedures. Although glass beakers can be substituted for the polyethylene beakers in the use of all but hydrofluoric-nitric acid solution, their easy breakage can result in a greater hazard. The polyethylene beakers should not be used for conditioning or surveillance tests with $H_2O_2$.

### 4.3.3 Cleaning and Passivation Solutions

Generally, the chemical solutions required in the passivation procedure may be prepared as described in the following paragraphs.

4.3.3.1 Detergent Solutions. A 1 w/o solution of a powdered commerical detergent such as Dreft, Naconal, Tide, All, Swerl, etc., in potable water is normally used for cleaning materials and glassware. Liquid detergent (of the same approximate concentration) or a mild solution (5 to 7 ounces/gal) of a commercial alkaline cleaner such as Turco No. 4090 (or its equivalent) may also be used; however, it should be noted that a strongly alkaline cleaning solution must be avoided. The container for the detergent solution should be rust-resistant and covered to minimize dirt pickup. Since most procedures recommend the use of hot detergent solution, provisions should be made for heating the detergent container to 140 to 160 F.

4.3.3.2 Degreasing Solvents. Commercial-grade trichloroethylene, perchloroethylene, or a commercial solvent such as Varsol or Sunoco cleaner are used for degreasing metals which are heavily soiled or very greasy. Alternate degreasing may be performed in a vapor degreaser using trichloroethylene (which meets the Mil-T-7003 specification) or an equivalent grade of one of the above solvents; however, it should be noted that the working temperature of the vapor degreaser must be higher than the boiling point of the selected solvent. The solvent should be stored in a covered galvanized iron, black iron, steel, or other suitable container. Care should be taken to prevent entry of water into the chlorinated solvents contained in the mild steel containers because the resulting conversion to acids will cause corrosion of the metal and subsequent contamination of the material during passivation.

4.3.3.3 Sodium Hydroxide (NaOH) Solution, Approximately 1/15 N. A mild (0.25 w/o) NaOH solution can be used as an alternate method for cleaning heavily soiled aluminum equipment. A supply of this solution, which should be available at all times, can be stored in a stainless-steel drum or polyethylene container which has been previously washed with a detergent solution and rinsed with clean potable water.

4.3.3.4 Sodium Hydroxide (NaOH) Solution, 10 w/o. A 10 w/o solution of NaOH solution is used for cleaning glassware which is heavily soiled or has contained an unknown solution.

4.3.3.5 Sulfuric Acid ($H_2SO_4$) Solution, 35 w/o. A solution of $H_2SO_4$ is used primarily for passivating glassware. The solution can be stored in a polyethylene-lined container or the glass carboys in which it is received. A lid must be provided if stored outdoors. Heated storage may be necessary depending upon the concentration of the acid and the winter temperature of the locality where stored.

4.3.3.6 Nitric Acid ($HNO_3$), 42 degrees Baume'. A nitric acid of 42 degrees Baume' (~70 w/o $HNO_3$) is recommended by FMC (Ref. 4.25) for passivating stainless-steel equipment. It should always be readily available and stored in the containers in which it is received.

4.3.3.7 Nitric Acid ($HNO_3$), 45 w/o. A 45 w/o $HNO_3$ solution is preferred by most organizations for the "basic passivation" step for aluminum and stainless-steel parts. The acid is normally stored in a polyethylene-lined or AISI 300 series stainless-steel container. A lid must be provided to keep out dirt and confine the acid fumes.

4.3.3.8 Nitric Acid ($HNO_3$), 35 w/o. A dilute $HNO_3$ solution of 35 w/o is recommended by FMC (Ref. 4.25) for passivating aluminum equipment. This acid is stored as above (Section 4.3.3.7).

4.3.3.9 Hydrofluoric Acid (HF)-Nitric Acid ($HNO_3$) Mixture, 3 w/o-10 w/o. A 3 w/o HF-10 w/o $HNO_3$ solution is used for pickling and cleaning stainless steel when rust or other surface contamination exists which cannot be removed by the nitric acid solution. A polyethylene-lined container, with a lid to keep out dirt and confine the acid fumes, should be used for storage.

4.3.3.10 Hydrofluoric Acid (HF)-Nitric Acid ($HNO_3$) Mixture, 1 w/o-10 w/o. Unanodized aluminum and aluminum alloy components that are excessively dirty or contain oxide film from welding, heat treating, etc., may be treated with a 1 w/o HF-10 w/o $HNO_3$ solution. This solution should be stored in the same manner as the solution discussed in Section 4.3.3.9.

4.3.3.11 Clean Potable Water. Drinking water, after filtration through a 40-micron nominal filter, is used for rinsing parts during the initial stages of passivation.

4.3.3.12 Fresh Distilled or Deionized Water. Distilled or deionized water, which is used for rinsing parts after passivation, should have a maximum specific conductivity of $10^{-6}$ mhos/cm. This water should not be stored in aluminum for periods longer than 1 week prior to or during use. Storage of distilled or deionized water in an aluminum $H_2O_2$ storage tank for any length of time results in slime formation which may render the tank unsuitable for $H_2O_2$. In the storage and handling of potable water, distilled water, or deionized water, the potential contamination by tanks, valves, lines, etc., should be considered (i.e., the use of copper in the system should be avoided). Storage time of deionized or distilled water should be minimized, preferably less than 1 week. Distilled water should be used for the preparation of deionized water.

4.3.3.13 Hydrogen Peroxide Solution, 35 w/o. Although a stabilized 35 w/o hydrogen peroxide solution is available (from various commercial manufacturers) for the initial propellant-conditioning step, many users utilize 35 w/o $H_2O_2$ solutions obtained by dilution of higher concentrations. However, various hydrogen peroxide manufacturers recommend that if the 35 w/o $H_2O_2$ is obtained by dilution of propellant-grade $H_2O_2$ (with no or minimum stabilization), a stabilizer should be added to the dilute $H_2O_2$ and the pH of the solution adjusted so that residual active metal sites can be deactivated by complexing with the stabilizer (recommendations of the hydrogen peroxide manufacturers are encouraged in this area). Regardless of the user's preference in the use of stabilizers, any dilution of $H_2O_2$ must be conducted with distilled or deionized water of suitable quality. The 35 w/o solution should be stored in an aluminum 1060, 5652, or 5254 container. The storage container must be vented at all times, and the vent line should be provided with a suitable filter to keep out dust or dirt. A hydrogen peroxide shipping drum is a convenient container; however, once removed, the hydrogen peroxide must not be returned to the original drum or container. Hydrogen peroxide from a satisfactory activity test may be reused, if economics dictate.

### 4.3.4 Typical Passivation Technique

Specific passivation procedures that are being or have been previously used by various organizations involved in hydrogen peroxide usage are contained in the following documents:

| | |
|---|---|
| Chance-Vought Aircraft* | Specification CVA 10-62a |
| Chance-Vought Aircraft* | Specification CVA 10-64a |
| FMC | Bulletin 104 (Ref. 4.25) |
| LTV Astronautics | Specification LTV 308-20-3 |
| McDonnell Aircraft | Specification 13002 |

*NOTE: CVA specifications were obtained from LTV Astronautics (Ref. 4.34 and 4.39).

| | |
|---|---|
| North American Aviation, Inc. | Specification NAA LA 0110-003 |
| Reaction Motors Division | Specification RMI 7000 |
| Walter Kidde Company | Specification 520007 |

There are numerous differences in the exact techniques and procedures used by various organizations for the passivation of materials, parts, systems, etc., for hydrogen peroxide service. However, for the most part, these differences are insignificant and the general techniques used are very similar. Although various storability and compatibility studies (see Section 4.1 and 4.2) have indicated the greater effectiveness of some techniques over others, it is believed that no one technique has consistently demonstrated a repeated superiority.

Thus, in developing a procedure to be used by any facility, the general or typical technique described below can be used as a starting point. More specific (in detail) procedures or modifications of these typical procedures may be developed and preferred with the acquisition of "passivation experience"; however, the typical procedures described will passivate most compatible materials. The solutions called out in the procedure are those designated in Section 4.3.3.

4.3.4.1 Degreasing and Cleaning. Excessively greasy metal parts should be initially degreased either by cold flushing with a solvent for 30 minutes (repeat with clean solvent if necessary), or through the use of a solvent vapor degreaser for at least 10 minutes. All metal parts should then be cleaned with a hot (140 to 160 F) commercial detergent solution or a mild alkaline commercial cleaner. (A 1/15 N NaOH solution has been used for nonanodized aluminum.) Cleaning can be accomplished by agitation of the part in the cleaning solution, scrubbing with a stiff nylon brush, and/or pumping the solution through the part (as in the case of tubing and piping). The metal parts should then be rinsed thoroughly in warm potable water to remove all traces of the cleaning compound.

Nonmetallic and bonded nonmetallic parts such as gaskets, O-rings, chevron rings, hoses, etc., should be degreased by immersion or scrubbing at 140 to 160 F, with a commercial detergent or a mild alkaline cleaner, followed by a thorough rinsing with warm distilled or deionized water. Teflon, polyethylene, Kel-F, or Viton, except when bonded to metal, may be cleaned with a solvent, but immersion time should be limited to a short period (~5 seconds). Items which have solvent or water remaining on their surface and are not to be chemically cleaned further, will be dried immediately with clean dry nitrogen gas or air.

> NOTE: Following the degreasing and cleaning step, the cleaned surfaces of the parts should be handled with clean gloves or tongs only. Any possible means of recontamination of the part should be avoided from this point.

4.3.4.2 Descaling. Newly fabricated or reworked metal parts, which have scale from welding, or heat treatment, or impurities from casting or forging, should be descaled ("pickled"). Descaling solutions should not be used after finish-machining of precision surfaces without protection, or on parts that do not have heavy oxide or foreign material buildups in the form of rust or scale. The contact time of the descaling solution with the item to be cleaned should be the minimum time necessary to clean the part or the maximum allowable time per this section, whichever is shorter. Only plastic-coated or nonmetallic gaskets should be used with nitric-hydrofluoric descaling baths to prevent excessive metal loss caused by electrolytic corrosion.

4.3.4.2.1 Stainless Steel. Stainless-steel parts should be etched for a minimum period, and not longer than 60 minutes, at room temperature (60 to 80 F) with a mixture of 3 w/o technical-grade hydrofluoric acid, 10 w/o technical-grade nitric acid, and the remainder water.

> CAUTION: A close visual check should be maintained during descaling operations with the $HF-HNO_3$ mixture to prevent material pitting or excessive etching. After descaling, the part should be thoroughly rinsed with potable water to remove all traces of descaling solutions. Loosely adhering smut or flux may be removed by spraying with water or scrubbing with a stainless steel or hemp brush. If the parts are to be passivated immediately after acid cleaning, they need not be dried. The parts may be dried completely by purging with dry, hydrocarbon-free nitrogen or air, or in an oven at 140 to 150 F. The AISI 400 series, 303S, 303SE, and AM 355 stainless steels will be descaled by mechanical methods such as machining, abrasive tumbling, or grit blasting.

4.3.4.2.2 Aluminum and Aluminum Alloys. Nonanodized aluminum and aluminum alloy parts may be descaled by immersion in a 1 w/o HF-10 w/o $HNO_3$ solution for 30 seconds to 5 minutes at 115 F maximum.

> CAUTION: A close visual check should be maintained during descaling operations with the $HF-HNO_3$ mixture to prevent material pitting or excessive etching. After descaling, the part should be thoroughly rinsed with potable water to remove all traces of the acid solution. It should be noted that a 35 w/o $H_2SO_4$ solution at ~115 F can also be used as an alternate "pickling" solution for aluminum and aluminum alloys.

4.3.4.3 "Basic Passivation." Immediately following the cleaning (or descaling) operation, the metal parts should be subjected to the "basic passivation" step. Although this step is always accomplished with $HNO_3$ solutions, the concentrations used by different organizations vary. The following procedures are those preferred by the majority. It should be noted that plastic and synthetic rubbers should not be subjected to this step in the passivation procedure.

4.3.4.3.1 Stainless Steel. Stainless-steel parts should be immersed in a solution of 45 w/o $HNO_3$ at 60 to 80 F, for a minimum period of 30 minutes. FMC (Ref. 4.25) recommends the use of 70 w/o $HNO_3$ for a period of 4 to 5 hours as the stainless-steel passivation step. The parts should then be rinsed and flushed thoroughly with deionized or distilled water to remove all traces of the passivating solution. Unless the part is immediately placed in the propellant-conditioning solution, it should be drained and dried by purging with dry, filtered, hydrocarbon-free nitrogen or air, or dried in a dust-free oven at 140 to 150 F; the part should then be protected from recontamination by sealing in a sealed clean plastic bag.

The nitric acid passivation solution should be used for the AISI 300 and 400 series stainless steel. The protective film resulting from this passivation process will not normally be visible, but surfaces will be uniform in appearance, free from scale, corrosion, pitting, and contaminants. Normal discoloration from welding will be permitted, provided no scale or rust is associated with the discoloration.

Some organizations recommend electropolishing of stainless-steel parts (except for AM 355) by the best available commercial practice as an alternate method for stainless-steel passivation. Following electropolishing, the material should be cleaned with detergent (Section 4.3.4.1) rinsed thoroughly with deionized or distilled water, and dried in an oven.

4.3.4.3.2 Aluminum and Aluminum Alloys. Aluminum and aluminum alloy materials are usually passivated with a solution of 45 w/o $HNO_3$ at room temperature for a period of 1 hour; however, FMC (Ref. 4.25) recommends the use of 35 w/o $HNO_3$ as the passivation acid. The materials should be rinsed and flushed with water to remove all traces of nitric acid, and unless immediately conditioned with the propellant, the materials should be drained and dried by purging with dry, filtered, hydrocarbon-free nitrogen or air, or dried in a clean oven at 140 to 150 F. Machined aluminum barstock parts do not normally require descaling or passivating processes and can be prepared for service by degreasing and thoroughly rinsing. Welded, cast, or corroded parts will require descaling, cleaning, and passivating. Anodized aluminum parts will not be descaled or passivated and should be prepared for service by degreasing and thorough rinsing.

4.3.4.4 Propellant Conditioning. Following cleaning and acid treatment steps, metallic materials should be propellant conditioned to check passivation ("activity testing") and passivate further potentially active sites in the materials. The nonmetallic materials are propellant conditioned following the cleaning step. Normally, most procedures recommend initial propellant conditioning with 30 to 35 w/o $H_2O_2$ (see Section 4.3.3.13). Following this conditioning, most procedures call for conditioning with hydrogen peroxide of the grade with which the material will eventually be applied. Propellant conditioning, which should be conducted for a minimum period of 3 to 6 hours, is conducted on both the unassembled parts and components and the assembled systems.

4.3.4.4.1 <u>Materials, Parts, and Components</u>. Before the initial activity tests are conducted, components such as valves, pumps, etc., should be assembled (care must be taken to avoid contamination during assembly). The passivated surfaces should be exposed to the selected $H_2O_2$ solutions by either immersion of the part or by filling the composite assemblies (components) with the $H_2O_2$. Low openings in the composite assembly may be closed with passivated plugs of the same material or polyethylene-covered rubber stoppers; however, there must be a vent to allow escape of gases from the assemblies. During the tests of the composite assemblies, all sliding surfaces must be completely wetted (through valve actuation, etc.) by the $H_2O_2$.

Acceptance of passivation is contingent upon no reaction of the material with the hydrogen perioxide (as evidenced by the lack of gas bubbles evolving from the $H_2O_2$). If, at the end of the exposure period, the gas bubble rate is very minimal, the unexposed surfaces of the materials are cool to the touch, and the gas bubbles are not confined to a particular location, the material or part is considered acceptable. If rapid bubbling, clouding of solution, or a local hot spot is observed during the test, the solution should be discarded and the active part repassivated in accordance with Sections 4.3.4.1 and 4.3.4.3. If it is practical, the active area should be marked for future observation. A component or part should be rejected if it fails three consecutive passivation tests. If a part shows only marginal unacceptable reaction, it should be removed from the $H_2O_2$ solution, rinsed several times with distilled or deionized water, and reconditioned with fresh $H_2O_2$ solution; the part should then be repassivated if it continues to demonstrate marginal unacceptability. Parts which cause discoloration of the $H_2O_2$ solution will be reimmersed in fresh $H_2O_2$ solutions; if discoloration continues, the part should be rejected and the discolored $H_2O_2$ solution disposed of immediately.

Any part which shows blackening, rust streaks, or signs of excessive corrosion should be rejected.

After the materials, parts, and/or assemblies have passed all activity checks in the selected $H_2O_2$ solutions, they should be rinsed thoroughly in distilled or deionized water and dried with clean dry air or nitrogen. Heat may be used to dry if the plastic materials are maintained below 120 F and the metals below 150 F. All parts must be handled with clean tongs and/or clean neoprene-gloved hands to prevent recontamination. After drying, the materials should be assembled in the final system or packaged according to Section 4.3.7.

4.3.4.4.2 System Assembly. After complete assembly of a handling installation, storage facility, or any other hydrogen peroxide system from compatible and passivated materials (that have undergone preliminary activity checks), the system should be conditioned as a whole. The entire system assembly should be filled with 30 to 35 w/o $H_2O_2$ (see Section 4.3.3.13) and activity checks conducted. Again, it is noted that the system should be vented and all valves and sliding surfaces should be operated to wet all surfaces with $H_2O_2$. The test should be conducted for a period of 4 hours unless a local heated area or excessive gas evolution indicates the test should be terminated. The observations and conclusions in the assembled system tests are identical to those of the materials, parts, and components conditioning (Section 4.3.4.4.1) with one exception; most organizations advocate an activity check of the system using a laboratory-type "wet test meter" to measure the actual gas rate.

After successful preliminary testing of the system with 30 to 35 w/o $H_2O_2$ solution, the system should be conditioned with $H_2O_2$ solutions of the grade it will eventually utilize. Following this passivation, the system is considered ready for hydrogen perioxide service. All such passivated systems should be protected against further contamination with dust caps. In addition, the system should be continuously surveyed during use for evidence of excessive $H_2O_2$ decomposition.

### 4.3.5 Glassware Passivation

Because glassware passivation is slightly different from that associated with the materials commonly used in hydrogen perioxide system fabrication and more often involves a laboratory-type operation, the technique used has been seperated from the typical passivation section. The procedure for the passivation of glassware, which includes thermometers and hydrometers, is contained in the following paragraphs.

Glassware that is heavily soiled should be immersed in a 10 w/o NaOH solution for 1 hour at room temperature. If the glassware is relatively clean, a commercial detergent should be used instead. Following this cleaning, the glassware should be rinsed thoroughly in clean potable water.

Chemical passivation is accomplished by immersion in 35 w/o $H_2SO_4$ for at least 1 hour at room temperature. After the glass is thoroughly rinsed in distilled or deionized water, it should be dried with clean air or nitrogen, or in an oven at 230 F.

The passivated glassware can be stored in a "ready-for-use" condition by packaging in accordance with Section 4.3.7. Bottles, flasks, or other containers can be stored by covering the opening tightly with aluminum foil.

4.3.6 <u>Passivation Aids</u>

So that materials passivation be accomplished with minimum difficulty, several general rules should always be observed. The primary rule is, of course, strict adherence to cleanliness thoughout the procedure. Other considerations, primarily associated with the materials treatment prior to initiation of passivation procedures, are noted below.

4.3.6.1 <u>Metal Machining</u>. In addition to the selection of compatible metals, the effectiveness of future passivation of these metals for hydrogen peroxide service depends upon eliminating contamination of the materials with incompatible materials during machining. Thus, the use of zinc, copper, copper alloys (i.e., bronze or brass), tin, iron (low carbon, nonstainless types), silver, lead, cadmium, carbide, sand, etc., should be avoided in tooling and machining operations.

4.3.6.2 <u>Surface Finish</u>. All surfaces which contact hydrogen peroxide should be as smooth as possible, with manufacturing marks, identification symbols, and irregularities reduced to a minimum. All surfaces contacting hydrogen peroxide should be free of cracks, pits, inclusions, and foreign material. Whenever practical, sharp corners should be broken and a surface finish of 40 rms (root mean square) or finer achieved.

4.3.6.3 <u>Abrasives</u>. Abrasive cleaning methods should not be used if a suitable chemical method is available. When abrasives are necessary, only glass beads, aluminum oxide abrasives, or stainless-steel wire brushes should be used. AM 355 should be cleaned only by mechanical methods. Acid descaling should be avoided if possible.

4.3.6.4 Anodized Aluminum. Aluminum surfaces which contact hydrogen peroxide should be anodized. Exceptions are surfaces whose shape makes anodizing impracticable (i.e., the interior of long tubes). Sulfuric acid anodizing is preferred and should be used where that process is available. Sealing of sulfuric acid-anodized surfaces should be done in hot water (195 ± 10 F for 30 minutes). Deionized water is preferred for sealing although tap water may be used.

4.3.6.5 Rework. All fabrication and fitting of detail parts and components should be completed prior to passivation treatment. Any rework on passivated areas makes repassivation mandatory.

4.3.6.6 Welded Assemblies. For welded assemblies, each part should be cleaned prior to welding. Completed weld assemblies must be passivated prior to further assembly.

4.3.6.7 Pressure Testing. Pressure testing of a system using various test fluids or replacement of a component in any assembly will automatically make it mandatory to repeat the activity testing procedure for that assembly.

### 4.3.7 Handling of Passivated Materials

Items that have been cleaned and passivated should be handled, stored, or packaged in a manner to prevent recontamination. Immediately following cleaning and passivation, large valves, piping sections, vessels, flex joints, subassemblies, and other prefabricated items should be dried and have ends and openings capped, plugged, or flanged and sealed with clean compatible sealing material. Small valves and components should be purged with clean, dry gaseous nitrogen and wrapped and sealed in clean plastic or metal foil bags. These components should be kept sealed until installation.

4.3.7.1 Acceptable Materials. Small items should be sealed in clean preformed envelopes, rolls, or sheets of: (1) polyethylene film, polyethylene-backed paper, polyethylene-backed cloth, or polyethylene-backed aluminum foil, (2) vinyl (Vinylite), (3) Koroseal, (4) Saran, or (5) Mylar. Materials for short-term storage of passivated items can also include aluminum foil (or aluminum-backed cloth or paper) and cellophane.

4.3.7.2 Indefinite Storage. In the packaging of small passivated items for long-term storage, the items should be dried and packaged as soon as practicable after passivation and activity testing. Any openings of the items should be sealed with clean new polyethylene or aluminum caps (used closures will be discarded to prevent reuse). The materials should be enclosed in a clean envelope and sealed to stop free passage of air. This envelope should then be wrapped in heavy paper or placed in a protective container.

4.3.7.3 Identification. The passivated parts should be identified with standard markings such as date, part number, part name, etc., but in addition, a tag should be attached which notes the equivalent of the following:

PASSIVATED PART

This part passivated for use with w/o hydrogen peroxide. Activity Test OK

________________ ____________________
(Date) (Inspector)

NOTE: If a part is contaminated before packaging or if a package containing a passivated part is torn, the part should be returned to proper area for passivation or activity test as needed.

## 4.4 FACILITIES AND EQUIPMENT

### 4.4.1 Storage and Handling Facilities

A facility for the storage and handling of hydrogen peroxide may exist in the form of: (1) a singular storage facility for hydrogen peroxide only, (2) a special handling area for hydrogen perioxide, such as an equipment passivation area, (3) a storage complex for oxidizers including hydrogen peroxide, (4) an area storage complex for fuels and oxidizers, or (5) a handling complex for various propellants. Although it is desirable that any such facility be located in an isolated area, out of necessity, it may be located in the proximity of a test or launch facility.

The specific design criteria for each type of hydrogen peroxide-containing facility must be considered independently although most considerations apply to all facilities. This is necessary because any other propellants stored or handled at the facility also require special considerations. In addition, a facility located in the proximity of a launch or test installation, for example, is exposed to vibrational, thermal, and possibly shrapnel effects, all of which require special considerations.

The design principles presented in this handbook apply to those criteria associated with storage and handling facilities for only hydrogen peroxide. Thus, in the use of these criteria in areas where other propellants are stored and/or handled, the facility designer must consider the integration of various other requirements in his design of the hydrogen peroxide facility.

4.4.1.1 Facility Layout and Orientation. Hydrogen peroxide storage and handling areas should be situated in such a manner as to provide the least hazard to surrounding facilities and personnel under any given condition. Since the layout of test areas is dependent upon particular requirements and considerations, in which many attendant hazards must be accepted, the layout considered here is related primarily to storage or handling areas which can be situated as desired. All such facilities should have adequate drainage and be situated so that they are exposed to the minimal climate changes for the particular area. Some air flow should normally be available.

4.4.1.1.1 Meteorological Considerations. Hydrogen peroxide does not present a serious toxicology threat to personnel through vapor inhalation because of its low vapor pressure and comparatively high threshold limit value. Thus, very little consideration is usually given to the potential release of hydrogen peroxide vapor into the atmosphere, either through venting or gross spillage. Normally, such situations do not pose a threat to personnel outside of the immediate area, particularly if spillage is immediately diluted with large quantities of water. However, site orientation should be such that a vent or spill of any conceivable magnitude will be reduced to relatively harmless concentrations by the time it reaches downwind population.

4.4.1.1.2 Quantity-Distance Considerations. All hydrogen peroxide solutions above 52 w/o $H_2O_2$ are classified as Hazard Group II propellants by the criteria established for the Department of Defense (Ref. 4.52). As such, these solutions are grouped with other strong oxidizers as a fire hazard. The DOD criteria (Ref. 4.52) also indicate that solutions above 96 w/o $H_2O_2$ can detonate and appropriate precautions should be taken (Ref. 4.53). Based on the Hazard Group II designation, the following criteria have been recommended in Ref. 4.52 for the location of hydrogen peroxide sites in relation to surround habitations and public transportation.

| Propellant Quantity, pounds | | Distance in Feet to | |
|---|---|---|---|
| Over | Not Over | Inhabited Buildings, Railroads, Highways, and Incompatible Group II Storage | Intragroup and Compatible Group II Storage |
| | 100* | 60 | 30 |
| 100 | 500* | 100 | 50 |
| 500 | 1,000 | 120 | 60 |
| 1,000 | 10,000 | 180 | 90 |
| 10,000 | 50,000 | 240 | 120 |
| 50,000 | 100,000 | 270 | 135 |
| 100,000 | 300,000 | 330 | 165 |
| 300,000 | 500,000 | 360 | 180 |
| 500,000 | 1,000,000 | 410 | 205 |

*NOTE: These criteria do not apply to a single standard minimum size shipping container (such as one 55-gallon drum); these should be stored and handled as prescribed by the controlling authority.

4.4.1.2 Storage Containers. The storage capacity of each facility is dependent upon the particular requirements of that facility. A user may require one large bulk storage facility with several ready storage facilities, each to supply a particular test site. Large storage facilities for propellant-grade hydrogen peroxide may contain one or more bulk storage tanks with capacities ranging from 5000 to 25,000 gallons. In addition, the various facilities may require areas for drum storage.

The propellant-grade hydrogen peroxide tanks and containers should be stored in an area by themselves and not integrated with other oxidizer storage (Ref. 4.24). The area layout should allow for easy access and egress for loading and unloading vehicles and adequate separation of the bulk storage tanks from each other, and from the drum storage area. All storage tanks and associated valves and piping should be located aboveground to facilitate the detection of leaks. All main tank connections should be made through the top portion of the tanks to reduce the possibilities of propellant spill.

4.4.1.3 **Buildings**. Hydrogen peroxide bulk storage tanks do not require surrounding buildings; however, they should, if possible, be shielded from direct sun radiation. Drums are usually stored on a raised pad under an open-wall roof. The structural framework for either protective covering should consist of either steel or masonry. Wooden supports should not be used. Any siding should be brick, tile, or other masonry units; corrugated sheet asbestos; aluminum; or steel with an approved protective coating. Slate shingles, corrugated sheet asbestos, aluminum, or coated steel can be used for roofing; but the use of petroleum-based roofing materials is prohibited. A vinyl-base, high-temperature aluminum paint can be used as weather protection for the applicable structural materials. Floors should be smooth, finished concrete with a built-in slope for drainage.

4.4.1.4 **Diking and Retainment**. Each hydrogen peroxide bulk storage tank should be installed within a separate dike, revetment, or walled area to retain spilled propellant. This containment should have a smooth, impervious, and acid-resistant cement lining. The dike or retainment should be capable of retaining 1.5 to 2 times the tank capacity. The diking system should be designed so that it will gravity drain into a collection basin via open-trough, concrete-lined drainage canals.

4.4.1.5 **Safety and Fire Protection**. Good system design, development and observation of good operating procedures, and good housekeeping are the best safety precautions in hydrogen peroxide storage and handling areas. These areas must be kept neat, clean, and absolutely free of any type of combustible material. All leaks and spills should be flushed immediately with large amounts of water. Frequent inspection of the areas to ensure compliance with these regulations should be maintained.

4.4.1.5.1 Personnel Education. Standard operating procedures should be established for all operations and potential situations that might occur in hydrogen peroxide storage and handling areas. Thorough education of all operating personnel with respect to these procedures is mandatory. In addition, these areas should be restricted to a minimum number of previously authorized personnel required for operation and safety.

4.4.1.5.2 Personnel Protection. Proper protective clothing, an adequate number of deluge safety showers and eye baths, and easy egress from the area should be provided for the protection of operating personnel. This equipment should be clearly located and marked.

4.4.1.5.3 Facility Protection. An adequate water supply must be available for fire fighting, flushing and decontamination, tank cooling, tank dilution, and personnel safety equipment. In storage areas where the tank temperature may be over 100 F for extended durations, a tank sprinkling system should be provided to cool the tanks. The locations for floor flushing, drainage flooding, and fire protection valves (either for hoses or fixed nozzles) should be clearly marked by signs and red lights. In the absence of a fixed tank dilution installation, an adequate hose length should be available to reach the dome of any storage tank for dilution in an emergency situation.

4.4.1.6 **Electrical Concepts.** All electrical installations throughout the hydrogen peroxide storage and handling areas should conform to the national, state, and local codes for the type of area and service involved. The areas should be floodlighted in accordance with good industrial and safety practices for the type of operation involved. Electrical power distribution within the areas should be through rigid aluminum or steel conduits, which are preferably located underground. Spark-proof or explosion-proof fixtures are not required, but vapor-proof fixtures are recommended. Adequate electrical receptacles should be strategically located for maintenance purposes.

All vent stacks, storage tanks, and steel structures should have integrally mounted lightning protection systems in accordance with Section 8 of Ref. 4.54. All storage tanks, pumps, loading points, electrical equipment, and propellant transfer lines should be grounded and bonded electrically, in accordance with national, state, and local codes.

4.4.1.7 **Access Roads.** At least two access roads to transfer and storage sites should be provided with adequate space at each site for turning. The use of asphalt-paved access roads in close proximity to storage and handling facilities should be prohibited.

4.4.1.8 **Fencing.** Storage and handling areas, drainage ditches, and catch ponds should be fenced and equipped with warning signs, safety placards, and other equipment and techniques typical of good industrial practice.

## 4.4.2 Equipment Design Criteria

In the design of an item of equipment for hydrogen peroxide service, the same basic principles of design apply as for any other fluid-handling system. For hydrogen peroxide service, simplicity in design is essential. Since the decomposition rate of hydrogen peroxide is a direct function of the surface area contacted, the material surface area relative to the hydrogen peroxide volume should always be minimized. The number of parts in a system or component assembly should be kept to a minimum that is consistent with the mechanical and structural requirements of the equipment, and the equipment must be designed so that all units can be easily disassembled into component parts for ease in passivation and inspection.

Throughout the design and layout of a hydrogen peroxide system, the potential integrity of the system with respect to cleanliness and compatibility with the hydrogen peroxide must be constantly reviewed. The use of each material and its potential contact with the propellant must be consistent with the material compatibility data, as illustrated in Section 4.2.2. Because of the possibility of unforeseen hydrogen peroxide contamination (with resulting decomposition and gas release), all systems must be designed so that they can be completely vented and pressure relieved. Whenever possible, the system should be designed to "fail open."

Typical equipment design and selection considerations are given in the following paragraphs. Although these considerations will aid the hydrogen peroxide user in the design of hydrogen peroxide storage and handling systems, they are not intended as a substitute for good engineering practices nor do they exclude other competent and knowledgeable considerations. It is also noted that the following criteria are primarily for semipermanent or permanent facilities and do not apply to flight hardware although many of the considerations may be applicable.

4.4.2.1 **Storage Vessels**. All pressure vessels for hydrogen peroxide storage and feed should be constructed in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, latest edition (Ref. 4.55). Also, all pressure vessel design and construction should satisfy applicable local and state codes for such vessels. All other storage vessels for hydrogen peroxide service should be designed and fabricated in accordance with good engineering practice for the pressure and service in which they are to be used. A minimum safety factor of 4 for vessel and vessel support material strength should be maintained in all designs with adequate allowances for local seismic and atmospheric disturbances, temperature conditions, and external and/or internal corrosion.

Hydrogen peroxide storage tanks are normally fabricated of Class 1 materials. The majority of the tanks used for bulk storage are fabricated from aluminum 1060, which is 99.6 w/o aluminum. When greater strength is required, aluminum alloys 5254 and 5652 are normally used for bulk storage. In consideration of requirements for high-pressure lightweight tankage, AM 350 stainless steel has been used successfully. The 17-7 precipitation hardening stainless steel has been used successfully in 76 and 90 w/o $H_2O_2$ systems; however, this material is generally more difficult to passivate than the AM 350 material, particularly when used in 90 and 98 w/o $H_2O_2$ systems. Both steels offer yield strengths of 160,000 psi.

The hydrogen peroxide tankage used in rocket test facilities and various other feed and ready storage applications (which required only short periods of hydrogen peroxide storage) are usually fabricated from 347 stainless steel. Other materials successfully utilized in tankage for these types of applications are the low-carbon 304, 316, and 321 stainless steels.

The cryogenic prestrained 301 stainless steel has demonstrated excellent compatibility with 90 and 98 w/o $H_2O_2$, and the high strength of this material (260,000 psi yield) favors its use for hydrogen peroxide tankage in flight vehicles and for high-pressure applications.

4.4.2.1.1 General Considerations. The particular requirements of the storage and handling facility will determine the size and number of storage and feed tanks. If hydrogen peroxide shipments are received in tank trucks or tank cars, storage tanks with capacities greater than 8000 gallons should be available, and more than one bulk storage tank is recommended at each particular installation. Bulk shipments should preferably be maintained in containers of similar size instead of being transferred to a number of smaller containers. In addition, the number of hydrogen peroxide transfers from the initial storage to final use should be minimized. Observation of these rules will limit the chance of contamination and the number of hazards involved.

Although atmospheric-pressure, horizontal tanks have usually been preferred to vertical tanks for the bulk storage of hydrogen peroxide, any well-engineered tank is suitable. High-pressure feed or ready storage tanks are usually vertical so they can be fully drained. It should be noted that the optimum stress-to-weight ratio is contained in a spherical tank, and this type of tank provides a minimum surface-to-volume ratio. A 2-to-1 length-to-diameter ratio tank is also advantageous with reference to strength-to-weight and surface-to-volume ratios. Regardless of the shape, the tank should be designed with sufficient volume capacity to limit the liquid level from rising above the head attachment weld.

Normally, all hydrogen peroxide tankage should be provided with openings for filling, draining, venting, special instrumentation (temperature, pressure, and liquid level indication), and pressure relief (usually a large burst disk). Large storage tanks should be provided with a top opening manway of at least 18 inches diameter for cleaning and inspection. All bulk storage tanks should have at least a 6-inch-diameter opening for use during cleaning and passivation. Many organizations fit the large openings on atmospheric-pressure bulk storage tanks with a floating cover, which is designed to exclude dirt but free to relieve pressure buildup in the tank. A cover of this type is especially effective in providing a large emergency vent to prevent pressure rupture of the tank in case of massive contamination of the contained hydrogen peroxide.

Top inlet and outlet connections are usually recommended for large bulk storage tanks; however, a bottom outlet is generally required for propellant feed and ready-storage tanks to provide complete drainage. Flanged connections should be used for all openings whenever possible. Storage tanks must have a filtered (to protect against inflow of dirt) vent of at least 2 inches, which cannot be inadvertently closed. Pressure vessels should be designed with fail-open vents. In addition, many storage tank designs incorporate a temperature alarm, in which a thermocouple is installed in a protective aluminum tube inside the tank or fastened to the outside wall of the tank below the liquid level (with external glass wool insulation). Mercury thermometers and liquid-type manometer gages should not be used in direct contact with the liquid.

4.4.2.1.2 <u>Pressure or Volume Changes</u>. Throughout the design, fabrication, and application of hydrogen peroxide storage vessels, the pressure and volume changes resulting from hydrogen peroxide decomposition must always be considered. A liberation of oxygen from decomposition results in a subsequent change in gas volume and/or pressure of a sealed container. To illustrate this point, Fig. 4.10 shows the volume of oxygen liberated per unit volume of hydrogen peroxide as a function of hydrogen peroxide concentration and temperature, assuming a decomposition rate of 0.1 percent AOL per year and a constant pressure of 14.7 psia. Figure 4.11 demonstrates the pressure increase resulting from this decomposition in an unvented system with an initial ullage volume of 10 percent. Pressure increases observed under actual storage conditions are illustrated in Fig. 4.3 and 4.6.

For these reasons, venting of systems for normal long-term hydrogen peroxide storage is necessary. This venting may be either continuous or of the intermittent variety. The latter is used when the rate of pressure increase is used as a measure of stability. Commercial shipping containers are normally of the continuous-venting type. A somewhat labyrinthine path is made with holes drilled through the cover material. The geometry is such that the possibility of contaminants entering through the holes is neglible, and the possibility of trapping and subsequent blowing overboard of liquid hydrogen peroxide is insignificant. For most aerospace applications, nonvented systems are employed and allowances for pressure increase during the storage period must be made in the design.

4.4.2.1.3 <u>Self-Heating</u>. Another important consideration in the design of storage tanks is related to self-heating of the hydrogen peroxide. This behavior, thoroughly discussed in Ref. 4.56, can be briefly summarized by the following comments from that discussion:

> "All hydrogen peroxide solutions decompose at a finite rate, and this decomposition releases a relatively large amount of heat (1200 Btu/lb of hydrogen peroxide consumed). Consequently, every hydrogen peroxide storage vessel must continually transfer heat to its surroundings, a corollary being that such storage vessels are always warmer than the surroundings. The magnitude of this temperature difference is established by the balance between heat released by decomposition and heat transferred to the atmosphere. The actual mechanism, of course, involves a gradual temperature rise in the contents of the vessel until the rate of heat transfer to the surroundings becomes equal to the rate of heat liberation by decomposition. However, the rate of heat transfer to the atmosphere increases only linearly with temperature, while the rate of decomposition increases exponentially. As a consequence, for any particular storage vessel there exists a critical decomposition rate beyond which the rate of heat liberation will always exceed the rate at which heat can be transferred to the surroundings. Once a storage vessel passes the critical condition, a self-accelerating decomposition will set in which, unless checked, may reach a very high rate. As hydrogen peroxide solutions are nearly impossible to detonate and vapor explosions are possible only over very strong solutions, the primary hazard is due only to pressure rise and possible rupture of the container."

Because of this potential effect in storage, the design of any hydrogen peroxide storage container should incorporate features which control self-heating. Assuming various hydrogen peroxide decomposition rates, a maximum safe-tank size can be calculated for a given hydrogen peroxide concentration stored at a given temperature in a given tank material (Ref. 4.56). Hydrogen peroxide tankage should be located so as to permit free movement of the surrounding air, and since heat dissipation from the tank is necessary to prevent self-heating, the insulation of hydrogen peroxide storage vessels under normal earth ambient storage conditions should be prohibited. Because knowledge of impending self-heating is desirable, adequate instrumentation should be provided for all bulk storage tanks; this instrumentation is discussed more thoroughly in Section 4.4.2.11.

4.4.2.1.4 Surface Area Effects. One of the important considerations in the design of hydrogen peroxide storage tanks is the effect of surface area. This is discussed in many other sections of the handbook, and the system designer should be well aware of its contribution to the decomposition of hydrogen peroxide. With proper knowledge of this effect, it can be minimized by proper design. Since the current high-purity of propellant-grade hydrogen peroxide minimizes the homogeneous decomposition reaction, the primary cause of decomposition results from the heterogeneous reaction. This is the controlling reaction under the normal ambient storage conditions assuming inadvertent contamination of the hydrogen peroxide does not occur in sufficient quantities to initiate the homogeneous reaction mechanism.

Surface area effects, which are the basis of the heteregeneous reaction, can be minimized by optimizing container design for minimum surface area per unit volume (the ultimate design being a sphere). Further optimization requires a minimum number of storage containers. Previous production plant storage data show that the active oxygen loss in the storage of hydrogen peroxide can be reduced 50 percent by going from an 8000-gallon storage tank to a 25,000-gallon storage tank (Ref. 4.25). Since such volumes are not practical for many applications, compromises have to be made with respect to convenience of handling and minimum quantity required at the storage site for assurance of continuing operation.

4.4.2.2 **Piping Systems**. Information of a general and specific nature relating to pipe, pipe material, and piping installation is extensively covered in Ref. 4.57 through 4.60.

4.4.2.2.1 **System Design**. All piping used in the storage, venting, and transfer of hydrogen peroxide should be designed in accordance with Sections 3 and 6 of Ref. 4.57. Allowable tensile stresses for pipe materials are listed in Table 12 of Ref. 4.57. Material specifications for pipe, fittings, valves, flanges, tubing, and boltings are listed in Table 8 of Ref. 4.57.

In design of hydrogen peroxide piping systems, all piping and items of equipment, especially valves and pumps, should be designed for complete drainage on shutdown. This can be accomplished by providing easily accessible draincocks at the low points and by placing equipment containing dams, such as some types of valves, in vertical rather than horizontal positions. A piping system which holds hydrogen peroxide in stagnant pools, even if properly vented, may be subject to excessive corrosion even when fabricated from the recommended materials of construction.

There should be no places in the flow system where hydrogen peroxide can be trapped for any period of time without a vent path or a relief arrangement. Since hydrogen peroxide solutions will constantly decompose at a slow but steady rate, the resulting gas, if completely confined, could eventually build up sufficient pressure to cause rupture. "Dead ends," of which a Bourdon tube gage is an example, should be avoided since foreign material can accumulate in these spots. Ball, plug, and gate valves are examples of valve designs where the hydrogen peroxide can be trapped when the valve is closed; if one of these types of valves

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In the use of pumps in the system where the point of pump discharge is lower than the storage tank liquid level, the pump suction line from the top outlet should have a valved vacuum breaker to prevent siphoning after the pump is stopped. The pump installation should also be designed to prevent hydrogen peroxide from flowing back to the storage tank upon pump shutdown.

4.4.2.2.2 Pipes and Fittings. Pipe and welding fittings are normally manufactured according to standard thickness and weight, as proposed by the American Standards Association. Adherence to these standards in the design of hydrogen peroxide piping systems will eliminate unnecessary cost in the purchase of pipe and will facilitate purchases in small lots. Pipe wall thicknesses should be determined in accordance with Ref. 4.57, Section 2, Chapter 4, Paragraph 214 (-3).

The most compatible piping for hydrogen peroxide service is 1060 aluminum, and this material is generally recommended, particularly if the liquid hydrogen peroxide is to remain in long-time static contact with it. However, where greater strength or hardness is required over that of aluminum 1060, or where other aluminum alloys (3003 and 6063) may be more readily obtainable in piping, other Class 1 or Class 2 aluminums may be used. Piping of 300-series stainless steel may also be used in certain Class 2 (Section 4.2.1.2) applications.

Welded and flanged construction is recommended in hydrogen peroxide piping with a minimum of fittings and joints. Bends are preferred to elbows, and joints should be stud-ends with lap joint flanges or flanges welded to the piping. The use of stainless steel and galvanized or aluminum-clad bolting with galvanized steel back flanges is recommended, because rusting of carbon steel would afford a source of possible contamination of the piping when the flanges are opened. If possible, threaded fittings and connections should be avoided; however, where they must be used, it is recommended that the tapered pipe threads be sealed with Teflon thread tape. Normal pipe thread compounds must never be used.

4.4.2.2.3 Pipe Hangers and Supports. Pipe supports, hangers, anchors, guides, and braces should be designed to prevent excessive stress, deflection, and motion in operation of the system, or too large a variation in loading with changes in temperature, and to guard against shock or resonance with imposed vibration and/or critical conditions. Design and selection of the pipe supports should be in full accordance with Section 6, Chapter I of Ref. 4.57. Additional information is included in Ref. 4.58 through 4.63.

4.4.2.2.4 Flexible Connections. A corrugated, seamless hose of 304 or 316 stainless steel, with open pitch construction and welded flanged ends is recommended as a flexible connection for hydrogen peroxide service. Flexible hose lines with Teflon or Silicone S-5711, fitted with flanged connections, also have been successfully used. Another type of flexible connection that has been applied successfully in hydrogen peroxide service is aluminum piping with swing joints of stainless steel and Teflon.

4.4.2.2.5 Identification. Hydrogen peroxide piping should be identified in accordance with MIL-STD-101A(10). The primary warning color (band) is green. The secondary warning color (arrow) is blue.

4.4.2.3 Stainless Steel Tubing and Fittings. Tubing and fittings of 300 series stainless steel are used almost exclusively for pressurized hydrogen peroxide systems. (It should also be noted that the X-15 experimental aircraft uses an all stainless-steel hydrogen peroxide system.) All systems designed with stainless-steel tubing should conform to MIL-T-8808A (for type 321) MIL-T-8606A (for type 347), or MIL-T-8504 (for type 304). Fittings should conform to AN or MS standards for flared tube fittings.

4.4.2.4 Valves. Selection of valves for hydrogen peroxide service imposes certain design requirements that are more stringent or critical than with most other propellants. The design should be such that trapping of hydrogen peroxide in any part of the valve is impossible during any operation cycle of the valve. As a result, globe or Y-type valves are usually recommended for hydrogen peroxide service. Modification of some types of gate, plug, and ball valves to provide self-venting has also permitted their use in certain applications.

Materials used in approved hydrogen peroxide valves are normally Class 1 or 2 (see Section 4.2.1.2). Stainless steels 321 and 347 have been employed successfully as valve materials; however, some aluminum alloy valves have been subjected to severe galvanic corrosion when used in conjunction with stainless-steel poppets or fittings. A metal-to-Teflon (or Kel-F) seal between the plug and valve seat is normally preferred over metal-to-metal contact. Materials approved for gaskets are normally used as valve packing.

4.4.2.5 Relief Devices. The preferred relief device for hydrogen peroxide systems is a rupture disk. The relief device should be rated at not more than 100 percent of the vessel or system rating when used as a primary relief device or 105 percent when used as a secondary relief device. Sizing of the device should be large enough to prevent the pressure from rising 10 percent above the maximum allowable working pressure of the system under any projected condition. Burst relief devices on hydrogen peroxide tank cars are designed to relieve at 45 psig pressure.

4.4.2.6 Regulators. Regulators are used primarily to supply regulated nitrogen gas for transfer, purge, and control systems. The selection of a regulator for service in hydrogen peroxide systems depends upon its particular intended service. If the regulator is in an attendant system which cannot be contaminated with hydrogen peroxide, no special requirements are necessary. However, when contamination is a possibility, the regulator materials must conform to compatible material specifications.

4.4.2.7 Pumps. Pumps manufactured from wrought or forged 300-series stainless steel (304, 316, 321 and 347) and pumps made with aluminum alloys B356, 356, or 43 which also have a 300-series stainless-steel shaft, are recommended for pumping hydrogen peroxide. Cast stainless steel should be avoided because it is subject to chromium leaching, which seriously contaminates the propellant and hastens decomposition. Self-priming pumps should be used for transferring hydrogen peroxide from tank cars or storage tanks with top outlets;

the pump normally used in this service is a 2-inch, self-priming centrifugal. Where higher pressure or low capacities are desired, a special rotary pump is recommended.

Pump shafts should be stainless steel, and any packing must be made of compatible materials. Where used, packing should be rings of either Teflon or Vitrium, lubricated with a fluorinated hydrocarbon; excessive gland tightening of the packing should be avoided, because overheating could result in the rupture of the gland. Stainless-steel mechanical seals with glass-filled Teflon and ceramic faces are recommended. All pumps should be equipped with drain valves and, where desired, temperature alarms to warn against overheating.

4.4.2.8 Filters. Liquid filters have been used in hydrogen peroxide storage and transfer systems to maintain propellant cleanliness from insoluble contaminants. Because of the massive surface area available (for promoting heterogeneous decomposition), the filter should be selected from Class 1 or 2 materials, and should be located where it is not constantly immersed in the liquid (such as the inlet or outlet of a transfer line). Also, it should be located for easy and repeated opening and cleaning. A 25-micron, type 316 stainless-steel filter with a 1000-sq in. minimum element area (100 gpm $H_2O_2$ at 15 psi $\Delta P$) has been used successfully in large handling systems.

4.4.2.9 Gaskets. The selection of gaskets for hydrogen peroxide service is related to the type of service to be provided. Materials normally used as gaskets are Teflon, Kel-F, certain silicone rubbers, some polyvinyl plastics, Koroseal 700, pure tin, and either a combination of spirally wound stainless steel and Teflon (Flexitallic) or a Teflon envelope over asbestos. The metal-containing gaskets are usually recommended for high-pressure and vacuum systems; however, contact between dissimilar metals should be avoided to prevent galvanic corrosion. The use of certain elastomeric meterials as gaskets must be avoided because the plasticizer or filler material may be incompatible or impact sensitive (see Section 4.2.2).

4.4.2.10 Lubricants. The use of lubricants in propellant-grade hydrogen peroxide service should be minimized or avoided wherever possible. Results of compatibility tests (Section 4.2.2.6) indicate that only the fluorinated hydrocarbons are sufficiently compatible with hydrogen peroxide to be considered, and even these materials may react under certain conditions.

4.4.2.11 Instrumentation. In the design of instrumentation internal probes or sampling tubes for hydrogen peroxide storage and handling systems, the proper selection of compatible materials is the primary consideration. Dissimilar metals in contact with hydrogen peroxide demonstrate a tendency for electrolytic corrosion, with the more concentrated solutions showing less galvanic action. However, even with 90 w/o hydrogen peroxide, the use of dissimilar metals should be avoided. Attempts at insulating one metal from the other by a plastic have not been very effective in past applications where intermittent wetting occurs. If two dissimilar metals must be in contact, the anodic metal should have a larger surface area than the cathodic metal. In addition, the use of soldered joints (particularly silver solder), which is common in various types of probes and sensors should be avoided (because of catalytic decomposition of the hydrogen peroxide).

As noted previously, "dead ends," which are those places that could be filled with hydrogen peroxide without permitting adequate recirculation of the fluid, should be avoided wherever possible. (A common example of this in instrumentation design is the typical Bourdon tube pressure gage.) The disadvantage of having a dead end in a piece of apparatus is that there is a possibility that small impurities will accumulate in the dead end until extensive hydrogen peroxide decomposition results. If dead ends cannot be avoided, they should be placed above the low point in the system so that liquid hydrogen peroxide solutions will not collect in them.

4.4.2.11.1 Pressure Gages. If gages are required or used in hydrogen peroxide service, they should be constructed of compatible materials and meet the other considerations noted above. Where Bourdon tube-type pressure gages are used, their design and assembly should allow for proper passivation and inspection of the gage inlet, and there should be no welds in contact with the hydrogen peroxide. For example, a stainless-steel diaphragm held between two bolted stainless-steel flanges should be used in conjunction with a Bourdon tube pressure gage, with the assembly placed in a vertical position. Gas legs and diaphragm protectors have also been used with success in preventing direct exposure of the gages to liquid hydrogen peroxide.

4.4.2.11.2 Storage Tank Temperature-Measuring Devices. A study of temperature-measuring devices for high-strength hydrogen peroxide storage systems has been reported in Ref. 4.64. A summary of this study, shown in Table 4.32 , illustrates the presently available techniques. Selection of any one of these techniques is dependent upon the requirements of the particular facility. However, regardless of which technique is used, its limitations, operating characteristics, and relationship to potential "red line" conditions must be fully understood by facility personnel to ensure the usefulness of the system.

In consideration of the various techniques described in Table 4.32 , the surface measuring system with its sensing point at the bottom of the tank (Method 3) would be less affected by high vapor space temperature than any of the other measuring devices. The Manufacturing Chemists' Association (Ref. 4.65) has, in effect, recognized this technique as a suitable method by stating."The temperature of a tank may be monitored by temperature indicators attached to the exterior of the tank below liquid level which records the temperature automatically or an operator may record the temperature on schedule." While not directly measuring liquid temperature, such a system would show tank temperature changes (although it would probably be unsuitable for inventory purposes). Using a dial thermometer, this type of system would be the most economical direct temperature indicating system.

The use of a dial thermometer inserted in a thermal well below the liquid level (Method 4) would more closely indicate the true liquid temperature and be less affected by ambient temperatures than surface mounted systems. High vapor space temperature would not affect such a system unless the liquid level fell below the well.

Another type of surface measuring system (Method 7) encompasses the vapor space using a capillary sensing element which is sensitive to the warmest spot along its length. However, any time the vapor space is warmer than the liquid, this instrument will indicate the vapor space tank surface temperature rather than the liquid. One organization reported that it was necessary to set the alarm point of such a system at 145 F to eliminate false alarms resulting from sun heating effects transferred into the vapor space. One manufacturer of this type of instrument does not recommend it for this use.

Another organization reported the use of an averaging surface measuring system covering the lower quadrant of the tank (Method 6). This system was affected in a manner similar to that of Method 7 at lower liquid levels, but to a lesser extent, since it averages the temperature rather than selects the warmest spot.

The Weston System (described as Method 10), using a resistance temperature element installed from top to bottom of the tank in a well, will average the liquid temperature from the liquid level to the bottom of the tank. A manual switch is provided to change the temperature-sensitive segment of the element to that position below the liquid level in up to six steps. This system gives good average liquid temperatures at any one vertical plane in the tank. Several elements installed in one tank or in several tanks could be used with one indicator. Such a system is expensive but might prove extremely valuable in the checkout of a new storage area, particularly by a group inexperienced in hydrogen peroxide handling and storage.

The use of automatic temperature alarms connected to the sensing device would be of little value in determining self-heating of the tank in the early stages. For example, in cold weather, self-heating could be progressing very rapidly by the time the alarm point set for 120 F would be reached. Conversely, in hot weather, the effects of the sun coupled with low liquid levels could result in frequent false alarms at this temperature. As a result of these false alarms, the alarm would soon be ignored (or if the alarm were set high enough to eliminate the false alarms, it might provide a false sense of security). An alarm system could be set up to operate on a given temperature differential between ambient and storage temperatures; however, this involves additional expense.

It is generally recommended that the use of continuous plots of tank (with any of the indicated devices) and ambient temperatures be used as the method of evaluating storage conditions, at least until personnel have sufficient experience to evaluate the facilities properly.

### 4.4.3 System Fabrication and Assembly

Hydrogen peroxide storage and transfer systems are similar to those employed for handling ordinary fluids, except for materials of construction. Pump motors, solenoid valves, electrical switch-gear, and other electrical equipment in the hydrogen peroxide transfer and storage systems should be selected and installed in accordance with the requirements of the National Electric Code, Article 500, Class 1, Division 2. All seals and joints in the propellant system should be periodically and frequently inspected for leaks and damage.

In the layout, placement, and arrangement of operating systems and units, ample spacing should be provided for proper maintenance clearances and adequate ventilation. In many cases, the removal, replacement, and servicing of valves, pumps, piping sections, instrumentation, and other equipment must be done by personnel in protective clothing. Ample room and access must be provided for use of tools and for easy movement of equipment. Where possible, equipment, valves, and lines should be located so that maintenance and service work can be accomplished from a position above the piping level to prevent propellant drips and leaks from falling on personnel.

Prior to fabrication and assembly of the system, the materials and equipment to be used should be carefully selected from the recommended lists as given in Section 4.2.2 and 4.4.2. Any questionable or unknown (with respect to compatibility) material or piece of equipment, which is to be used in the system, should be thoroughly checked in accordance with the procedures given in Section 4.2.1. In addition, the identity of each material used in the fabrication and assembly of hydrogen peroxide systems must be ensured; test kits are available for the identification of metals in the field (Ref. 4.66).

These selections should be judiciously reviewed by knowledgeable personnel who have had prior experience in the operation of hydrogen peroxide facilities. The selected materials and equipment should then be cleaned, passivated, and "activity" checked and the system fabricated and assembled according to the considerations given in the following paragraphs.

4.4.3.1 General. In the fabrication and assembly of hydrogen peroxide systems, the user is again reminded of general "rules of thumb" that should be observed in the design, preparation, and assembly of the system. These are noted as follows (Ref 4.25).

1. All hydrogen peroxide tanks should be designed with a minimum surface-to-volume ratio for maximum storage stability (i.e., a sphere is the optimum shape).

2. All storage tanks, vessels and drums should be designed so that sampling of their contents may be accomplished without the use of a sample thief or insertion of any device into the storage container.

3. Various seamless stainless-steel tubing can be used for high-pressure systems, but the 304L, 316L, 321, or 347 alloys should be used if welding is required.

4. Stainless-steel and aluminum components should not be coupled in the same system because electrolytic corrosion may result.

5. Free-machining, stainless-steel alloys should not be used.

6. Cast stainless-steel components should not be used unless the particular casting is thoroughly proved to be suitably compatible with hydrogen peroxide.

7. All markings should be removed from stainless-steel plates before they are formed into a tank.

8. Lap joints should not be used in fabrication of materials. Lap joints provide cracks, crevices, etc. (which cannot be readily cleaned), and may furnish a source of contamination; they also provide dead spaces for retention of hydrogen peroxide.

9. Clean rolling equipment must be used in material fabrication.

10. Head forming dies should be free of rust and smooth.

11. It is often advisable to degrease and passivate the tank head and bottom closures prior to fabrication. This eliminates difficulties in future tank and system passivations.

12. Flux and carbon formed in fabrication should be cleaned from welded areas in stainless steels by a 300 series stainless-steel wire brush. Any inclusions remaining should be ground out. For the grinding of cast surfaces, welds, and weld spatter on surfaces that will contact propellant-grade hydrogen peroxide, a clean white aloxide (aluminum oxide) abrasive is recommended.

13. Carborundum is not recommended for grinding because the iron in the carborundum is catalytic with hydrogen peroxide.

14. Metallizing or sprayed metal coatings are not suitable techniques for preparing surfaces for hydrogen peroxide service. It is possible for the hydrogen peroxide to seep behind the coating or an exposed edge, and cause the coating to blister.

15. Sandblasting is not recommended because it reduces the compatibility of metals with hydrogen peroxide due to the formation of a porous or pitted surface. The rougher surface decreases its compatibility with hydrogen peroxide.

16. Mechanical polishing of aluminum alloys is not advisable because of the possibility of introducing materials which are not compatible and could cause decomposition of the hydrogen peroxide. Electrochemical polishing (anodization) of aluminum is the recommended method.

17. If an aluminum system is employed, it should be anodized per Specification Mil-A-8625 (with no dyes), followed by a 1-hour rinse in boiling distilled water.

18. Aluminum materials and components should be handled carefully to prevent the possibility of embedding metal particles in the surface.

19. Hydrogen peroxide system components should not be brazed or silver soldered.

20. All plastic materials must be checked for metal particles, inclusions, etc., prior to use. The entrapment of organic solvents in porous materials should be avoided during cleaning operations.

21. Chromic acid solutions should not be used for cleaning because chromium is one of the better decomposition catalysts for hydrogen peroxide.

4.4.3.2 Welding. In general, the standards for welding pipe will conform to Chapter 4 of Ref. 4.57. Pipe fittings should be procured from reputable sources who permanently mark their fittings as to: (1) manufacturer, (2) size and schedule of pipe, and (3) material and heat code. The fittings should be of the butt-welded type to facilitate system cleaning and purging operations. A typical set of standards for the acceptance of pipe welds is as follows:

1. Cracks of any nature, whether crater, underbead, transverse, longitudinal, or parent metal will be cause for rejection.

2. Crater cracks which are determined to be only surface defects may be removed by machining or grinding. They need not be rewelded provided buildup is not less than 10 percent nor more than 30 percent of the metal thickness, nor if drop-through is not less than flush nor more than 30 percent of the metal thickness.

3. Normally acceptable defects occurring in conjunction with or adjacent to cracks will be cause for rejection if they occur within a distance of 2 inches each way from the crack.

4. Butt joints will have 100-percent penetration throughout 100 percent of the linear length of the weld.

5. Any lack of fusion will not be accepted.

6. Undercut, excessive drop-through, and excessive roughness will be cause for rejection. Folds in drop-through will be accepted if they are not greater in depth than 10 percent of the thickness of the parent metal.

7. Porosity or inclusions occurring in the weld metal, exclusive of the weld reinforcements, in which any radiographic image is darker than the parent metal or larger in its greatest dimension than 15 percent of the parent metal thickness will be rejected.

8. Porosity and inclusions in the weld reinforcement will be acceptable provided they do not extend through the surface of the reinforcements and provided they do not result in an objectionable stress riser.

9. Porosity and inclusions whose greatest dimensions are equal to or less than 15 percent of the parent metal thickness will be acceptable to the extent of one pore per inch of weld length.

10. Tungsten inclusions located in the penetration zone will be accepted provided the greatest dimension of any particle is not over 25 percent of the parent metal thickness.

In the welding of hydrogen peroxide systems, specific considerations must be observed to ensure the passivation and compatibility of the fabricated and assembled system with hydrogen peroxide. These considerations, noted in Ref. 4.25, are essentially dependent upon the design of tanks and equipment, which should be such that good welding techniques and machining practices can be readily utilized. Since weld splatter on surfaces which will contact the hydrogen peroxide will cause excessive decomposition, the design should allow for removal of weld splatter if it should occur.

Stainless-steel welds exposed to hydrogen peroxide should also be machined smooth if possible; however, aluminum welds should not be wire brushed or machined because this may introduce impurities and thus do more harm than good. Allowance for good machining will result in smooth surfaces which will cause less decomposition of the hydrogen peroxide than rough or poorly machined surfaces.

4.4.3.2.1 Aluminum Alloys. Weldability of aluminum and aluminum alloys varies over a wide range. The same procedures and techniques are employed in welding aluminum and its alloys as are used in welding other weldable alloys. In general, the less constitutents in the alloy, the more weldable the alloy.

The welding rod to be selected should be of the same composition as the parent metal. Unlike other alloys, the aluminum alloys do not lose any appreciable amount of the alloying elements during welding. In most cases, dissimilar aluminum alloys, which can be welded individually, can also be readily welded in combinations; the welding rod to be used should be of the harder material in the combination (i.e., in welding aluminum alloys 1060 and 5652, a 5652 rod would be used). The use of 5-percent silicon rods such as 43S, which are commonly used in aluminum welding, is not recommended for propellant-grade hydrogen peroxide service. During passivation and contact with hydrogen peroxide, such welds turn black and may cause decomposition of the solution. If use of the 43S rod is required, subsequent sulfuric acid anodization is necessary to stop the weld from turning black during passivation. During anodization, there may still be some blackening of 43S welds, but this discoloration does not seem to be a prior indication of an active site. Normally, a 5254 welding rod is recommended for welding of the 6061 alloy to other alloys.

Aluminum welds should not be wire brushed or machined if at all possible, because impurities may be introduced into the metal. In instances where wire brushing is a necessity, a 300 series stainless-steel brush will be used, and care must be taken to confine the brushing to the immediate weld area.

Automatic inert-gas welding processes, such as the Aircomatic or Sigma processes, give excellent results when used with the proper welding rod. The welds, in general, are nonporous, soft, and uniform. Electrode tip cups should be of stainless steel rather than copper (or other such materials) because the latter might melt into and contaminate the weld.

Heliarc inert-gas welding is, in general, a satisfactory process. Although it has many of the advantages of the automatic processes, it does have the disadvantage of "spitting" of tungsten from the tungsten electrode into the weld when the arc is initiated and when the arc is discontinued; these exposed tungsten deposits will cause decomposition of the hydrogen peroxide. The tungsten "spitting" may be decreased and, in many cases, eliminated by using a pure tungsten electrode, striking the arc on a separate piece of material and carrying the weld into the work, and then discontinuing the arc on a separate piece. For inert-gas welding, where the welding rod is not coated, it is recommended that strips be cut off the work scrap and used as the welding rod. Stainless-steel electrode tip cups should be used,

The weld resulting from the metal-arc process has two disadvantages: (1) porosity, and (2) brittleness. These characteristics are highly undesirable in hydrogen peroxide systems, and for this reason, the inert-gas processes are usually preferred and recommended. The metal-arc process can be used, however, for structural aluminum welding (such as tank supports or ramps,) and is quite suitable for this purpose.

Oxyacetylene gas welding also has two undesirable features (for hydrogen peroxide system welds) when compared to the inert-arc processes. These are: (1) the excessive heat required causes warpage, and (2) the flux tends to be trapped in the weld. However, the welds are satisfactory from a strength point of view and, if the noted disadvantages can be tolerated, this process is acceptable. Oxyacetylene gas welding has been utilized for pipe and small parts made of aluminum when highly skilled and experienced welders are available. Thin sections can be welded more satisfactorily with this type of welding. Napolitan welding flux or its equivalent is recommended for use in gas welding.

4.4.3.2.2 Stainless Steel. Inert-gas and metal arc-welding processes are satisfactory in the welding of stainless steel for hydrogen peroxide systems. The inert-gas process is preferred because the inert-gas blanket results in a weld with less foreign material. In general, thoriated tungsten electrodes are used. Standard welding procedures should be used for both of these processes, and it is necessary that all welds be of high quality, smooth, homogeneous, and free of inclusions and blowholes. Carbide precipitation during welding must be avoided by the use of stabilized alloys such as 347 or 321 or the extra low-carbon alloys, 304 or 316.

After a weld is completed, all weld scale should be removed with a 300 series stainless-steel brush, and the inner weld surface should be ground with a white aloxide wheel to a maximum 32 rms finish.

Any installation of a flange or discharge pipe at the low point of a hydrogen peroxide tank should be welded from the tank interior and ground smooth prior to welding the bottom closure in place.

> NOTE: A carborundum wheel should not be used for grinding, or else iron will be deposited in the metal surface.

A narrow and thin stainless-steel backing ring should be installed at the weld placement in vertical tanks.

Polishing of stainless steels following welding is generally unnecessary but, for certain borderline cases, it may improve the compatibility of the metal with the hydrogen peroxide by smoothing the surface. In general, the smoother surface will provide a lower rate of hydrogen peroxide decomposition. For mechanical polishing, a wet or dry paper (aluminum oxide abrasive) with a kerosene lubricant can be used.

Electropolishing of stainless steel has also been effective in improving the compatibility of steel for hydrogen peroxide service. For routine hydrogen peroxide applications, electropolishing is not required because stainless steel is usually only applied in limited contact time service. For special applications, electropolishing of stainless steel might be justified, and in such cases, standard electropolishing techniques should be used.

4.4.3.3 Brazing and Soldering. Brazing and soldering techniques are not recommended for application in hydrogen peroxide systems. The joints produced by these methods are usually incompatible with the propellant.

4.4.3.4 Mechanical Joints. The advantages of relatively leak-free all-welded transfer systems are obvious. From a practical standpoint, however, some type of joint, whether flanged or otherwise, is required to provide adequate system flexibility. Small valves and components should be selected with AN flared-type connections. Large valves and components should be selected with flanged connections. Instrumentation connections should be of the AN type, and can be provided by welding boss fittings on large pipelines or by installing tee fittings on small lines.

4.4.3.5 Inspection. In the construction, installation, and modification of hydrogen peroxide systems, inspection is important to ensure quality of materials; adherence to design specifications; and proper fabrication techniques. Before installation, each piece of equipment, such as pumps, flex joints, valves, filters, etc., will be inspected and tested for:

1. Cleanliness
2. Proper lubricants (if allowable)
3. Leakage, internal and external
4. Pressure-proof test
5. Sealant and gasket materials
6. Proper operation
7. Freedom from defects
8. Adherence to applicable specifications--type, size, rating, dimensions, etc.

Piping and tubing sections will be inspected and tested for:

1. Conformance to design specifications and building codes
2. Identity and quality of materials of construction
3. Adequacy of supports; freedom from "cold spring"
4. Cleanliness

5. Proper fabrication workmanship

6. Proof-pressure and leak tests

7 Proper installation of flex joints

Electrical installations and equipment will be inspected and tested for:

1. Conformance to design specifications and applicable codes

2. Adequate grounding

3. Insulation resistance

4. Circuitry continuity and proper termination

5. Workmanship and fabrication technique

6. Proper support of conduits and wiring

Instruments (flowmeters, gages,transducers, etc.) will be shop tested, and calibrated and certified with due regard to using conditions, fluid density, operating range, material identity, repeatability, and sealing capability. These instruments must be inspected for cleanliness prior to installation.

Roads, buildings, structures, etc., should be inspected for conformance to design specifications and building codes.

4.4.3.6 Hydrostatic and/or Pneumatic Tests. All components and tanks to be placed in hydrogen peroxide service should undergo applicable hydrostatic and/or pneumatic proof testing before they are cleaned and passivated.

NOTE: Hydrostatic testing should be conducted with water.

After passivation, all proof and leak testing should be conducted only with deionized or distilled water, or with clean, filtered, hydrocarbon-free nitrogen gas or air.

## 4.5 DECONTAMINATION AND DISPOSAL

The initial step in the decontamination of equipment or facilities and subsequent disposal of hydrogen peroxide is its dilution with large quantities of water. All facilities which store and handle hydrogen peroxide should be equipped with an adequate water supply to ensure a maximum dilution of the hydrogen peroxide prior to its flush into the facility drainage system. Normally, dilution to 3 w/o $H_2O_2$ or less should be completed before the hydrogen peroxide solution is dumped or pumped into the drainage system (which should terminate in a large body of water). Further dilution is required before dumping into a public water table. Under no circumstances should hydrogen peroxide be dumped into sewers or drains that lead to public water tables, unless this maximum dilution has been performed at the originating site.

### 4.5.1 Equipment Decontamination

Equipment being removed from service, temporarily flushed of residual propellant, and/or being decontaminated of possible impurities, is normally flushed with distilled or deionized water. Emergency decontaminations may use water supplied by the normal facility water or "firex" (fire-fighting equipment) systems. Once flushed from the equipment, the hydrogen peroxide should be diluted further with facility or "firex" water.

### 4.5.2 Facility Decontamination

The decontamination of gross spillage or leakage at a facility is best accomplished through the use of a facility floor flush or a flooding water spray system. Large-volume fire hoses may be used as a substitute technique, but the method of attack should preclude washing concentrated hydrogen peroxide solutions into the drainage system ahead of the dilution water. Ordinary garden-type hoses can be used for small spills or for rinsing hydrogen peroxide from the outside of equipment.

> CAUTION: Unless an emergency exists (and massive water spray of equipment is required), care should be taken in flushing the outside of the equipment to prevent water damage to the attendant electrical and control systems.

All facility flushing should be thorough and can be conducted with normal facility water.

### 4.5.3 Drainage

All hydrogen peroxide facility drainage ditches (or other spillage catch basins) should be open and lined with impervious acid-resistant concrete. These ditches and catch basins should be kept clean of debris and combustible material. The use of the hydrogen peroxide drainage system for other chemical dumps should be prohibited unless an adequate water flow is maintained to ensure maximum dilution and drainage system flushing of all chemicals. The main drainage ditch should be supplied with a large water flush outlet at the highest point of hydrogen peroxide drainage and should be fenced from the facility to the catch basin. The design of the facility should be such that all areas are adequately drained by gravity into the main drainage system.

### 4.5.4 Catch Basins

Because hydrogen peroxide dumping into public water tables can be potentially hazardous if it has not been sufficiently diluted, most facilities utilize a catch basin which either stores the water for facility recirculation or acts as a settling or dilution pond prior to drainage into a public water table. In either situation, the hydrogen peroxide is diluted or reacted further with other chemicals (contained in the catch basin) to form water solutions that are nontoxic.

### 4.5.5 Final Dilution Requirements

Although local, state, and federal codes are not sufficiently clear with respect to regulation of hydrogen peroxide dumping into public streams, lakes, etc., it has been generally accepted that dilution to less than 3 w/o $H_2O_2$ concentration is required to ensure human safety.

In a bioassay study conducted by the Academy of Natural Sciences of Philadelphia for E. I. duPont de Nemours and Co. (Ref. 4.67), a concentration of 165 ppm $H_2O_2$ in water at ~70 F (with a dissolved oxygen content of 5 to 9 ppm) resulted in a 100-percent mortality rate of fish (4 to 10 centimeters long) of the Lepomis macrochirus Raf. (bluegill) species, which had been exposed to the contaminated water for a period of 24 hours. The resulting 24-hour $TL_m$ (maximum threshold limit) for these species was 65 ppm at a solution pH of 7 and 90 ppm at a solution pH of 8.5.

Internal regulations used by the Rocketdyne Division of North American Aviation, Inc., have established a maximum concentration of 100 ppm $H_2O_2$ for water dumped into public water tables; these regulations have been accepted by local, state, and federal authorities.

## 4.6 REFERENCES

4.1 Shell Development Company, Emeryville, California, Concentrated Storable Hydrogen Peroxide, Report No. S-13974, Report period: May 1964 - August 1965, Contract DA-04-200-AMC-569(Z).

4.2 McCormick, James C., F.M.C. Corporation, Buffalo, New York, Hydrogen Peroxide Rocket Manual, 1965.

4.3 Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide - Physical and Chemical Properties," Ind. Eng. Chem., 39, 1536-43(1947).

4.4 LTV Astronautics Division, Dallas, Texas, Peroxide Contamination Study, Final Summary Report, Report No. ER 23.210, 30 April 1965.

4.5 Roth, E. M., Jr., and E. S. Shanley, "Stability of Pure Hydrogen Peroxide," Ind. Eng. Chem., 45, 2343-9 (1953).

4.6 E. I. DuPont de Nemours and Co., Inc., Wilmington, Delaware, Final Report, Research on the Stability of High Strength $H_2O_2$, Report No. AFRPL-TR-66-13, 15 March 1966, Contract AF04(611)-10216.

4.7 F.M.C. Corporation, Buffalo, New York, Storage of 90% and 98% by Weight Hydrogen Peroxide in Sealed Containers for Extended Periods, Report No. SSD-TR-61-29, September 1961, Contract AF04(611)-6342.

4.8 Shell Development Company, Emeryville, California, Storable Concentrated Hydrogen Peroxide, Report No. AFRPL-TR-66-207, Report period: March - May 1966, Contract AF04(611)-11416.

4.9 Shell Development Company, Emeryville, California, *Storable Concentrated Hydrogen Peroxide*, Report No. AFRPL-TR-66-262, Report period: June - August 1966, Contract AF04(611)-11416.

4.10 LTV Astronautics Division, Dallas, Texas, "Relationship of Active Oxygen Loss (AOL) and Surface To Volume Ratio of Materials in Contact with Concentrated Hydrogen Peroxide, Report No. 3-52100-0043-TR, 23 July 1965.

4.11 LTV Astronautics Division, Dallas, Texas, "Effects of Dissimilar Metals on the Stability of Concentrated Hydrogen Peroxide," Report No. LR-3-52100-0039, 30 July 1965.

4.12 LTV Astronautics Division, Dallas, Texas, "Compatibility of Various Materials with 90% Hydrogen Peroxide at 40°F and 75°F for 10 Days," Report No. 3-52100-0011, 17 December 1964.

4.13 LTV Astronautics Division, Dallas, Texas, "Establishment of Effective Lifetime of Hydrogen Peroxide Passivated Systems," Report No. LR-3-52100-0047, 28 April 1965

4.14 LTV Astronautics Division, Dallas, Texas, "Evaluation of the Influence of Surface Finish of Materials on the Stability of Concentrated Hydrogen Peroxide," Report No. 3-52100-0049, 26 March 1965.

4.15 LTV Astronautics Division, Dallas, Texas, "Verification of the Classification of Materials Used in the Scout Vehicle Hydrogen Peroxide System," Report No. LR-23-TR-0005, 30 April 1965.

4.16 LTV Astronautics Division, Dallas, Texas, "Compatibility of Various Bladder Materials with Concentrated Hydrogen Peroxide and 6061 Aluminum at 160°F," Report No. 3-52100-0041, 5 February 1965.

4.17 LTV Astronautics Division, Dallas, Texas, "Hydrogen Peroxide Compatibility Evaluation of Three Candidate Expulsion Bladder Materials," Report No. TR-3-52100-0038, January 1965.

4.18 LTV Astronautics Division, Dallas, Texas, "Evaluation of 316L and 321 Stainless Steel Tubing for Service in Hydrogen Peroxide Systems," Report No. TR-3-52100-0037, February 1965.

4.19 Explosives Research and Development Establishment, Waltham Abbey, England, *The Behaviour of Stannic Acid Sols in Concentrated Hydrogen Peroxide, Part 4. Quantitative Evaluation of the Precipitating Efficiency of Aluminum Ions*, Report No. 25/R/63, November 1963.

4.20 Lewis, T. J. and T. M. Walters, "The Behaviour of Stannic Acid Sols in Concentrated Hydrogen Peroxide. I. Factors Affecting the Stability of Stannic Acid Sols in Concentrated Hydrogen Peroxide," *J. Appl. Chem.*, *10*, 396-403 (1960).

4.21 LTV Astronautics Division, Dallas, Texas, *Effects of Elemental Ions on The Stability of Concentrated Hydrogen Peroxide*, Report No. LR-3-52100-0044, 30 April 1965.

4.22 United States Naval Underwater Ordnance Station, Newport, Rhode Island, *Condition for Self-Heating of Exothermally Decomposing Liquids (e.g. Hydrogen Peroxide)*, Technical Memo 227, January 1960.

4.23 United States Department of the Navy, Bureau of Aeronautics, *Handbook for Field Handling of Concentrated Hydrogen Peroxide (over 52 w/o $H_2O_2$)*, Report No. NavAer 06-25-501, January 1957.

4.24 United States Government, Office of the Director of Defense Research and Engineering, Washington, D.C., *The Handling and Storage of Liquid Propellants*, January 1963.

4.25 F.M.C. Corporation, New York, New York, *Materials of ConStruction for Equipment in Use with Hydrogen Peroxide*, BECCO Bulletin 104, 1966 Revision.

4.26 Shell Development Company, Emeryville, California, Shell Analytical Methods for Hydrogen Peroxide, SMS 705/58, 1958.

4.27 Military Specification, Propellant, Hydrogen Peroxide, Mil-P-16005D, 18 March 1965.

4.28 Private communication, S Long, Bell Aerosystems, Buffalo, New York, to M. T. Constantine, Rocketdyne, Canoga Park, California, December 1966.

4.29 Aerojet-General Corporation, Sacramento, California, Final Report, Advanced Propellant Staged Combustion Feasibility Program, Phase I, Parts 1 and 2, Report No. AFRPL-TR-66-6, April 1966, Contract AF04(611)-10785, CONFIDENTIAL.

4.30 The Battelle Memorial Institute, Columbus, Ohio, Compatibility of Rocket Propellants with Materials of Construction, Defense Metals Information Center Memo 201, January 1965.

4.31 U. S. Department of the Navy, Bureau of Aeronautics, Field Handling of Concentrated Hydrogen Peroxide (over 52 w/o), Report No. NavAer 06-25-501, January 1957.

4.32 Private Communication, U. M. Robinson, LTV Astronautics Division, Dallas, Texas, to M. T. Constantine, Rocketdyne, Canoga Park, California, January 1967.

4.33 Fisch, K. R., L. Peale, J. Messina, and H. Gisser, "Compatibility of Lubricants with Missile Fuels and Oxidizers," ASLE Transactions, 5, 287-96 (1962).

4.34 LTV Astronautics Division, Dallas, Texas, "Preparation of Metallic Surface for Exposure to Concentrated Hydrogen Peroxide," CVA 10-62a Specification.

4.35 North American Aviation, Inc., El Segundo, California, "Process Specification, Processing of Hydrogen Peroxide System Components and Assemblies," No. IA0110-003, April 1961.

4.36 Walter Kidde and Company, Inc., Belleville, New Jersey, Specification No. 520007, as given by Ref. 4.26.

4.37 McDonnell Aircraft Company, St. Louis, Missouri, Specification A/C 13002, no reference located; see Tables 4.21, 4.23, 4.26, and 4.29.

4.38 LTV Astronautics Division, Dallas, Texas, LTV Specification 308-20-3, as given by Ref. 4.13.

4.39 LTV Astronautics Division, Dallas, Texas, "Preparation of Non-Metallic Surfaces for Exposure to Concentrated Hydrogen Peroxide," CVA 10-64a Specification.

4.40 Shell Chemical Company, New York, New York, *Concentrated Hydrogen Peroxide. 2nd Ed. Properties, Uses, Storage, Handling*, Report No. SC: 62-23, 1962.

4.41 Liquid Propulsion Information Agency, *Liquid Propellant Manual*, "Hydrogen Peroxide," 1958.

4.42 The Battelle Memorial Institute, Columbus, Ohio, *Liquid Propellants Handbook*, "Hydrogen Peroxide," Vol. 1, 1958, CONFIDENTIAL.

4.23 Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, *Review of Materials Compatible with Hydrogen Peroxide*, Report No. R-755.

4.44 Private communication, W. C. DeKleine, F.M.C. Corporation, Princeton, New Jersey, to J. C. McCormick, F.M.C. Corporation, Buffalo, New York, 11 January 1967.

4.45 Bell Aerosystems Company, Buffalo, New York, *Compilation of Materials Compatibility Test Data with Propellants*, Report No. 2084-939-001, Contract AF33(657)-8555, December 1962.

4.46 Bellinger, F., H. B. Friedman, W. H. Bauer, J. W. Eastes, and W. C. Bull, "Corrosion and Stability Studies," *Ind. Eng. Chem.*, *38*, 310-20-(1946).

4.47 F.M.C. Corporation, New York, New York, *Final Report, Hydrogen Peroxide: Catalytic Decomposition, Compatibility Materials at High Temperature*, and *Surveillance Devices*, Report No. 224-17, Contract NOas 58-689c.

4.48 Aerojet-General Corporation, Sacramento, California, *Compatibility of O-Ring Materials with 90% $H_2O_2$*, Materials Section Report No. 1847, as given by Ref. 4.29.

4.49 Monsanto Research Corporation, Dayton, Ohio, *Evaluation of Elastomers as O-Ring Seals for Liquid Rocket Fuel and Oxidizer Systems*, Report No. ASD-TDR-63-496, Contract AF33(616)-8483, September 1963.

4.50 McDonnell Aircraft Corporation, St. Louis, Missouri, *Evaluation of "O" Rings for Compatibility with 90 Percent Hydrogen Peroxide at 150°F*, Report No. A752, June 1964.

4.51 Explosives Research and Development Establishment, Waltham Abbey, England, *The Sensitiveness of Fluorocarbon Lubricant/HTP Mixtures*, E.R.D.E. Tech Memo 16/M/52, October 1952, CONFIDENTIAL.

4.52 Department of Defense, *Quantity-Distance Storage Criteria for Liquid Propellants*, Instruction 4145.21, 26 May 1964.

4.53 Naval Ordnance Laboratory, White Oak, Maryland, Report NOLTR 63-12.

4.54 United States Department of the Army, *Ordnance Safety Manual*, Report No. ORD M7-244.

4.55 *ASME Boiler and Pressure Vessel Code*, Section VIII, "Rules for Construction of Unfired Pressure Vessels," latest edition.

4.56 Shanley, E. S., "Self Heating of Hydrogen Peroxide Storage Vessels," *Ind. Eng. Chem.*, *45*, 1520-4 (1953).

4.57 *American Standard Code for Pressure Piping*, ASA B31.1, 1955 Edition.

4.58 Crocker, Sabin, *Piping Handbook*, McGraw-Hill Book Company, New York, New York.

4.59 M. W. Kellogg Company, Jersey City, New Jersey, *Design of Piping Systems*, John Wiley & Sons, Inc., New York, New York.

4.60 Littleton, Charles T., *Industrial Piping*, McGraw-Hill Book Company, New York, New York.

4.61 The Grinnell Company, *Piping Design and Engineering*.

4.62 Crane Company, *Catalog No. 53*.

4.63 The Grinnell Company, *Catalog on Pipe Hangers and Supports*.

4.64 Shell Chemical Company, New York, New York, *Technical Bulletin, Study of Temperature Measuring Systems for High Strength Hydrogen Peroxide Storage*, Report No. IC:63-7, May 1963.

4.65 Manufacturing Chemists Association, Washington, D.C., *Supplement B, Chemical Safety Data Sheet SD 53*.

4.66 International Nickel Company, *Rapid Identification (Spot Testing) of Stone Metals and Alloys*.

4.67 Academy of Natural Sciences of Philadelphia, Department of Limnology, Philadelphia, Pennsylvania, *Bioassay Tests for the Engineering Department, E. I. duPont de Nemours and Company*, December 1962.

## TABLE 4.1

## STORAGE STABILITY OF HYDROGEN PEROXIDE(1)

| Concentration, weight percent $H_2O_2$ |  | Container Material | Storage Time, months | $O_2$ loss/year,(2) weight percent |
|---|---|---|---|---|
| Initial | Final |  |  |  |
| Unstabilized 90 w/o $H_2O_2$ (Stored(3) 1945-1948) |  |  |  |  |
| 90.5 | 88.6 | -(4) | 36 | 0.254 |
| 90.5 | 89.1 | - | 36 | 0.210 |
| 90.5 | 87.8 | - | 36 | 0.381 |
| 90.5 | 89.3 | - | 36 | 0.169 |
| 90.5 | 89.3 | - | 36 | 0.169 |
| 90.5 | 88.7 | - | 36 | 0.254 |
| Unstabilized 90 w/o $H_2O_2$ (Stored(3) 11/1954 to 12/1955) |  |  |  |  |
| 91.25 | 89.27 | 1060 Al | 13 | 0.60 |
| 90.72 | 90.56 | 1060 Al | 13 | 0.063 |
| 90.91 | 90.45 | 5652 Al | 13 | 0.425 |
| 88.13 | 87.54 | 5652 Al | 13 | 0.54 |
| 90.91 | 90.81 | 5254 Al | 13 | 0.039 |
| 90.61 | 90.17 | 5254 Al | 13 | 0.20 |
| Unstabilized 98 w/o $H_2O_2$ (Stored(3) 8/1960 to 5/1963) |  |  |  |  |
| 98.59 | 98.47 | -(4) | 33 | 0.021 |
| 98.14 | 97.64 | - | 33 | 0.088 |
| 98.8 | 98.31 | - | 33 | 0.086 |
| 98.59 | 98.28 | - | 33 | 0.054 |
| 98.8 | 98.36 | - | 33 | 0.077 |
| 98.14 | 97.79 | - | 33 | 0.061 |
| 98.8 | 98.34 | - | 33 | 0.098 |
| 98.14 | 97.43 | - | 33 | 0.125 |
| Stabilized Torpedo-Grade $H_2O_2$ (Storage(3) Completed 8/1962) |  |  |  |  |
| 90 | 88.51 | 1060 Al | 62 | 0.12 |
| 90 | 86.75 | 1060 Al | 63 | 0.26 |
| 70 | 68.32 | 1060 Al | 76 | 0.088 |

(1) Data taken from Ref. 4.2

(2) $O_2$ loss/year does not correspond with concentration change

(3) Ambient storage in 30-gallon drum (S/V = 0.38 in.$^{-1}$)

(4) Drum material unknown; assumed to be aluminum alloy

## TABLE 4.2

## A COMPARISON OF THE RATE OF DECOMPOSITION OF 90 w/o HYDROGEN PEROXIDE MANUFACTURED IN 1947, 1953, AND 1965(1)

| Effect of Temperature | | | |
|---|---|---|---|
| Temperature, F | Rate of Decomposition (AOL) | | |
| | 1947(2) | 1953(3) | 1965(4) |
| 86 | 1% per year | 0.5 to 1.0% per year | 0.02 to 0.01% per year |
| 151 | 1% per week | 10% per year | 0.1% per year |
| 212 | 2% per day | 4% per week | 1% per year |

| Effect of Contamination | | |
|---|---|---|
| Additive to 90 w/o $H_2O_2$ | Decomposition Rate at 212 F | |
| | 1947(2) | 1965(5) |
| None | 2% per day | 1% per day |
| Al 10 mg/liter | 2% per day | - |
| Cr 0.1 mg/liter | 96% per day | 2% per day |
| Cu 0.01 mg/liter | 24% per day | 10% per day |
| Cu 0.1 mg/liter | 85% per day | 66% per day |
| Fe 1.0 mg/liter | 15% per day | 25% per day |
| Zn 10 mg/liter | 10% per day | - |
| Sn 10 mg/liter | 2% per day | - |

(1) Data reported as generalized criteria from tests using assorted test parameters and techniques; data generally represent tests under minimum S/V conditions.

(2) Data reported in Ref. 4.3

(3) Data reported for 99+ w/o $H_2O_2$ in borosilicate glass containers (Ref. 4.5)

(4) Data reported in Ref. 4.1

(5) Data reported in Ref. 4.4

TABLE 4.3

CRITERIA FOR CLASSIFICATION OF MATERIALS FOR HYDROGEN PEROXIDE SERVICE ON THE BASIS OF LABORATORY TESTS (REF. 4.25)

| Class | Material | Maximum Amount of AOL Week | | Minimum Stabilization of $H_2O_2$ After Test, percent | Other Observations |
|---|---|---|---|---|---|
| | | 86 F | 150 F | | |
| 1 | Metals | 0.2 | 5.0 | 95 | No other effect on $H_2O_2$ or material and non-impact sensitive to 3 kg-meter impact at 212 F |
| 1 | Bladder Material (plastics for diaphragms, drums and liners) | 0.2 | 5.0 | 95 | ↓ |
| | Plastics for Gaskets, Tubing, O-rings, etc. | 0.4 | 6.0 | 95 | ↓ |
| 1 | Oil and Greases | 1.0 | 10.0 | 95 | ↓ |
| 2 | Metals (stainless steel) | 6.0 | 80.0 | 90 | No other effect on $H_2O_2$; slight bronzing of the metal allowable, but no corrosion |
| 2 | Plastics for O-rings and Expulsion Devices | 6.0 | 80.0 | 90 | No other effect on $H_2O_2$; slight bleaching, swelling, embrittlement, or occasional blistering accepted; non-impact sensitive to 3 kg-meter impact at 212 F |
| 2 | Elastomers (bladder material) | 6.5 | 95.0 | 90 | No other effect on $H_2O_2$; slight beaching, or loss of small amount of elasticity of the material accepted; non-impact sensitive to 3 kg-meter impact at 212 F |
| 2 | Oils and Greases | 6.0 | 80.0 | 90 | No other effect on $H_2O_2$; non-impact sensitive to 3 kg-meter impact at 212 F |

TABLE 4.3

(Concluded)

| Class | Material | Maximum Amount of AOL/Week | | Minimum Stabilization of $H_2O_2$ After Test, percent | Other Observations |
|---|---|---|---|---|---|
| | | 86 F | 150 F | | |
| 3 | Metals | 11.0 | 100/24 hours | 15(1) | Bronzing and staining, but not rusting or other corrosion products; slight attack may be allowed |
| 3 | Plastics | 11.0 | 100/24 hours | 15(1) | May become partially bleached, distorted, disintegrated, after 1 week of test; non-impact sensitive to 3 kg-meter impact at 212 F |
| 3 | Elastomers | 11.0 | 100/24 hours | 15(1) | Surface may be embrittled, bleached, blistered or lose elasticity; non-impact sensitive to 3 kg-meter impact at 212 F |
| 3 | Oils and Greases | 11.0 | 100/24 hours | 15(1) | Non-impact sensitive to 3 kg-meter impact at 212 F; excessive $H_2O_2$ decomposition approaching catalytic rate |
| 4 | Metals | | | | Metals pitted and corroded during or after test |
| | Plastics | | | | Plastics disintegrated, burned, blistered |
| | Elastomers | | | | Elastomers burned, swollen, dissolved, disintegrated, blistered, gummy; loss of elasticity |
| | Oils and Greases | | | | Oils and Greases melted, disintegrated, burned; any material which is impact sensitive to 3 kg-meter impact at 212 F |

(1) The stability of the $H_2O_2$ after exposure to the material.

TABLE 4.4

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH ALUMINUM ALLOYS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent(2) Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| **Cast** | | | | | | | | |
| 13(11) | | 90 | 4 | — | — | — | | |
| 40E | O.P.W. Corp. (Kam Lok) | 90 | 2 | — | 2 | 95.4 | None(3) | Used successfully as pump impeller and quick disconnect |
| 40E | Frontier Bronze | 90 | 4 | — | 100 | 0 | None | |
| 43 | Alcoa | 90 | 2 | — | 17.8 | — | None | |
| 42B(12) | — | 90 | 4 | — | — | — | | |
| 53B(11) | — | 90 | 4 | — | — | — | | |
| 150 | Kaiser | 90 | 2 | — | 28.7 | — | None | Limited use |
| 150S(11) | — | 90 | 2 | — | — | — | None | |
| 214(11) | — | 90 | 4 | — | — | — | | |
| 214B | Alcoa | 90 | 2 | — | 50.0 | — | Stained | Not recommended |
| 214F | Alcoa | 90 | 2 | — | 39.5 | — | None | Not recommended |
| R214F | Alcoa | 90 | 3 | — | 96.4 | — | | Not recommended |
| 218 | — | 90 | 4 | — | 100.0 | 0 | Corroded | Not recommended |
| 355(11) | — | 90 | 2 | — | — | — | | |
| 355 | — | 98 | 3 | — | 100.0 | — | None | |
| 355F | Alcoa | 90 | 4 | — | 100.0 | 0 | None | Not recommended |
| 356F | Alcoa | 90 | 2 | — | 50.0 | — | None | Not recommended |
| B356 | Alcoa | 90 | 1 | — | 2.8 | 98.0 | None | Pumps, valves, housings |
| B356 | — | 98 | 1 | — | 3.9 | 98.0 | None | For coating use |
| A360 | Alcoa | 90 | 3 | — | 96.8 | — | None | Not recommended |
| 750 | Alcoa | 90 | 4 | — | 100.0 | — | None | Not recommended |
| A750 | Alcoa | 90 | 4 | — | 100/3 days | — | None | Not recommended |
| B750 | Alcoa | 90 | 4 | — | 100/3 days | — | None | Not recommended |
| **Wrought** | | | | | | | | |
| 1060 | Alcoa | 90 | 1 | 0.3 | 1.5 | 98.8 | None | Storage tanks, piping |
| 1060 (99.6) | Alcoa | 98 | 1 | — | 1.5 | 98.0 | None | Storage tanks |
| 1100 (2S) | Alcoa | 90 | 1(4) | 0.4 | 3.0 | — | None | Storage tanks, piping |
| 1160 | Alcoa | 90 | 1 | 0.4 | 1.5 | 98.9 | None | Storage tanks, piping |
| 1160 | Alcoa | 98 | 1 | — | 1.5 | 98.0 | None | Storage tanks |

## TABLE 4.4
## (Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent(2) Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| **Wrought** | | | | | | | | |
| 1260 | Alcoa | 90 | 1 | — | 1.5 | 98.8 | None | Storage tanks, piping |
| 1260 | Alcoa | 98 | 1 | — | 2.1(5) | 98.0 | None | Storage tanks |
| 1260 | Alcoa | 98 | 1 | — | 1.2(6) | 98.0 | None | Storage tanks |
| 1260, Pretreated(7, 13) | Alcoa | 90 | 1 | — | 0.7 to 0.8(7) | — | None | Storage vessels, piping |
| 1260, Pretreated(8, 13) | Alcoa | 90 | 1 | — | 2.5(7) | — | None | Storage vessels, piping |
| 1360(10) | | | 1 | — | | | | |
| 2014 (14S) | — | 90 | 4 | — | 100.0 | — | None | Not recommended |
| 2017 (17S) | Alcoa | 90 | 4 | — | 100.0 | — | None | Not recommended |
| 2017, $H_2SO_4$ Anodized | Alcoa | 90 | 3 | — | 23.3 | — | None | Limited service life (1 to 2 years) |
| 2024 (24S) | Colonial Alloys | 90 | 3 | — | 16.4 | — | None | Not recommended |
| 2024 (24S) | | 98 | 4 | — | 100.0 | — | None | Not recommended |
| 2024, Hardas Coated | Anachrome | 90 | 3 | — | 20.6 | 50.3 | Coating dissolved in spots | Not recommended |
| 2024, Chromic Acid, Anodized | Colonial Alloys | 90 | 4 | — | 100.0 | — | None | $H_2SO_4$ anodized is better |
| 2024, $H_2SO_4$ Anodized | Alcoa | 90 | 3 | — | 15.0 | — | None | Limited service life |
| 3003 (3S) | Alcoa | 90 | 2 | — | 13.8 | 94.4 | None | Various uses, piping |
| 4043 (43S) | Alcoa | 90 | 2 | — | 52.0 | 98.8 | None | Not recommended |
| 5052 (52S) | Alcoa | 90 | 2 | — | 8.3 | — | None | Tubing, pipe |
| 5052 (52S) | | 98 | 1 | | 2.6 | — | None | Storage vessels |
| 5052, Chromic Acid Anodized | Colonial Alloys | 90 | 2 | — | 11.0 | — | None | $H_2SO_4$ anodized is better |
| 5052, $H_2SO_4$ Anodized | Alcoa | 90 | 2 | — | 5.0 | — | None | Limited service life (1 to 2 years) |
| 5054 (54S) | Alcoa | 90 | 2 | — | — | — | None | Tubing, pipe |
| 5056 (56S) | Alcoa | 90 | 2 | 1.5 | 13.1 | — | None | Tubing, pipe |
| 5058 | — | 90 | 2 | — | — | — | None | — |
| 5086(9) | — | 90 | 2 | — | — | — | None | — |
| 5254 (XP54S) | Alcoa | 90 | 1(3) | — | 0.3 | 98.0 | None | Storage tanks, piping |
| 5254 | Alcoa | 98 | 1 | — | 1.7 | 99.0 | None | Storage tanks, missile tankage |
| 5254-0 | Alcoa | 90 | 1 | — | 0.3 | 98.0 | None | Storage tanks, piping components |

## TABLE 4.4

## (Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability After Test[(2)] | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| **Wrought** | | | | | | | | |
| 5254-H34 | Alcoa | 90 | 1 | — | 0.3 | 98.0 | None | Storage tanks, piping |
| 5652 (XF525)(9) | | 90 | 1 | — | — | — | None | — |
| 5652-0(13) | Alcoa | 90 | 1(3) | — | 5.0 | 98.4 | None | Storage tanks, components |
| 5652-0 | Alcoa | 98 | 1(3) | — | 5.2 | 98.4 | None | Storage vessels |
| 6061 (61S) | Alcoa | 90 | 2 | — | 4.8 | 98.7 | None(3) | Subject to corrosion |
| 6061 | — | 98 | 2 | — | 5.2 | — | Pitted | |
| 6061, Chromic Acid Anodized | Colonial Alloys | 90 | 3 | — | 15.5 | — | None | $H_2SO_4$ anodized is better |
| 6061, $H_2SO_4$ Anodized | Alcoa | 90 | 2 | 1.3 | 4.1 | — | None | Limited service life (1 to 2 years) |
| 4% $HNO_3$ Passivated | Alcoa (Keystone Chromium) | 90 | 2 | — | 2.4 | 89.4 | None | Limited service life (1 to 2 years) |
| Detergent Washed | (Keystone Chromium) | 90 | 2 | — | 4.5 | 90.8 | None | Limited service life (1 to 2 years) |
| WFNA Passivated | (Keystone Chromium) | 90 | 2 | — | 3.6 | 87.2 | None | Limited service life (1 to 2 years) |
| Hard Coat | Woodward-Governor | 90 | 3 | — | 42.0 | — | None | Coatings |
| 0.001 Inch Thick | Stolle Corp. | 90 | 3 | — | 23.2 | 64.2 | None | Must be checked before using |
| 0.002 Inch Thick | Stolle Corp. | 90 | 3 | — | 24.7 | 69.8 | None | Must be checked before using |
| 0.003 Inch Thick | Stolle Corp. | 90 | 3 | — | 26.5 | 52.3 | None | Must be checked before using |
| 6063 (63S)(9) | Reynolds | 90 | 2 | | | | | |
| Sheet | Reynolds | 90 | 1 | — | 1.7 | 98.0 | Dulls finish | Pipe and other items |
| Tubing | Reynolds | 90 | 1 | — | 3.3 | 97.4 | Slight dulling | Pipe and tubing |
| Hard Coat (Sanford) | Reynolds | 90 | 2 | — | 3.1 | 98.0 | Bleaching, spotting | Needs further checking |
| 6063(14) | — | 90 | - | 1.6 | 2.9 | 97.8 | — | — |

## TABLE 4.4
## (Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week At 151 F | Percent[2] Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| **Wrought** | | | | | | | | |
| 6363 | Alcoa | 90 | 2 | — | 7.6 | 96.2 | None | Various uses |
| 7072 (72S) | Alcoa | 90 | 1[4] | — | 2.1 | — | None | Cladding material |
| 7072 (72S) | Alcoa | 98 | 1 | — | 4.1 | — | None | Storage vessels |
| 7075 (75S) | Kaiser | 90 | 4 | — | 100.0 | 0 | None | Not recommended |

(1) Data taken from Ref. 4.25 unless otherwise noted

(2) Stability essentially defined as (100 - AOL) percent from test of 24 hours at 212 F

(3) Field experience shows this alloy to be subject to corrosion if not protected by anodizing

(4) Previously considered Class 2 (Ref. 4.40)

(5) Test temperature 74 C (165 F)/week, pretreated 90 w/o $H_2O_2$ 24 hours at 66 C (151 F)

(6) Test temperature 74 C (165 F)/week, pretreated with Alcoa treating solution No. 1 48 hours at room temperature

(7) Sample preheated with 90 w/o $H_2O_2$ for 24 hours at 66 C (151 F)

(8) Test temperature 74 C (165 F)

(9) Reference 4.40

(10) Reference 4.41

(11) Reference 4.42

(12) Reference 4.43

(13) Reference 4.29

(14) Reference 4.44

## TABLE 4.5

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH STAINLESS STEEL ALLOYS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability(2) After Test | Effect on Material | Comments |
|---|---|---|---|---|---|---|---|---|
| 202 | Brace Mueller | 90 | 2 | — | 19.0 | — | Bronzed | Machined parts |
| 301 | Portland Copper and Tank Works | 90 | 3 | — | 20.0 | 57 | Slight stain | Machined parts, end-use components |
| 301 | Arde Portland Corp. | 98 | 2 | — | 8.7 | 95 | Bronzed | High-pressure tankage |
| 301 (cryogenically prestrained) | Arde Portland Corp. | 90 | 2 | — | 4.2 | 94 | Slight stain | High-pressure tankage, 260,000 psi yield |
| 302 | Whitehead | 90 | 2 | — | 21.0 | 89.0 | Bronzed | Machined parts, tubing |
| 302 | Various suppliers | 98 | 2 | Excellent service record | | — | — | Machined parts, tubing |
| 302 (porous) | | 90 | 3 | — | — | — | Bronzed | |
| 303 C | Allegheny-Ludlum | 90 | 3 | — | 98.9 | — | Heavily bronzed | Not recommended |
| 304 | Allegheny-Ludlum | 90 | 2 | — | 40.0 | 77(3) | Bronzed | Machine parts, tubing |
| 304 | Allegheny-Ludlum | 98 | 2 | — | 12.0 | — | Slight bronzing at higher temperatures | Tubing, machined parts |
| 304 (extra low carbon) | Allegheny-Ludlum | 90 | 2 | — | 58.6 | — | Bronzed | Test tanks, machined tanks |
| 309 | Carnegie | 90 | 2 | — | 54.2 | — | Bronzed | Machined parts |
| 310 | Carnegie | 90 | 2 | — | 37.1 | — | Bronzed | High-acid tank, $H_2O_2$ component baths |
| 316 | Republic | 90 | 2 | — | 19.8 | — | Bronzed | Machined parts |
| 316 | Republic | 98 | 2 | — | 53.0 | — | Bronzed | Machined components |
| 316 (porous(7)) | | 90 | 4 | — | | | | |
| 316 (extra low carbon) | Armco Steel | 90 | 2 | — | 10.5 | — | — | Test vessels, machined parts |
| 317 | Allegheny-Ludlum | 90 | 2 | — | 36.0 | — | Bronzed | Machined parts; 302, 304, 316 preferred |
| 318 | Allegheny-Ludlum | 90 | 2 | — | 69.4 | — | Bronzed | Machined parts; 302, 304, 316 preferred |

## TABLE 4.5
(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability[(2)] After Test | Effect on Material | Comments |
|---|---|---|---|---|---|---|---|---|
| 319 | Union Steel Co. | 90 | 3 | 19.1 | 62.3 | — | Bronzed | Machined parts; 302, 304, 316 preferred |
| 319L | Union Steel Co. | 90 | 3 | 15.1 | 75.3 | — | Bronzed | Machined parts; 302, 304, 316 preferred |
| 321 | Carnegie | 90 | 2 | — | 37.0 | — | Bronzed | Test tanks, 347 preferred |
| 322 | Carnegie | 90 | 2 | — | 30.0 | — | Bronzed | Heat treatable; do not exceed 40 Rc(11) |
| 329 | Hydromatic, Inc. | 90 | 2 | — | 5.5 | — | Dull finish | 10 to 15 rms(12) finish, machined parts |
| 329 | Crane Valve Co. | 90 | 4 | — | 100 | — | Bronzed | Not recommended, rough finish |
| 329 | Crane Valve Co. | 98 | 3 | — | 30.0 | — | Bronzed | Machined components |
| 329 | Universal Cyclops | 90 | 2-3 | — | 100 | — | Bronzed | Rough finish |
| 347 | Carnegie | 90 | 2 | — | 57 | — | Bronzed | Gas generators; thrust motors |
| 347 | Various suppliers | 98 | 2 | Excellent service record | | — | — | Pressure vessels |
| 347 | Whitehead Metals | 98 | 2 | — | 13.2(4) | — | Slightly bronzed | Machined components |
| 347 | Whitehead Metals | 98 | 2 | — | — | 30.0 | Slight bronzing at high temperature for all samples | — |
| AM 350 (heat treat I) | Allegheny-Ludlum | 90 | 3 | — | 7.8 | 90 | Heavy bronzing | High-pressure vessels, 160,000 psi yield |
| AM 350 (heat treat II) | Allegheny-Ludlum | 90 | 4 | — | 14.6 | 31 | Very heavy bronzing | High-pressure vessels, Rc(11) above 42 |
| AM 355 | Allegheny-Ludlum | 90 | 3 | — | 74.9 | — | Bronzed | High-pressure vessels |
| 410 | Diesel Engineering | 90 | 4 | — | 91.4 | 16.6 | Rusted | To be avoided |
| 416 | Bendix | 90 | 4 | — | 100 | 0 | Rusted | To be avoided |
| 420 | Lee Co. | 90 | 4 | — | 100/18 hours | 0 | Rusted | To be avoided |
| 430 | Allegheny-Ludlum | 90 | 4 | — | 74.4 | 37.5 | Rusted | To be avoided |
| 431 | | 90 | 4 | — | 100 | 0 | Rusted | To be avoided |
| 440 | Bendix | 90 | 4 | — | 100/24 hours | 0 | Rusted | To be avoided |
| 440 C (56 to 58 Rc(11) 10 to 20 rms(12)) | Bendix | 90 | 3(5) | 2.5 | 100/13 hours | — | Slight bronzed | Refer to note (6) |

TABLE 4.5

(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability(2) after Test | Effect on Material | Comments |
|---|---|---|---|---|---|---|---|---|
| 440 C, Malcomized RC(11), 50 | Bendix | 90 | 3(5) | 5.2 | 100/48 hours | — | Slight stain | Refer to note (6) |
| 443 | | 90 | 4 | — | 100 | 0 | Rusted | To be avoided |
| 446 | Allegheny-Ludlum | 90 | 4 | — | 100 | 0 | Rusted | To be avoided |
| 613 (extra low carbon(8)) | | 90 | 2 | — | — | — | — | |
| 10-9 DL(10) | | 90 | 3 | — | — | — | — | |
| 17-4 PH(9) | Armco Steel | 90 | 3 | — | 90 to 100 | — | Heavily bronzed | Not recommended |
| 17-7 PH (unhardened) | Armco Steel | 90 | 2 | — | 43.0 | — | Bronzed | This alloy more suitable for use with lower than 90 percent $H_2O_2$ concentrations; high-pressure-system components. |
| 17-7 PH (37-45 RC 120-grit surface finish; special passivation) | Armco Steel | 90 | 2 | — | 20 | | Bronze in vapor phase and interface; very slight browning in liquid | ↓ |
| 17-7 PH (37-45 RC(11), 120-grit surface finish, buffed, special passivation) | Armco Steel | 90 | 2 | — | 22.0 | — | ↓ | ↓ |
| 17-7 PH (37-45 RC(11) welded, 120-grit surface finish; special passivation) | Armco Steel | 90 | 2 | — | 28.0 | — | ↓ | ↓ |
| 17-7 PH (45 RC(11), 120-grit surface finish, electro-polished) | Armco Steel | 90 | 3 | — | 57.5 | — | ↓ | ↓ |
| 17-7 PH (45 RC(11), pickled to prevent intergranular attack; special passivation) | Armco Steel | 90 | 3 | — | 100.0 | — | ↓ | ↓ |
| γ-(8) | | 90 | 2 | — | — | — | ↓ | ↓ |

## TABLE 4.5
(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability$^{(2)}$ After Test | Effect on Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Carpenter 20 | Carpenter Steel | 90 | 3 | — | 100 | — | Bronzed | Satisfactory room temperature use |
| Durimet 20 | Duriron Co. | 90 | 3 | — | 100 | — | Bronzed | Satisfactory room temperature use |
| Durimet T$^{(8)}$ | | 90 | 4 | — | — | — | | |
| Hasco-O-Seven | Hasco Valve and Machinery | 90 | 2 | — | 27 | — | None | Machine parts |
| Malin-Wilstabrite | Malin & Co. | 90 | 2 | — | 25 | — | None | Springs |
| 15-7 Mo (Cond. A.Y.S.) | Air Research Mfg. Co. | 90 | 3 | — | 34 | 28.0 | Heavily bronzed | Machine parts, gas generator |
| 15-7 Mo | Air Research Mfg. Co. | 98 | 3 | — | 21.0 | — | Heavily bronzed, liquid phase | Machine parts |
| Proley Type 302 Porous Wire$^{(10)}$ | | 90 | 3 | — | 21 | — | Heavily bronzed | Machine parts |
| Rigimesh J Stainless Steel Porous Wire$^{(10)}$ | | 90 | 4 | — | — | — | | |
| 300 Series Stainless Steel Powder Compact$^{(10)}$ | | 90 | 4 | | | | | |
| Type 302 Powder Compact$^{(10)}$ | | 90 | 4 | — | — | — | | |
| Type 302B Powder Compact$^{(10)}$ | | 90 | 4 | — | — | — | | |
| Type 316 Powder Compact$^{(10)}$ | | 90 | 4 | — | — | — | | |

## TABLE 4.5
## (Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Percent Stability[2] After Test | Effect on Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Type 316 + Cb Powder Compact[10] | | 90 | 4 | — | — | — | | |
| Inconel X-718 | Aerojet-General | 90 | 2 | | 5[13] | 94 | None, 24 hours at 66 C (151 F) | High temperature service |
| Inconel X-718 | Aerojet-General | 90 | 4 | — | 100 | 0 | Severe browning after 7 days | Not recommended |
| Inconel X-718 | Aerojet-General | 98 | 2 | — | 5[13] | 94 | None, 24 hours at 66 C (151 F) | High-temperature short period use |
| Inconel X-718 | Aerojet-General | 98 | 4 | — | 100 | 0 | Heavy browning after 7 days at 66 C (151 F) | Not recommended for extended high-temperature service |

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(1) Data taken from Ref. 4.25 unless otherwise noted

(2) See footnote 2, Table 4.4

(3) Percent $H_2O_2$ remaining after 7 days at room temperature

(4) Stabilized 98 percent $H_2O_2$ used

(5) Surface finish must be better than 10 rms; avoid elevated-temperature $H_2O_2$ service

(6) Additional test data available from FMC Corp. for samples with special surface treatments in contact with stabilized $H_2O_2$.

(7) Reference 4.40

(8) Reference 4.42

(9) See also Ref. 4.45

(10) Reference 4.30

(11) Rockwell hardness C scale

(12) Surface finish-root mean square

(13) Based on 1-day test

TABLE 4.6

COMPATIBILITY OF HYDROGEN PEROXIDE WITH PURE METALS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability (2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Aluminum (See Table 4.2) | | 90 | — | — | — | — |
| Beryllium | | ↓ | 4 | 100 | 0 | Pitted |
| Cadmium | | ↓ | ↓ | ↓ | ↓ | Pitted |
| Chromium | | ↓ | ↓ | ↓ | ↓ | Very slightly soluble |
| Cobalt | | ↓ | ↓ | ↓ | ↓ | Slightly soluble |
| Columbium | Heraus-Germany | ↓ | ↓ | ↓ | ↓ | Pitted |
| Copper | | ↓ | ↓ | ↓ | ↓ | Very slightly soluble |
| Gold | | ↓ | ↓ | ↓ | ↓ | None |
| Iron | | ↓ | ↓ | ↓ | ↓ | Rusted |
| Lead | | ↓ | ↓ | ↓ | ↓ | Dissolved |
| Magnesium | | ↓ | ↓ | ↓ | ↓ | Slightly soluble |
| Manganese | | ↓ | ↓ | ↓ | ↓ | None |
| Mercury | | ↓ | ↓ | ↓ | ↓ | Violent decomposition of $H_2O_2$ |
| Molybdenum | | ↓ | ↓ | ↓ | ↓ | Dissolved |
| Nickel | | ↓ | ↓ | ↓ | ↓ | None |
| Platinum | | ↓ | ↓ | ↓ | ↓ | None |
| Silicon | General Electric Co. | ↓ | 2 | 3.5 | 97 | Slight surface dulling |

TABLE 4.6

(Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability[2] After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Silver | | 90 | 4 | 100 | 0 | Attacked |
| Sodium | | ↓ | 4 | 100 | — | Violent decomposition and flame |
| Tantalum | Fansteel Met. Corp. | ↓ | 1[3] | — | — | None |
| Tin–C.P. | Baker Chem. Co. | ↓ | 2 | 28.7 | — | None |
| Titanium | Rem–Cru Titanium, Inc. | ↓ | 4 | 100 | 0 | Pitted |
| Tungsten | | ↓ | 4 | 100 | 0 | Dissolves |
| Zinc | | ↓ | 4 | 100 | 0 | Pitted |
| Zirconium | | ↓ | 1 | 3.2 | — | None |

(1) Data taken from Ref. 4.25

(2) See footnote 2, Table 4.4

(3) Based on Service Experience

## TABLE 4.7

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH METAL ALLOYS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Aluminum Oxide, Flame-Plated on Armco 17-7 PH | Linde Co. | 90 | 4 | 100 | — | One rust spot |
| Beryllium-Bronze | — | ↓ | ↓ | ↓ | 0 | None |
| Beryllium-Nickel | | ↓ | ↓ | ↓ | ↓ | None |
| Chemalloy H-3 | Electro-Alloys Div. | ↓ | ↓ | ↓ | ↓ | Pitted |
| Chlorimet | Durimet | ↓ | ↓ | ↓ | ↓ | None |
| Chromaloy Coated Steel(4) | — | ↓ | ↓ | — | — | — |
| Croloy 16-13-3(5) | — | ↓ | ↓ | 100 | 0 | — |
| Dow Metal J1A | Dow Chem. Co. | ↓ | ↓ | ↓ | ↓ | None |
| Dow Metal MA | Dow Chem. Co. | ↓ | ↓ | ↓ | ↓ | None |
| Duriron (cast) | Duriron | ↓ | ↓ | ↓ | ↓ | None |
| Elgiloy | Elgin Watch Co. | ↓ | ↓ | ↓ | ↓ | Bronzed |
| Fanweld "0" | Fansteel Met. Corp. | ↓ | ↓ | ↓ | ↓ | None |
| H-975 | Carbide & Carbon | ↓ | 3 | 90 | — | None |
| Hastelloy "A"(5) | Haynes-Stellite Corp. | ↓ | 4 | 100 | 0 | Some rust in solution |
| Hastelloy "B" | Haynes-Stellite Corp. | ↓ | 4 | 100/ 16 hours | 0 | None |

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Hastelloy "C" | Haynes-Stellite Corp. | 90 | 4 | 100/<br>16 hours | 0 | None |
| Hastelloy "D" | | | 4 | 100/<br>3 hours | | Bronzed |
| Haynes-Stellite | | | 3 | 65 to 72.7 | | Bronzed |
| Haynes 3 | | | 4 | 100/48 hours | | None |
| Haynes 6 | | | 4 | 100/3 hours | | None |
| Haynes 12 | | | 4 | 100/3 hours | | None |
| Haynes 25 | | | 4 | 100/1 hour | | Bronzed |
| Haynes C1712-3 | | | $H_2O_2$ evaporated completely | | | — |
| Haynes C3087-3 | | | 4 | 100 | 0 | Bronzed |
| Haynes F 17-3 | | | 4 | 97.8 | | Bronzed |
| Haynes L #3 | | | 4 | 100 | | Bronzed |
| Haynes L6 | | | 4 | 100 | | Bronzed |
| Haynes L1316 | | | 4 | 100 | | Bronzed |
| Haynes M1516-3 | | | 4 | 26.1 | | Bronzed |
| Illium "G" | Illium Corp. | | 4 | 100 | | Rusted |
| Inconel | International Nickel Corp. | | 4 | 100 | | None |
| Inconel "X" (Full Hard) | International Nickel Corp. | | 3 | 100/72 hours | — | Discolored |

## TABLE 4.7
(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability[(2)] After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Inconel X-718 | Aerojet-General | 90 | 2 | $5^{(7)}$ | 94 | None, 24 hours at 66 C (151 F) |
| Inconel X-718 | Aerojet-General | 90 | 4 | 100 | 0 | Severe bronzing after 7 days |
| Inconel X-718 | Aerojet-General | 98 | 2 | $5^{(7)}$ | 94 | None, 24 hours at 66 C (151 F) |
| Inconel X-718 | Aerojet-General | 98 | 4 | 100 | 0 | Heavy bronzing after 7 days at 66 C (151 F) |
| Kanegin Plated Mild steel | Keystone Chromium | 90 | 2 | $0.6^{(3)}$ | 96.3 | Slightly stained |
| Sample 3 | Keystone Chromium | ↓ | 3 | 82.1 | 88.8 | Slightly stained |
| Sample 7 | Keystone Chromium | ↓ | 3 | 51.2 | 95.1 | Slightly stained |
| Sample 13 | Keystone Chromium | ↓ | 3 | 60.3 | 92.5 | Slightly stained |
| Kennametal K-3H | Kennametal, Inc. | ↓ | 4 | 100 | 0 | None |
| Kennametal K-138 | Kennametal, Inc. | ↓ | 4 | 100 | 0 | None |
| Kennametal K-501 | Kennametal, Inc. | ↓ | 4 | 100 | 0 | None |
| Kennametal K-M | Kennametal, Inc. | ↓ | 4 | 100 | 0 | None |
| Monel | International Nickel Corp. | ↓ | 4 | 100 | 0 | None |
| Multimet N-155 | Haynes-Stellite Corp. | ↓ | 4 | 100/ 16 hours | 0 | None |
| Ni-Resist Alloy | International Nickel Corp. | ↓ | 4 | 100 | 0 | Rusted |
| Refractalloy 26 | Westinghouse | ↓ | 3 | 45.3 | — | None |

TABLE 4.7

(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Refractalloy 27(6) | — | 90 | 3 | — | — | — |
| Refractalloy 70 | Westinghouse | | 3 | 100 | 0 | None |
| Rene' (Nickel Base) | Muskegon | | 4 | 100 | 0 | Bronzed |
| Steel, Mild | Commercial | | 4 | 100 | 0 | Rusted |
| Steel, Mild | Keystone-Chromium | | 2 | 0.9(3) | 94.2 | Slightly stained |
| Super Alloy, S-588 | Allegheny-Ludlum | | 4 | 100 | 0 | None |
| Super Alloy, S-590 | Allegheny-Ludlum | | 4 | 100 | 0 | None |
| Tantung | Allegheny-Ludlum | | 4 | 100 | 0 | None |
| Timkin 16-25-6 | Timkin Roller Brg. Co. | | 3 | 50 | — | Slight bronzing |
| Tin-Plated Mild Steel | Keystone Chromium | | 2 | 0.6(3) | 96.7 | Slight staining |
| Titanium B120 VCA | Crucible Steel Co. | | 4 | 100 | 0 | Severely discolored |
| Titanium, C120 AV | Crucible Steel Co. | | 4 | 100 | 0 | Severely discolored |
| UCC-Star "J" Metal | Union Carbide | | | 100/ 4 hours | — | Bronzed |
| Utiloy 3 | Utility Steel Foundry | | 4 | 100/ 2 hours | — | None |
| Utiloy 20 | Utility Steel Foundry | | 4 | 100/ 2 hours | — | None |
| Utiloy H | Utility Steel Foundry | | 4 | 100/ 3 hours | — | None |
| Utiloy NH | Utility Steel Foundry | | 4 | 100/ 2 hours | — | None |

TABLE 4.7

(Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Worthite | Worthington Corp. | 90 | 3 | 100 | — | Bronzed |
| 19-9DL | Universal Cyclops Steel | 90 | 3 | 100 | — | Bronzed |

(1) Data taken from Ref. 4.25 unless otherwise noted

(2) See Footnote 2, Table 4.4

(3) Test conducted at room temperature rather than 66 C (151 F)

(4) Reference 4.40

(5) Reference 4.46

(6) Reference 4.42

(7) Based on 1-day test

# TABLE 4.8

# COMPATIBILITY OF HYDROGEN PEROXIDE WITH POLYETHYLENE AND HALOGENATED POLYETHYLENES

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent[2] Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Aclar | Allied Chemical | 90 | 1 | 0.6 | 1.2[3] | 99.0 | None | Bladder materials, drum liners |
| Aclar | Allied Chemical | 98 | 1 | 0.5 | 0.5 | 99.0 | None | Tank liners, bladders |
| 70 Duro No. 5809 | Belmont Packing | 90 | 4 |  | 10.2 | 78.5 | Severly blistered | Not recommended for 12 F use |
| Enjay Rubber | Humble Oil | 90 | 4 | — | — | — | Severly blishered | — |
| Ethylene Propylene (MD 460) | Enjay Chemical | 90 | 4 |  | 42.0 | 0.0 | Blistered | Not recommended |
| Fairprene PS 57-167[10] (Viton A, 116 glass) | DuPont | 90 | 3 |  | — | — | Surface attack and moderate blistering (1 week at 150 F) | — |
| Fairprene PS 57-168[10] (Viton A, Dacron) | DuPont | 90 | 2 |  | — | — | Moderate surface attack (1 week at 151 F) | — |
| Fluorel[10] | Minn. Min. & Mfg. | 90 | 3 | — | 12.1 | 8.9 | Blistered | — |
| Fluorel 2140 | Seals Eastern, Inc. | 90 | 4 | — | 2.6 | 96.0 | Blistered | Not recommended for extended 150 F service |
| Fluorel 2140 | Minn. Min. & Mfg. | 90 | 1 | 1.0 | — | 98.0 | None | O-rings, seals bladders |
| Fluorel 2140 | Minn. Min. & Mfg. | 90 | 2 | — | 1.1 | 98.5 | Very slight blistering | — |
| Fluorel 2140 | Seals Eastern, Inc. | 90 | 1 | — | 0.3 | 99.0 | None after 24 hours at 66 C (151 F) | Not recommended at this temperature |
| Fluorel 2140[4] | Minn. Min. & Mfg. | 98 | 1 | 0.9 | — | 98.0 | None | O-rings, seals, bladders |
| Fluorel 2140 | Minn. Min. & Mfg. | 98 | 4 | — | — | 98.0 | Blisters after 24 hours at 66 C (151 F) | — |
| Fluorel 2141, Elastomer | Minn. Min. & Mfg. | 90 | 3 | — | 2.9 | 98.1 | Swollen and blistered | — |
| Fluorel 4121 | Seals Eastern, Inc. | 90 | 1 | — | 2.4 | 98.6 | None | O-rings, seals, bladders |
| Fluorel 4121 | Seals Eastern, Inc. | 98 | 1 | — | 0.9[5] | 99.3 | None | O-rings, seals, bladders |
| Fluoroflex T-TP1001 | Resistoflex Corp. | 90 | 1 | — | 3.6 | — | None | High-pressure hose |
| Fluoroflex T-TP1001 (Black) | Resistoflex Corp. | 90 | 2 | — | 6.7 | — | None | High-pressure hose |
| Fluran B-4100 | U. S. Stoneware | 90 | 3 | — | 48.3 | 0.0 | Partially bleached | Not recommended |
| Fluorosint | Polymer Corp. | 90 | 3 | — | 38.8 | 33.1 | None | Further testing required |
| Furane CP/9070 (black) | Whitre Assoc. | 90 | 4 | — | — | — | Disintegrated, $H_2O_2$ decomposed | Not recommended |
| Nalgene | Nalge Lab Supplies | 90 | 2 | — | 4.6 | — | None | Seals |
| Hypalon S-2 | DuPont | 90 | 4 | — | 100.0 | — | Sample destroyed (1 hour) | Unsatisfactory |
| Hypalon Gasket | Metal Hose & Tubing | 90 | 4 | — | 74.2 | 2.0 | Severe attack | Unsatisfactory |
| Hypalon V-54-B (grey) | Raybestos-Manhattan | 90 | 4 | — | 100.0 | — | Blistered and swollen | Unsatisfactory |

## TABLE 4.8
## (Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Hypalon V-56-A (Grey) | Raybestos-Manhattan | 90 | 4 | — | 100.0 | — | Badly swollen | Unsatisfactory |
| Hypalon V-153-A (Black) | Raybestos-Manhattan | 90 | 4 | — | 100.0 | — | Blistered and swollen after 1 hour | Unsatisfactory |
| Hypalon O-Ring (GCR 98-5) | Goshen Rubber Co. | 90 | 3 | — | 19.0 | 74.4 | Moderate surface attack | Not recommended |
| Irrathane 101 (irradiated polyethylene) | General Electric | 90 | 2 | — | 3.0 | 96.6 | None at room temperature; can ignite with 90 to 98 percent $H_2O_2$ if heated above 160 F | Seals, gaskets |
| Kel-F | — | 98 | 2 | — | 8.3 | — | None | — |
| Kel-F | Minn. Min. & Mfg. | 98 | 1 | — | 1.3 | — | None | Seals |
| Kel-F (unplasticized) | Minn. Min. & Mfg. | 90 | 1 | — | 3.5 | — | None | Gaskets, seals, seats |
| Kel-F 800(3) | Minn. Min. & Mfg. | 90 | 1 | — | 2.9(3) | 98.0 | None | High-temperature service, seals, seats |
| Kel-F 800 (Lot 9649) | Minn. Min. & Mfg. | 90 | 1 | — | 4.5 | 97.8 | Very slight hardening | Gaskets, seals, seats |
| Kel-F 800 | Minn. Min. & Mfg. | 98 | 1 | — | 0.33 | 98.0 | None | Seals |
| Kel-F 820 (64028) | Minn. Min. & Mfg. | 90 | 2 | — | 9.0 | 96.4 | Slight hardening | Gaskets, seals, seats |
| Kel-F 3700 (gum) | Minn. Min. & Mfg. | 90 | 3 | — | 8.8 | 93.2 | Blistering and bleaching | Gaskets, seals, seats |
| Kel-F 3700, Kel-F 800 (50-50) | Minn. Min. & Mfg. | 90 | 2 | — | 3.6 | 97.0 | Slight blistering | Gaskets, seals, seats |
| Kel-F 5500 (unpigmented) | Minn. Min. & Mfg. | 90 | 2 | — | 26.3 | 95.7 | Slightly tacky | Gaskets, seals, seats |
| Kel-F 5500 (gum) | Minn. Min. & Mfg. | 90 | 3 | — | 18.5 | — | Blistered and distorted | Not recommended |
| Kel-F 5500-121 | Minn. Min. & Mfg. | 90 | 2 | — | 19.0 | — | Bleached | Use other compounds |
| Kel-F 5500-61 | Minn. Min. & Mfg. | 90 | 2 | — | 9.0 | — | Bleached | — |
| Kel-F 5500, Kel-F 800 (50-50) | Minn. Min. & Mfg. | 90 | 1 | — | 3.6 | 97.7 | None | Gaskets, seals, seats |
| Kel-F 5500, Kel-F 800 (75-50) | Minn. Min. & Mfg. | 90 | 2 | — | 3.2 | 94.2 | Slight blistering | Gaskets, seals, seats |
| Kel-F O-Ring (Cpd. 7761-70) | Linear, Inc. | 90 | 2 | — | 6.4 | 95.5 | Moderate surface attack; slightly sticky | O-rings, gaskets |
| Kel-F D316 | Firestone Tire & Rubber | 90 | 2 | — | 5.1 | 97.0 | Very slight bleaching | Expulsion bladders |
| Kel-F D316 | Firestone Tire & Rubber | 98 | 2 | — | 5.1 | 97.0 | Very slight bleaching | Bladder material |
| Kel-F D385 | Firestone Tire & Rubber | 90 | 2 | — | 9.8 | 94.0 | Very slight bleaching | Expulsion bladders |
| Kel-F D385 | Firestone Tire & Rubber | 98 | 2 | — | 6.3 | 94.0 | Very slight bleaching | Bladder material |

## TABLE 4.8
(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Kel-F Elastomer 5160 | Minn. Min. & Mfg. | 90 | 2 | — | | | | |
| Kynar | Whitco Assoc. | 90 | 2 | — | 1.1 | 96.0 | Slight bleaching | Seals |
| Kynar-Vinylidene | Tube Turns, Inc. | 90 | 2 | — | 3.8 | 91.0 | Bleached and slightly distorted | — |
| Lexan Plastic Tube | General Electric | 90 | 2 | — | 2.1 | 97.1 | Bleached | Plastic lines, components |
| Malyon-P-73-223 | Veplex | 90 | 2 | — | 1.9 | 99.0 | Bleached | Plastic components |
| Omni (Viton ..) | David Clark Co. | 90 | 1 | 0.7 | — | 96.0 | None | O-rings, seals, coatings |
| Omni (Viton A) | David Clark Co. | 90 | 2 | — | 1.3 | 96.0 | Very slight bleaching | Seals, coatings |
| Penton 9215(5) | Hercules Powder | 90 | 2 | — | 1.4 | 96.0 | Bleached from olive to grey | Possibly plastic pipe and tube use |
| Penton 9215 | Hercules Powder | 90 | 2 | — | 7.9 | 95.0 | Bleached from olive to grey | |
| Polyester M-85 | Whitco Assoc. | 90 | 4 | — | 4.0 | 97.0 | Discolored, swollen | Not recommended |
| Polyethylene (porous) | Kem-E-Quip Corp. | 90 | 4 | — | 6.6 | 90.0 | Samples became brittle | Not recommended |
| Polyethylene (black) | Cabot Corp. | 90 | 3 | — | 7.4 | 84.0 | Bleached slightly | Not recommended except for room temperature use |
| Polyethylene | DuPont | 90 | 2 | — | 1.0 | 95.0 | None at room temperature; can detonate with $H_2O_2$ if heated | Laboratory use |
| Polyethylene(6) | DuPont | 98 | 2 | — | 2.3 | 95.0 | None; see (6) | Laboratory use |
| Polyethylene (pure unpigmented) | Several | 90 | 2 | — | 2.3 | — | Will detonate at melting point of plastic | For service below 100 F |
| Polyethylene H.D.(3) | General Electric | 90 | 1 | — | 2.9(3) | 98.0 | None | Not recommended for high temperature |
| Polyethylene PE-2(10) | Plax Corp. | 90 | 4 | — | — | — | — | — |
| Polyethylene Foam(11) | Dow Chem. | 90 | | — | — | — | No apparent swelling, but some bleaching (1 day at room temperature) | — |
| Polypenco K-51(3) | Pall Filt. | 90 | 2 | — | 4.1(3) | 98.0 | None | Filter media |
| Polypenco K-51 | Polymer Corp. | 98 | 2 | — | 6.3 | 99.0 | Slight bleaching | Plastic parts |
| Polypropylene (black) | Tube Turns, Inc. | 90 | 2 | — | 1.7 | 98.3 | Slight bleaching | Tube and pipe fittings |
| Rulon (Teflon base) | Dixon Corp. | 90 | 2 | — | 5.9 | — | Bleached slightly | — |
| Rulon (Teflon base) | DuPont | 90 | 2 | — | 5.9 | 95.5 | None | — |
| Rulon "A" | Dixon Corp. | 90 | 4 | — | 54.7 | 0.0 | Bleached | — |
| Rulon "B" | Dixon Corp. | 90 | 3 | — | 15.6 | 78.2 | None | — |

## TABLE 4.8
## (Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent[(2)] Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Vicone 185 | North American Aviation | 90 | 2 | 3.8 | 2.8 | 99.0 | Slight bleaching | Bladder material |
| Vicone 185 | North American Aviation | 90 | 2 | 0.1 | 3.4 | 99.0 | Very slight bleaching | Excellent elastomer |
| Vicone 185(9) | North American Aviation | 90 | 2 | 0.6 | 1.1 | 99.0 | Very slight bleaching | Bladder material |
| Vicone 195 | North American Aviation | 98 | 2 | 1.3 | 2.4 | 99.0 | Very slight bleaching | Bladders |
| Vicone 51-4 | North American Aviation | 90 | 2 | — | 12.0 | 98.0 | Slight bleaching | Expulsion bladders |
| Vicone 51-4 | North American Aviation | 98 | 3 | 13.0 | 12.0 | 98.0 | Slight bleaching | Bladders |
| Vinyliden-Fluoride | Pall Filtration Corp. | 90 | 1 | 0.5 | — | 98.0 | None | Filter media |
| Vinyliden-Fluoride | Pall Filtration Corp. | 90 | 2 | — | 1.3 | 97.0 | Two out of three samples showed low stability | Filter media |
| Vinylite VU 1930 | Prince Rubber Co. | 98 | 2 | — | 2.7 | — | Became opaque | Not recommended |
| Vinton A (247; black) | DuPont | 90 | 2 | — | 16.8 | — | Slightly tacky | — |
| Viton A (271-7; 77545) | Parker Hannefin | 90 | 2 | 0.75 | — | 98.6 | Excellent service record | O-rings, diaphragms, bladders |
| Viton A (271-7) | Parker Hannefin | 90 | 4 | — | — | — | Blisters after 3 days at 151 F | — |
| Viton A (271-7; 77-545) | Parker Hannefin | 98 | 2 | 0.58 | — | 99.5 | Excellent service experience | O-rings, seals, bladders |
| Viton A (05-100 BR 31) | Seals, Inc. | 90 | 2 | — | 15.6 | 95.0 | None | O-rings |
| Viton A (05-100 BR 31) | B. F. Goodrich | 90 | 2 | — | 15.4 | 98.0 | None | O-rings, seals |
| Viton A (411A4; black) | Hewitt Robbins | 90 | 3 | — | 80.6 | 82.1 | Blistered and swelled; bleached to blue color | Not recommended for service above 120 F |
| Viton A-8070 | Nichols Engineering | 90 | 2 | — | 4.3 | 97.0 | None | O-rings, bladders |
| Viton A-1700A(13) | Precision Rubber | 90 | - | — | — | — | No noticeable attack in 1 day at room temperature, severe attack in 1 day at 200 F | — |
| Viton A-SR-251-70(13) | Stillman Rubber Co. | 90 | - | — | — | — | No noticeable attack in 1 day at 150 F; minor attack in 1 day at 200 F | — |
| Viton A-SR-270-70(13) | Stillman Rubber Co. | 90 | - | — | — | — | No noticeable attack in 1 day at 150 F; minor attack in 3 days at 200 F | — |
| Viton B (805) | DuPont | 90 | 1 | — | 0.6 | 98.5 | No effect after 72 hours at 151 F | O-rings, seals, bladders |
| Viton B (805) | DuPont | 90 | 1 | 1.0 | 0.6 | 99.0 | No effect after 72 hours at 151 F | O-rings, seals, bladders |

## TABLE 4.8
## (Continued)

| Material | Source | $K_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent[(2)] Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Scotch Pak 20A5(8) | Minn. Min. & Mfg. | 90 | 1 | — | 1.1 | 98.0 | None | Film material |
| Scotch Pak 45A10(8) | Minn. Min. & Mfg. | 90 | 1 | — | 1.1 | 98.0 | None | Film material |
| Teflon (white) | DuPont | 90 | 1 | — | 2.8 | 95.0 | None | Various uses |
| Teflon, 100X FEP Flurocarbon | DuPont | 90 | 1 | — | 2.6 | 98.3 | None | Not effectively heat sealable |
| Teflon, 5-milliliter (molded 100X) | DuPont | 90 | 1 | 0.56 (2 hours at 270 F, 545 psig) | | 98.0 | None | — |
| Teflon Tape | DuPont | 90 | 1 | 0.3 | 2.8 | — | None | Thread compound |
| Teflon Tape, JRP 7321(10) and JRP 7962 | DuPont | 90 | 1 | — | — | — | — | — |
| Teflon Tape, 547(10) | Minn. Min. & Mfg. | 90 | 1 | — | — | — | — | — |
| Teflon-Impregnated(10) Glass Cloth | DuPont | 90 | 1 | — | — | — | — | — |
| Teflon Welded | DuPont | 90 | 1 | 2.0 | 2.7 | — | None | Seals, bladders |
| Teflon (virgin) | DuPont | 98 | | | 2.6 | 95.0 | — | Seals, gaskets |
| Teflon (fuel cell)(5) | Dielectrix Corp. | 98 | | | 2.2(5) | 97.0 | — | Bladder material |
| Teflon and Fluorsint | Potter Aeronautical | 90 | 2 | — | 11.1 | 95.0 | None | Bearing for turbine flow meter |
| Dispersion Teflon(8, 14) (fuel cell) | Dielectrix Corp. | 98 | 2 | — | 7.4 | 94.0 | Very slightly bleached | Bladder material |
| Dispersion Teflon TFE(8,14) | DuPont | 98 | 1 | — | 0.55 | 98.0 | None | Tank liner, bladders |
| Teflon Fuel Cell | Chemengineers, Inc. | 90 | 1 | — | 3.3 | 96.0 | None | Expulsion bladders |
| Teflon Fuel Cell | Dielectrix Corp. | 90 | 3 | — | 2.9(5) | 97.0 | Very slightly bleached | Expulsion bladders |
| Teflon Fuel Cell | Dielectrix Corp. | 90 | 2 | — | 4.0(8) | 94.0 | Very slight bleaching | Expulsion bladders |
| Teflon TFE Cell | Chemengineers, Inc. | 90 | 2 | — | 3.6 | 97.5 | Bleached | Expulsion bladders |
| Teflon TFE | DuPont | 90 | 1 | — | 1.5(5) | 98.0 | None | Bladder material |
| Teflon, Carbon-Filled(12) | | | | | Decomposition rates were excessive in 24 hours | | | — |
| Teflon, Molybdenum(12) Disulfide-Filled | | | | | Decomposition rates were excessive in 24 hours | | | — |

## TABLE 4.8

## (Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Month at 86 F | Percent AOL Per Week at 151 F | Percent[2] Stability After Test | Effect On Material | Comments |
|---|---|---|---|---|---|---|---|---|
| Viton B (805) | DuPont | 90 | 4 | — | 3.6 | 98.0 | 7 days at 151 F, slight blistering | Not recommended |
| Viton B (805) | DuPont | 98 | 1 | — | 0.6 | 98.5 | No effect to 72 hours | O-rings, seals, bladders |
| Viton B (5187)[15] | DuPont | 90 | 2-3 | — | 15 percent fluid loss in 26 weeks | — | — | O-rings, seals |
| Viton B-4411-A-805 | DuPont | 90 | 1 | 0.7 | — | 98.0 | None | Gaskets, seals |
| Viton B-Cure No. 23 | Seals Eastern, Inc. | 90 | 3 | — | 5.0 | 91.0 | Very slight blistering | — |
| Viton B-Cure No. 805 | DuPont | 90 | 3 | — | 2.6 | 98.4 | Swollen and moderate blisters | Not recommended for temperatures above 120 F |

(1)Data taken from Ref. 4.25 unless otherwise noted
(2)Footnote 2, Table 4.4
(3)7 days at 74 C (165 F)
(4)5 months storage at 20 to 22 C (68 to 72 F)
(5)1 week at 49 C (120 F)
(6)Not suitable for use above 200 F
(7)Subject to ignition if heated above 71 C (160 F) when contacting 90 or 98-percent $H_2O_2$
(8)3 days at 74 C (165 F)
(9)Stabilized $H_2O_2$ used
(10)Reference 4.40
(11)Reference 4.45
(12)Reference 4.47
(13)Reference 4.48
(14)Reference 4.29
(15)Reference 4.49

## TABLE 4.9

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH POLYVINYLCHLORIDE AND CO-POLYMERS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Alanel Tubing | Nalge | 90 | 3 | 10.3 | — | Embrittled |
| Beltaren 6200 (grey) | Belta | 90 | 2 | 3.0 | — | None |
| Enselite(6) | — | 90 | - | — | — | Retained resiliency, but decreased in tensile strength; swelling; bleached |
| Geon 118 | B. F. Goodrich | 90 | 4 | 8.5<br>(4 days) | 85.6<br>(4 days) | Milky white, blistered, distorted |
| Geon 404 (yellow) | B. F. Goodrich | 90 | 3 | 8.0 | — | Bleached and became brittle |
| Geon 2042(5) | B. F. Goodrich | 90 | 4 | — | — | — |
| Geon 8372(5) | B. F. Goodrich | 90 | 4 | — | — | — |
| Geon PVC | B. F. Goodrich | 90 | 2 | — | 85.0 | Slight bleaching |
| Geon PVD Pipe(7) | B. F. Goodrich | 90 | 2 | 1.3(3) | 85.0 | Slight bleaching |
| Grey(7) | B. F. Goodrich | 90 | 3 | 10.6 | 97.0 | Slight bleaching |
| I.P.S. Uscalite | Stritt and Priebe | 90 | 4 | 7.2 | 89.8 | Severely attacked and blistered |
| Koroseal 116 | B. F. Goodrich | 90 | 3 | 23.0 | — | Bleached and hardened |
| Koroseal 116 (molded)(5) | B. F. Goodrich | 90 | 3 | — | — | — |
| Koroseal 117 (molded) | B. F. Goodrich | 90 | 3 | 16.0 | — | Bleached and hardened |
| Koroseal 117 (calendered)(5) | B. F. Goodrich | 90 | 4 | — | — | — |
| Koroseal 700 | B. F. Goodrich | 90 | 2 | 2.9 | — | Slightly swollen, bleached, and stiffened |
| Koroseal 700 (molded)(5) | B. F. Goodrich | 90 | 2 | — | — | Bleached |
| Koroseal 700 With Hycar 1041 Plasticizer | Prince Rubber | 90 | 4 | 14.9 | 0.0 | Blistered and bleached |
| Koroseal Pipe (grey) | B. F. Goodrich | 90 | 3 | 10.6 | 97.0 | Slight bleaching |
| Lacoflex (translucent) | Lacoflex Plastic Fab. | 90 | 3 | 10.1 | — | Blistered and bleached |
| Lacoflex (white) | Lacoflex Plastic Fab. | 90 | 3 | 11.2 | — | Darkened, slight blistering |
| Marvinol 218-200 | U. S. Rubber | 90 | 4 | 100/2 hours | — | Sample became tacky after 1 hour |
| Marvinol 218-201 | U. S. Rubber | 90 | 4 | 100/1 hour | — | Deformed, charred |
| Marvinol MP-3005 | U. S. Rubber | 90 | 4 | 100/1 hour | — | Sample became tacky |
| Marvinol MR-6010 | U. S. Rubber | 90 | 4 | 100/1 hour | — | Became tacky and deformed |
| Pliovic(5) | Goodyear Tire | 90 | 2 | — | — | — |
| PVC | Walworth Pipe | 90 | 2 | 1.2 | 98.4 | Moderate bleaching |
| PVC | Walworth Pipe | 90 | 2 | 10.5 | 86.0 | Moderate bleaching |
| PVC | Prince Rubber | 90 | 3 | 13.1 | 87.7 | No change |
| PVC, Rigid | Vanco | 90 | 2 | 5.3 | 90.4 | Bleached and slight blistering |

## TABLE 4.9
## (Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent[2] Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| PVC, Rigid | Whitehead | 90 | 2 | 7.5 | 96.0 | Bleached |
| PVC, Sheet (dark grey) | Prince Rubber | 90 | 3 | 13.0 | 87.0 | Slight bleaching |
| Rubatex, R-310V[6] | — | 90 | - | — | — | Retained resiliency but decrease in tensile strength; swelling; bleached |
| Saran | Dow Chemical | 90 | 2 | 12.3 | — | Bleached |
| Saran Rubber Q-187 | Dow Chemical | 90 | 4 | — | — | Burned |
| Transflex Tubing | Irvington Varnish & Insulation | 90 | 4 | 1.1 | — | Blistered badly |
| Tygon B-20 | U. S. Stoneware | 90 | 3 | 2.3 | — | Bleached, blistered, and slightly distorted |
| Tygon B-32 | U. S. Stoneware | 90 | 3 | 2.2 | — | Bleached, blistered, and slightly distorted |
| Tygon B-63 | U. S. Stoneware | 90 | 3 | 1.7 | — | Bleached, blistered, and slightly distorted |
| Tygon B-71 | U. S. Stoneware | 90 | 3 | 3.5 | — | Bleached, blistered, and slightly distorted |
| Tygon B-72 | U. S. Stoneware | 90 | 3 | 1.0 | — | Bleached, blistered, and slightly distorted |
| Tygon B-136 | U. S. Stoneware | 90 | 3 | 2.0 | — | Bleached, blistered, and slightly distorted |
| Tygon S-22-1 | U. S. Stoneware | 90 | 4 | — | — | Blistered and swollen |
| Tygon TL-103 | U. S. Stoneware | 90 | 4 | — | — | Blistered and swollen |
| Tygon 2807 | U. S. Stoneware | 90 | 4 | — | — | Disintegrated |
| Tygon 3400 | U. S. Stoneware | 90 | 4 | — | — | Embrittled and swollen |
| Tygon 3603 | U. S. Stoneware | 90 | 4 | — | — | Swollen |
| Tygon 3604 A | U. S. Stoneware | 90 | 2[4] | — | — | Becomes opaque |
| Tygon 3604 B | U. S. Stoneware | 90 | 2[4] | — | — | Becomes opaque |
| Vinyl 79139 | U. S. Rubber | 90 | 2 | 1.7 | — | Slight opaque; small blisters |
| Vinylite VS 1310 | Bakelite Div. | 90 | 3 | 2.3 | — | Turned opaque; slight blistering |
| Vinylite VMD-9947[5] | Union Carbide | 90 | 2 | — | — | Turned opaque; slight blistering |
| Vinylite VU 1900 | Bakelite Div. | 90 | 3 | 2.5 | — | Turned opaque; slight blistering |
| Vinylite VE 1907 | Bakelite Div. | 90 | 3 | 3.0 | — | Turned opaque; slight blistering |
| Vinylite VG 1914 | U. S. Rubber | 90 | 2 | 1.5 | — | Blistered slightly, bleached |
| Vinylite VU 1920 | Bakelite Div. | 90 | 3 | 2.0 | — | Turned opaque; slight blistering |
| Vinylite VU 1930 | Bakelite Div. | 90 | 3 | 2.4 | — | Turned opaque; slight blistering |
| Vinylite VU 1940 | Bakelite Div. | 90 | 3 | 2.0 | — | Turned opaque; slight blistering |
| Vinylite VU 1940 | U. S. Rubber | 90 | 2 | 1.6 | — | Bleached |

(1) Data taken from Reference 4.25 unless otherwise noted

(2) Footnote 2, Table 4.4

(3) Tested at 86 F

(4) Based on service experience

(5) Reference 4.40

(6) Reference 4.45

(7) Reference 4.29

# TABLE 4.10

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH SILICONE RUBBER COMPOUNDS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Fluorosilicone LS-53 | Dow-Corning | 90 | 2 | 16.7 | 91.3 | None |
| GE 4078-217-1 | General Electric | 90 | 4 | 34.3 | — | — |
| GE 1240 | General Electric | 90 | 2 | 72.4 | — | None |
| GE 12601 | General Electric | 90 | 4 | 99.5 | — | Hardened |
| GE 12062 | General Electric | 90 | 3 | 95.0 | — | None |
| GE 12650 (unpigmented) | General Electric | 90 | 2 | 48.5 | — | Slight swelling |
| GE 12650 (pigmented red) | General Electric | 90 | 3 | 89.0 | — | Slight bleaching, swelled, distorted |
| GE 12670 | General Electric | 90 | 4 | 47.5 | — | Hardened |
| GE 12670 (pigmented brown) | General Electric | 90 | 4 | 45.0 | — | Cracked; bleached |
| GE 15060 (pigmented) | General Electric | 90 | 3 | 31.9 | — | Blistered and warped slightly |
| GE 15080 | General Electric | 90 | 3 | 32.2 | — | Blistered |
| GE 81223 | General Electric | 90 | 4 | 27.7 | — | None |
| GE X7181 | General Electric | 90 | 3 | 18.3 | — | Slightly hardened |
| Hadbar No. 8000-71(3) | Hadbar | 90 | - | — | — | Soft; pitted |
| Parkone White 467-1 O-Ring | Parker Appliance | 90 | 4 | 29.6 | — | Hardened and broke |
| SE 450 (unpigmented) | General Electric | 90 | 2 | 13.3 | — | Slight bleaching and swelling |
| Silastic 152 | Dow-Corning | 90 | 3 | 17.8 | 68.1 | Slightly bleached |
| Silastic 160 | Dow-Corning | 90 | 3 | 37.8 | — | Lost elasticity |
| Silastic 160 O-ring | Linear Inc. | 90 | 4 | 71.0 | — | Embrittled |
| Silastic 161 | Dow-Corning | 90 | 3 | 43.4 | — | Lost elasticity |
| Silastic 181 | Linear Inc. | 90 | 3 | 39.3 | — | Slightly blistered |
| Silastic 240 | Dow-Corning | 90 | 2 | 24.9 | — | None |
| Silastic 250 | Dow-Corning | 90 | 4 | 92.6 | — | Curled |
| Silastic 261 | Dow-Corning | 90 | 3 | 16.7 | — | Lost elasticity |
| Silastic 675 | Dow-Corning | 90 | 3 | 5.0 | — | Blistered and embrittled |
| Silastic 6-128 | Dow-Corning | 90 | 2 | 6.7 | 99.7 | Slightly blistered; bleached |
| Silastic 7-180 | Dow-Corning | 90 | 3 | 17.7 | — | Embrittled |
| Silastic 9711 | Dow-Corning | 90 | 2 | 7.4 | 99.1 | Slightly bleached |
| Silastic 9711 | Dow-Corning | 90 | 2 | 5.7 | 98.0 | Slightly bleached |
| Silastic ER-9711 | Hewitt-Robins, Inc. | 90 | 2 | 7.8 | 96.5 | Slightly bleached |
| Silicone S-9711(4) | Farge Rubber | 90 | - | — | — | No noticeable attack; material bleached (168 hours at 200 F) |

## TABLE 4.10

## (Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent[2] Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Silicone PR-11555[5] | Precision Rubber | 90 | 2-3 | 16-percent fluid loss in 24 weeks | — | — |
| Silastic 9711 Welded With S-2200 | Dow-Corning | 90 | 2 | 13.6 | 96.0 | Weld unaffected; slight bleaching, mottling |
| Silastic HR-39631[6] | Hewitt-Robbins, Inc. | 90 | 2 | — | — | — |
| Silastic S-2000-4-480 | Dow-Corning | 90 | 2 | 16.1 | 95.5 | Bleached and slightly mottled |
| Silicone 407-B-217-1 | F. S. Bacon Lab. | 90 | 3 | 34.5 | — | Embrittled |
| Silicone 407-B-437-1 | F. S. Bacon Lab. | 90 | 2 | 20.3 | — | None |
| Silicone HT 656 | Connecticut Hard Rubber | 90 | 3 | 17.4 | 95.7 | Blistered |
| Silicone K-1034 | Union Carbide | 90 | 3 | — | — | None |
| Silicone O-ring[5] No. 8419-80 | Linear | 90 | - | 13.4 | 86.7 | No pitting, swelling, or bleaching |
| Silicone O-ring[5] Compound V399-7 | Parker | 90 | - | — | — | Bleached completely |
| Silicone O-ring[5] No. S-455-7 | Parker | 90 | - | 32.2 | 0.0 | Slight distortion |
| Silicone K-1038[6] | Union Carbide | 90 | 4 | — | — | Lost flexibility; cracked |
| Silicone Rubber SR5550 | Connecticut Hard Rubber | 90 | 2 | 32.4 | — | None |
| Silicone Rubber SR5550 | DuPont | 90 | 2 | 45.0 | — | None |
| Silicone Rubber SR5570 | Connecticut Hard Rubber | 90 | 2 | 30.9 | — | None |
| Silicone Rubber SR5570 | DuPont | 90 | 2 | 46.5 | — | None |
| Silicone X-7181 | Stalwart Rubber | 90 | 3 | 18.3 | — | Lost some elasticity |
| Silicone Y-1419[6] | Union Carbide | 90 | 3 | — | — | None |
| Silicone Y-1749 | Union Carbide | 90 | 2 | 12.3 | — | Small white blisters |
| Silicone TR-1047 | Stillman Rubber | 90 | 2 | 10.3 | 97.0 | No effect |
| Silicone TR-1057[4] | Stillman Rubber | 90 | - | — | — | No apparent attack (1 day at 200 F); slightly attacked after 156 hours at 200 F |
| Silicone TR-1131 | Stillman Rubber | 90 | 2 | 15.0 | 94.0 | Bleached slightly |
| Silicone Rubber[4] Comp. 78-038 | Parker Seal | 90 | - | — | — | No noticeable attack (1 day at 200 F); slight brittleness after 3 days at 200 F |
| O-Ring No. 945-70[5] | Plastic Rubber | 90 | - | — | — | Swelled |
| O-Ring No. 005-18057[5] | P.R.P. | 90 | - | Failed | — | Completely disintegrated at 72 hours |
| O-Ring No. SR277-70[5] | Stillman Rubber | 90 | - | 10.1; Failed | — | Swelled, pitted, very soft |
| O-Ring No. TR 1057[5] | Stillman Rubber | 90 | - | 13.0 | 65.8 | No swelling, pitting, or bleaching |

(1) Data taken from Reference 4.25 unless otherwise noted

(2) Footnote 2, Table 4.4

(3) Reference 4.50

(4) Reference 4.48

(5) Reference 4.49

(6) Reference 4.40

## TABLE 4.11

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH GENERAL RUBBERS AND PLASTICS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Acrylon Rubber BA-12 | American Monomer | 90 | 4 | — | — | $H_2O_2$ turned black; sample partially dissolved in 2 days |
| Acrylon EA-5 | American Monomer | 90 | 4 | — | — | $H_2O_2$ turned black; sample partially dissolved in 2 days |
| Adiprene C | Hewitt Robbins | 90 | 4 | 100.0 | — | Decomposed in 1 hour |
| Bisolin No. 50 | Bishop Mfg. | 90 | 2 | 9.7 | — | Slightly blistered |
| Buna N | — | 90 | 4 | — | — | — |
| Buna S(3) | — | 90 | 4 | — | — | — |
| Butyl Rubber A3405 | Esso Lab | 90 | 4 | 100.0 | — | Softened to sticky mass in 24 hours |
| Butyl Rubber SR-384 | | 90 | 4 | 5.0 | — | Became tacky |
| Cycolac (natural color) | Marbon Chem. Div. | 90 | 4 | 7.6 | | Embrittled, swollen, solution turned yellow |
| Delrin | DuPont | 90 | 4 | 100.0 | | Dissolved |
| Epon Resin(3) | Shell Chem. | 90 | 4 | — | | — |
| Estane Plastic | B. F. Goodrich | 90 | 4 | 6.0 | 55.0 | Disintegrated |
| Garlock No. 5681 (Teflon-impregnated asbestos) | Garlock Packing | 90 | 4 | 100/1 hour | — | Sample fell apart |
| Hycar PA 478-1-1 (black) | F. S. Bacon Labs | 90 | 4 | 100/24 Hours | — | Dissolved completely |
| Haveg 41 (asbestos-filled phenolic) | Haveg Corp. | 90 | 4 | 100.0 | — | Partially dissolved |
| Haveg 60 (phenolic) | Haveg Corp. | 90 | 4 | 100.0 | — | Dissolved |
| Hysol 4-77 C (clear) | Houghton Labs | 90 | 4 | 100.0 | — | Bleached; distorted |
| Hysol 4-77D (amber) | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-77E | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-77F | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-78A (white) | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-78B (brown) | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-78C (amber) | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 4-78D (amber) | Houghton Labs | 90 | 4 | 100.0 | — | Blistered; distorted |
| Hysol 6000B (amber) | Houghton Labs | 90 | 4 | 100.0 | — | Partially dissolved |
| Kralite (Kraylite) | U. S. Rubber | 90 | 3 | 26.7 | — | Swollen and distorted |

## TABLE 4.11
(Concluded)(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Lexan | General Electric | 90 | 2 | 2.1 | 97.0 | Slight bleaching |
| Melmax No. 1077 | Mechanical Products | 90 | 4 | 100.0 | — | Partially dissolved |
| Methyl Methacrylate(3) | Whitehead Metal Products | 90 | 4 | — | — | Softened |
| Mylar "A" | DuPont | 90 | 1 | 5.0 | — | None |
| Mylar "B" | DuPont | 90 | 1 | 1.7 | — | None |
| Neoprene Pure Gum | Spray Dip | 90 | 4 | — | — | Ignited and burned |
| Neoprene SB 365-B | Eclipse Pioneer Div.,<br>Bendix Aviation | 90 | 4 | 100.0 | — | Ignited and burned |
| Nylon | DuPont | 90 | 4 | 100.0 | — | Ignited and burned |
| Orlon(3) | — | 90 | 4 | — | — | — |
| Penton(3) | Hercules Chemical | 90 | 2 | — | — | — |
| Phenol-Formaldehyde | Durez Plastics Div.,<br>Hooker Electrochem | 90 | 4 | 100.0 | — | Ignited |
| Plexiglass | Rohm and Haas | 90 | 4 | 100.0 | — | Softened and partial solution |
| Polystyrene (Polyflex) | Plax Corp. | 90 | 2 | 9.1 | — | None |
| Polyurethane (green) | Dunlap | 90 | 3 | 8.5 | 50.2 | Partially dissolved |
| Polyurethane (tan) | B. F. Goodrich | 90 | 3 | 56.0 | 59.9 | Completely dissolved |
| Polyurethane (black) | B. F. Goodrich | 90 | 4 | 98.5 | 0.0 | Completely dissolved |
| Thiokol EC-801-LP2 | Thiokol Chem. Corp. | 90 | 4 | 100.0 | — | Burst into flame |
| Thiokol 3000 FA | Thiokol Chem. Corp. | 90 | 4 | 100.0 | — | Dissolved |
| Thiokol 3000 ST | Thiokol Chem. Corp. | 90 | 4 | — | — | — |
| Thiokol 1620 AH | Thiokol Chem. Corp. | 90 | 4 | — | — | — |

(1) Data taken from Reference 4.25 unless otherwise note

(2) Footnote 2, Table 4.4

(3) Reference 4.40

## TABLE 4.12

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH LAMINATES, DIAPHRAGMS, AND ADHESIVES(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Chemelic MI-411 (Teflon fiberglass) | U. S. Gasket | 90 | 2(3) | 11.5 | — | Bleached during screening |
| Duroid 5600 (fiber-reinforced Teflon) | Rogers Corp. | 90 | 3 | 44.7 | 70.1 | None |
| Fairprene PS 57-167 (Viton A, 116 glass) | DuPont | 90 | 3 | 29.0 | 91.6 | Moderate blistering and surface attack |
| Fairprene PS 57-168 (Viton A, Dacron) | DuPont | 90 | 2 | 23.0 | 94.5 | Moderate surface attack |
| Fairprene (Viton A) | | | | | | |
| 5806 | DuPont | 90 | 2 | 48.4 | — | None |
| 5807 | DuPont | 90 | 2 | 53.9 | — | None |
| 5809 | DuPont | 90 | 2 | 7.5 | — | None |
| 80-080 (1/32 inch) | DuPont | 90 | 2 | 4.0 | — | None |
| Glass Resins | Owen-Illinois Tech. Center | 90 | 1 | 1.3 | 97.5 | None |
| Kel-F Dacron, Diaphragm-VL-1101m4 | Vernay Labs, Inc. | 90 | 4 | 95.0 | — | Coatings and Dacron separated in 2 days |
| Kel-F 5160 Diaphragm | Nichols Engineering | 90 | 2 | 30.6 | — | Slightly blistered and tacky |
| Kel-F 5500 (grey) Diaphragm | Nichols Engineering | 90 | 2 | 13.7 | — | Slightly blistered and tacky |
| Kel-F 5500 (grey) on Dacron Diaphragm | Nichols Engineering | 90 | 2 | 43.8 | — | None |
| Korda Flex (Teflon-coated glass fabric) | Chicago Gasket | 90 | 2 | 2.5 | 97.0 | None |
| Polyester Fiberglass | | | | | | |
| Duracor 1000 | Will Corp. | 90 | 3 | 25.9 | 15.7 | Bleached |
| 2000-5 | Will Corp. | 90 | 3 | 18.6 | 81.7 | Bleached |
| 6000-4 | Will Corp. | 90 | 3 | 21.4 | 70.0 | Bleached |
| 6000-8 | Will Corp. | 90 | 3 | 49.5 | 39.8 | Bleached |
| E | Will Corp. | 90 | 3 | 15.0 | 10.7 | Dissolved |
| Red | Buffalo Forge | 90 | 3 | 12.0 | 79.7 | Discolored and bleached |
| Straw | Buffalo Forge | 90 | 3 | 22.0 | 28.0 | Discolored and bleached |
| Ridgidon | Heil Process & Equipment | 90 | 3 | 27.4 | 67.0 | Slightly dissolved and bleached |
| 9711 Silicone Seal Washer DC, Chemloc 607 Adhesive on Aluminum | Kirkhill Rubber | 90 | 3 | 11.6 | 83.4 | None |
| Silastic DC-9711 on Dacron Diaphragm | Kirkhill Rubber | 90 | 3 | 9.7 | 96.4 | Bleached and distorted |
| Vinyl-Coated Fiberglass | Birma Mfg. | 90 | 3 | 49.8 | — | None |
| 9711 Silicone Seal Washer DC A4094 Adhesive (Dow Corning Silicate base) on Aluminum | Kirkhill Rubber | 90 | 3 | 15.5 | 69.1 | None |

(1) Data taken from Reference 4.25

(2) Footnote 2, Table 4.4

(3) After 24-hour screening at 151 F

## TABLE 4.13

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH POROUS MATERIALS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Percent(2) Stability After Test | Effect On Material |
|---|---|---|---|---|---|---|
| Al-Si Mag, Porous Ceramic No. 393 | Lava Corp. of America | 90 | 3 | 100/3 days | — | None |
| Aluminum Oxide, Porous-RA-98 | Norton Abrasives | 90 | 2 | 19.0 | — | None |
| Armalon-Teflon Felt (impregnated) | DuPont | 90 | 3 | 70.0 | — | Bleached |
| Armalon | DuPont | 90 | 3 | 28.0 | — | Bleached |
| Dacron Cloth | | | | | | |
| Dac-2100 | Nat. Filter Media Corp. | 90 | 2 | 5.0 | — | Resiliency decreased |
| Dac-2101 | Nat. Filter Media Corp. | 90 | 2 | 3.0 | — | Resiliency decreased |
| Dac-2102 | Nat. Filter Media Corp. | 90 | 2 | 6.0 | — | Resiliency decreased |
| Filtros C Stone (55 micron) | Filtros Corp. | 90 | 2 | Classification based on experience | | None |
| Glass Cloth G-206-C | Nat. Filter Media Corp. | 90 | 2 | 18.0 | — | None |
| Poroley-30288 Wire | Bendix Filter Div. | 90 | 3 | 100.0 | — | None |
| Porous Kel-F (15-micron pore) | Pall Filtration Corp. | 90 | 2 | 9.8 | 98.0 | Less brittle |
| Porous Porcelain (1.4 micron) | Selas Corp. of America | 90 | 2 | 16.0 | — | None |
| Porous Teflon (9-micron pore) | Pall Filtration Corp. | 90 | 2 | 14.0 | 96.5 | None |
| Rigimesh J Stainless-Steel Wire | Pall Filtration Corp. | 90 | 4 | 100.0 | — | Deep bronzing |
| Sintered 300-Series Stainless-Steel Powder Compact | Calif. Inst. of Tech. | 90 | 4 | 100/2 hours | — | Bronzed and rusted |
| Sintered 302 Stainless-Steel Powder Compact | Amplex Div. | 90 | 4 | 100/2 1/2 hours | — | Bronzed |
| Sintered 316 Stainless-Steel Powder Compact | Titeflex, Inc. | 90 | 4 | 100/24 hours | — | Bronzed heavily |
| Sintered 316 Stainless-Steel Powder Compact | Pall Filtration Corp. | 90 | 4 | 100/24 hours | — | Bronzed |
| Sintered 302B Stainless-Steel Powder Compact | S-K-C Research Assoc. | 90 | 4 | 100/2 hours | — | — |
| Sintered 316 and Cb Stainless-Steel Powder Compact | Rensselaer Poly. Inst. | 90 | 4 | 100/5 hours | — | — |
| Teflon Cloth (25 grade) | Pall Filtration Corp. | 90 | 3 | 20.0 | 79.0 | Completely bleached |
| Teflon Cloth—Repeat (25 grade) | Pall Filtration Corp. | 90 | 2 | 17.0 | 98.0 | None |
| Teflon Cloth (40 grade) Teflon Felt (impregnated) | Pall Filtration Corp. | 90 | 3 | 15.3 | 83.1 | Completely bleached |
| Teflon Cloth T-2300 | Nat. Filter Media Corp. | 90 | 3 | 100.0 | none remaining | Bleached white |
| Teflon Cloth T-2305 | Nat. Filter Media Corp. | 90 | 2 | 28.2 | — | None |
| Zirconium Silicate (10 micron) | Selas Corp. | 90 | 2 | 17.0 | 97.0 | None |

(1) Data taken from Reference 4.25

(2) See Footnote 2, Table 4.4

## TABLE 4.14

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH LUBRICANTS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Impact(2) Sensitive |
|---|---|---|---|---|---|
| Alkaterge C | Commercial Solvents | 90 | 4 | — | Yes |
| Amino Silane Oil and Grease | — | 90 | 4 | — | Yes |
| Apiezon Hard Wax "W" | J. G. Biddle | 90 | 4 | Excessive | — |
| Arochlor 1221 | Monsanto Chem. | 90 | 4 | — | Yes |
| Arochlor 1232 | Monsanto Chem. | 90 | 4 | — | Yes |
| Arochlor 1242 | Monsanto Chem. | 90 | 4 | — | Yes |
| Arochlor 1248 | Monsanto Chem. | 90 | 4 | — | Yes |
| Arochlor 1254 | Monsanto Chem. | 90 | 4 | — | Yes |
| Bardahl | Bardahl Corp. | 90 | 4 | — | Yes |
| Carum 200 | Esso Labs | 90 | 4 | 5.2 | Yes |
| Ceresin Wax | — | 90 | 4 | — | Yes |
| CFE-1 | Carbide and Carbon | 90 | 4 | — | Yes |
| Dichloro-bis-tri-fluoromethyl Benzene | Hooker Electro-Chem. | 90 | 3 | 3.3 | No(3) |
| Dichlorohexafluorobutene | Hooker Electro-Chem. | 90 | 3 | 9.2 | No(3) |
| Fluorolube FS | Hooker-Electro-Chem. | 90 | 2 | 4.2 | No(2) |
| Fluorolube FS + 5-Percent Fluorolube Light Grease | Hooker-Electro-Chem. | 90 | 2 | — | No(3) |
| Fluorolube Heavy Grease 10214 | Hooker-Electro-Chem. | 90 | 2 | 1.7 | No(3) |
| Fluorolube Oil 10213 | Hooker-Electro-Chem. | 90 | 2 | 1.0 | No(3) |
| Fluorolube S | Hooker-Electro-Chem. | 90 | 2 | 2.5 | No(3) |

TABLE 4.14

(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Impact(2) Sensitive |
|---|---|---|---|---|---|
| Fluorolube T | Hooker-Electro-Chem. | 90 | 2 | 8.5 | No(3) |
| Fluorolube Oil, S-30 | Hooker-Electro-Chem. | 90 | 2 | | No(4) |
| Fluorolube Grease, Hg-1200 | Hooker-Electro-Chem. | 90 | 2 | | No(4) |
| Fluorolube Grease, GR-560 | Hooker-Electro-Chem. | 90 | 2 | — | No(4) |
| Formulation: | | | | | |
| F-9 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-16 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-22 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-23 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-27 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-28 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-30 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-32 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-33 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-34 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-35 | Monsanto Chem. | 90 | 4 | — | Yes |
| OS-37 | Monsanto Chem. | 90 | 4 | — | Yes |
| CP-3898-2 | Monsanto Chem. | 90 | 4 | — | Yes |
| Skydrol (uncolored) | Monsanto Chem. | 90 | 4 | 1.0 | Yes |
| Halocarbon Oil 8-25-AV | Halocarbon Products Corp. | 90 | 2 | 1.8 | No(3) |

TABLE 4.14

(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Impact(2) Sensitive |
|---|---|---|---|---|---|
| Halocarbon Oil 10-21 | Halocarbon Products Corp. | 90 | 2 | 2.9 | No(3) |
| Halocarbon Heavy Oil 10-25(6) | Halocarbon Products Corp. | 90 | 2 | — | — |
| Halocarbon Light Oil 11-14 | Halocarbon Products Corp. | 90 | 2 | 2.1 | No(3) |
| Halocarbon Medium Oil 11-21(6) | Halocarbon Products Corp. | 90 | 2 | — | — |
| Halocarbon Stopcock Grease | Halocarbon Products Corp. | 90 | 2 | 1.8 | No(4) |
| Halocarbon High Temperature(7) Stopcock Grease | Halocarbon Products Corp. | 90 | 2 | — | No(4) |
| Halocarbon Grease, 25-10(7) | Halocarbon Products Corp. | 90 | 2 | — | No(4) |
| Hexachlorobutadiene | Hooker Electro-Chem. | 90 | 3 | 3.7 | No(3) |
| Hexachloropropylene | Hooker Electro-Chem. | 90 | 4 | 100.0 | — |
| H-2 Hydraulic Fluid(6) | R. M. Hollingshead Corp. | 90 | 2 | — | — |
| Hydraulic Fluid RPM | Standard Oil of Calif. | 90 | 4 | 1.4 | Yes |
| Hydraulic Oil-Houghton Safe 620 | Houghton | 90 | 3 | 7.1(5) | — |
| Kel-F Alkane | Minn. Min. & Mfg. | 90 | 2 | 1.0 | No(4) |
| Kel-F Light Oil No. 1 | Minn. Min. & Mfg. | 90 | 2 | 1.7 | No(3) |
| Kel-F Heavy Oil No. 10 | Minn. Min. & Mfg. | 90 | 2 | 3.2 | No(3) |
| Kel-F No. 90 Grease | Minn. Min. & Mfg. | 90 | 2 | 33.2 | No(4) |
| Lindo HF (tricresyl phosphate) | Celanese Corp. | 90 | 4 | — | Yes |
| Lindol HFX | Celanese Corp. | 90 | 4 | — | Yes |
| Liqui-Moly Concentrate | Climax Molybdenum | 90 | 4 | — | Yes |
| Lubriseal | Arthur H. Thomas | 90 | 4 | — | Yes |

TABLE 4.14

(Continued)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Impact[(2)] Sensitive |
|---|---|---|---|---|---|
| Mil-G-3278 | — | 90 | 4 | — | Yes |
| Mil-G-4343 | — | 90 | 4 | — | — |
| Mineral Oil | Various | 90 | 4 | -- | Yes |
| Paraffin | Various | 90 | 4 | — | Yes |
| Perfluorolube Grease FCD-759 | DuPont | 90 | 2 | 10.5 | No(3) |
| Perfluorolube Oil FC-331 | DuPont | 90 | 2 | 1.4 | No(3) |
| Perfluorolube Oil FC-332 | DuPont | 90 | 2 | 1.7 | No(3) |
| Perfluorolube Oil FC-333 | DuPont | 90 | 2 | 1.4 | No(3) |
| Perfluorolube Oil FC-334 | DuPont | 90 | 2 | 0.8 | No(3) |
| Perfluorolube Oil FC-335 | DuPont | 90 | 2 | 1.0 | No(3) |
| Petrolatum | Various | 90 | 4 | — | Yes |
| Polychloropentane (stabilized) | Hooker Electro-Chem. | 90 | 4 | — | Yes |
| FR-240AC Grease(9) | DuPont | 90 | - | 1.6 | — |
| FR-240AC Grease (9) | DuPont | 98 | - | 1.6 | — |
| Renex | Atlas Powder | 90 | 4 | — | Yes |
| Silicone XF 224 | Dow-Corning | 90 | 4 | — | Yes |
| Silicone Grease DC-11(8) | Dow-Corning | 90 | 3-4 | — | Yes |
| Silicone Oil DC-7 | Dow-Corning | 90 | 4 | — | Yes |
| Silicone Oil DC-44 | Dow-Corning | 90 | 4 | — | Yes |
| Silicone Oil DC-200 | Dow-Corning | 90 | 3-4 | — | Yes |
| Silicone Oil DC-550 | Dow-Corning | 90 | 4 | — | Yes |

## TABLE 4.14
(Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL Per Week at 151 F | Impact(2) Sensitive |
|---|---|---|---|---|---|
| Silicone Oil DC-701 | Dow-Corning | 90 | 4 | -- | Yes |
| Silicone Oil DC-702 | Dow-Corning | 90 | 4 | -- | Yes |
| Silicone Oil DC-710 | Dow-Corning | 90 | 4 | -- | Yes |
| Silicone Oil GE 2V3733 | General Electric | 90 | 4 | -- | Yes |
| Silicone Oil GE 51346 | General Electric | 90 | 4 | -- | Yes |
| Tectyl | -- | 90 | 4 | -- | Yes |
| 1, 1, 2, 2, Tetrafluoroethyl Dodecylether | DuPont | 90 | 4 | -- | Yes |
| Texaco Uni-Temperature | Texaco | 90 | 4 | -- | -- |
| Tributyl Phosphate | Commercial Solvents | 90 | 4 | -- | Yes |
| Ucon Hydrolube U-4 | Carbide & Carbon Chem. | 90 | 4 | 8.4 (ppt. formed) | -- |

(1) Data from Reference 4.25 unless otherwise noted
(2) No weight-distance data were given with the positive results
(3) Non-impact sensitive to 1 kg-m at room temperature
(4) Non-impact sensitive to 100 ft-lb at room temperature
(5) Non-impact sensitive at 1 kg-m at room temperature, but clouded during 150 F, 7 day test
(6) Reference 4.40
(7) Reference 4.29, 4.40
(8) Reference 4.43
(9) These tests were conducted by smearing the grease on the walls of the container. Contamination from an external source caused the loss of one of the 90-percent $H_2O_2$ and one of the 98-percent $H_2O_2$ samples. The results are therefore from a single analysis (Ref. 4.44)

NOTE: Ref. 4.51 tested a number of fluorolubes with 90-percent $H_2O_2$ at 10 kg-m impact sensitivity and found none which were 100-percent negative under these conditions.

## TABLE 4.14a

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH POTENTIAL LUBRICANTS(1)(2)

NO VISIBLE REACTION

### Halogenated Aliphatic Hydrocarbons

- Polytetrafluoroethylene (solid)
- Tetrafluoroethylene-hexafluoropyropylene copolymer (solid)
- Polychlorotrifluoroethylene (molecular weight < 800)
- Polychlorotrifluoroethylene (molecular weight > 800)
- Perfluorokerosene
- Dispersion of Polytetrafluoroethylene in Trichlorotrifluoroethane (solid)
- Perchloropentacyclodecane (solid)
- Perfluorodiethylcyclohexane (mixed isomers)
- Dichlorodecafluoroheptane
- Chlorofluoro Hydrocarbon (approximate molecular weight 725)
- Chlorofluoro Hydrocarbon (approximate molecular weight 1000)
- Fluorinated Hydrocarbon (77.4 percent F; approximate molecular weight 640)
- Polychlorotrifluoroethylene (approximate molecular weight, 775; 80 percent halogens)

### Silicon Compounds

- Silicon Fluorides
  - Tri(p-trifluoromethyl phenyl) Silicon Fluoride
  - Trilaurysilicon Fluoride
  - Tris (3,5,5-trimethylhexyl) Silicon Fluoride
- Dimethylpolysiloxanes
  - Dimethylpolysiloxane (2 to 500 Cs)
- Fluoropolysiloxanes
  - $HCF_2(CF_3)_5CH_2O[Si(CH_3)_2O]_nCH_2(CF_2)_5CF_2H$, Fluoropolysiloxane, $n = 1-26$

## TABLE 4.14a

(Continued)

NO VISIBLE REACTION (Continued)

Cyclic Fluorosiloxanes

Cyclic Fluorosiloxane (solid)

$CH_3(R)SiOSi(CH_3)(R)OSi(CH_3)(R)O$

$R = CF_3CF_2CF_2CH_2-$

Cyclic Fluorosiloxane (solid)

$CH_3(R)SiOSi(CH_3)(R)OSi(CH_3)(R)O$

$R = CF_3CH_2CH_2-$

Fluorosiloxane Elastomer (solid) Made From

$CF_3(CH_2)_2Si(CH_3)C_2$

Cyclic Fluorosiloxane (solid)

$CH_3(R)SiOSi(CH_3)(R)OSi(CH_3)(R)O$

$R = CF_3CF_2CF_2CH_2-$

Mixed Cyclic Fluorosiloxane (solid)

$CH_3(R)SiO[Si(CH_3)(R)O]_n\ Si(CH_3)(R)O$

$R = CF_3CF_2CF_2CH_2-$ $n = 3$ and higher

Dimethylpolysiloxane-Cyclic

Fluoropolysiloxane Blends

Fluorosiloxane Grease (No. 33 + inorganic gelling agent)

Fluorosiloxane Grease (No. 34 + inorganic gelling agent)

Mixed Dimethylpolysiloxane and Cyclic Fluoropolysiloxane

Mixed Dimethylpolysiloxane (average molecular weight < previous compound)

Halogenated and Nonhalogenated Aromatic Hydrocarbons

3-Heptyl-m-terphenyl

Isopropyl-m-terphenyl

Dinonylnaphthalene (mixed isomers)

1,3-Bis (trifluoromethyl) Benzene

## TABLE 4.14a
(Continued)

**NO VISIBLE REACTION (Continued)**

2,3,5,6-Tetrachlorofluorobenzene (solid)
1,3,5-Trimethyl-2,4,6-Trifluorobenzene (solid)
1,3,5-Trimethyl-2,4-Difluorobenzene
Hexafluorobenzene
2,5-Dichlorobenzotrifluoride
2-Fluorobiphenyl (solid)
3,3'-Difluorobiphenyl (solid)
4,4'-Difluorobiphenyl (solid)
3,6,4'-Trifluorobiphenyl (solid)

### Esters

Mixed Fluoroalkyl Camphorates Fluoroalkyl-$HCF_2(CF_2)_n\ CH_2$- n = 3,5,7
Bis-1H,1H,5H-perfluoropentyl Camphorate
Bis-1H,1H,11H-perfluoroundecyl Camphorate (solid)
Tetrabutyl Pyromellitate
Mixed Fluoroalkyl Pyromellitates
Bis (2,2,3,3,4,4,5,5,-octafluoropentyl)3-methylglutarate
Bis (2,2,3,3,4,4,5,5,6,6,7,7,-dodecafluoroheptyl)3-methylglutarate
2,2,3,3,4,4,-Hexafluoropentyl 1,5-bis (trimethyl acetate)
Bis(1-methylcyclohexylmethyl) Sebacate
Poly (1,1,5,5-tetrahydrohexafluoropentamethylene adipate)(solid)
Bis (2-ethylhexyl) Chlorendate
Dibutyl Chlorendate

### Nitrogen Compounds

Hexadecytriphenylurea
2,2'-Dinitrophenyl Ether (solid)
4,4'-Dinitrophenyl Ether (solid)

## TABLE 4.14a
### (Continued)

**NO VISIBLE REACTION (Continued)**

2,6-Difluoro-3,5-dinitrochlorobenzene (solid)

2,4-Dinitro-5-fluorobromobenzene (solid)

Perfluorotributylamine

Perfluoro Compounds

Polytetrafluoroethylene (solid)

Tetrafluoroethylene-hexafluoropropylene Copolymer (solid)

Perfluorokerosene

Perfluorodiethylcyclohexane (mixed isomers)

Mixed Perfluorocyclic Ether, $C_8F_{16}O$ (five- or six-membered ring with side chain, oxygen in the ring)

Perfluorotributylamine

Perfluorodihexyl Sulfide

4-Chloro-3,5-difluoronitrobenzene (solid)

3,3'-Difluoro-4,4'-dimethoxybiphenyl (solid)

Ethers

Bis(m-phenoxyphenyl) Ether

1,4-bis(cresoxy) Benzene (mixed isomers)

$CF_3CF_2O(CF_2)_2SF_5$

2,2'-Dinitrodiphenyl Ether (solid)

4,4'-Dinitrodiphenyl Ether (solid)

4-Fluoro-6-methoxyacetanilide (solid)

3,3'-Difluoro-4,4'-dimethoxydiphenyl Sulfoxide (solid)

3,5-Difluoro-6-methoxyacetanilide (solid)

Mixed Perfluorocyclic Ether, $C_8F_{16}O$ (five- or six-membered ring with side chain, oxygen in the ring)

# TABLE 4.14a
## (Concluded)

**SOLUBLE IN 90-PERCENT $H_2O_2$ WITH NO VISIBLE SIGN OF REACTION**

2,2,3,3,4,4,5,5-Octafluorohexyl 1,6-bis (trimethylacetate)

2,2,3,3,4,4,5,5-Octafluorohexyl 1,6-bis (3,3-dimethylbutyrate)

Diethylene Glycol Succinate Polyester

Chlorotetrafluorobenzotrifluoride

p-bis(m-trifluoromethylphenoxy) Benzene

**PARTLY MISCIBLE**

2,4,6,3',5' Pentafluorobiphenyl (10-percent decrease in volume)

3,3' Difluoro-6,6' dimethoxybiphenyl (solid; 20-percent decrease in volume)

p-chlorobenzotrifluoride (20-percent decrease in volume)

**SOME COLOR CHANGE**

Bis(p-phenoxyphyenyl) Ether (solid)

3,5-Difluoronitrobenzene

**GELLED ON MIXING**

Tetrachlorodiphenyl Ether (solid)

---

(1) Data taken from Ref. 4.33

(2) During testing, 1 milliliter (liquid) or 1 gram (solid) was mixed with 1 milliliter of 90 weight percent $H_2O_2$.

## TABLE 4.15

## RECOMMENDED JOINT SEALING COMPOUNDS FOR USE WITH(1) 90- AND 98-PERCENT HYDROGEN PEROXIDE

| Name | Supplier | Formulation | Class | Remarks |
|---|---|---|---|---|
| Dixseel | Dixon Corp. | Teflon | 1 | Suitable for small-pipe service |
| T-Film | Eco Engineering | Dispersion Teflon-Water | 1 | Suitable for small-pipe service |
| Teflon Tape | Various | Teflon | 1 | Suitable for most applications |

NOTE: Use sparingly to prevent carry-off into the $H_2O_2$ stream. Avoid threaded connections; use AN flares and flanges.

Compounds Not Recommended

| Compound | Supplier |
|---|---|
| Calbar CB Pipe Seal | Calbar Paint & Varnish |
| Crane Thread Lubricant | Crane |
| Fel-Pro, C-5 | Felt Products Mfg. |
| Graphite Paste | Key Graphite |
| Goop (blue) | Carl A. Pearson |
| Goop (silver) | Carl A. Pearson |
| Cyl-Seal | West Chester Chemical |
| Molybdenite Pipe Dope | |
| Permatex, Aviation Form A Gasket No. 3 | |
| OS-18 Lubricant | Monsanto Chemical |
| Pecora Compound | Pecora Paint |
| Plastic Metal No. 22 | National Engineering Products |
| Rutland Pipe Dope | Rutland Fire Clay |
| Skydrol | Monsanto Chemical |
| Weco No-Gall | Well Equipment Mfg |
| X-Pando | X-Pando Corp. |

TABLE 4.15
(Concluded)

| Compound | Supplier |
|---|---|
| Kel-F Grease No. 90 | Minnesota Mining & Mfg. |
| Tin Plating on Aluminum 6061 | |
| Alcoa Thread Lubricant | Alcoa |
| Rectorseal No. 15 | Rector Well Equipment |

(1) Recommendations taken from Ref. 4.25

## TABLE 4.16

## COMPATIBILITY OF HYDROGEN PEROXIDE WITH CERAMICS, REFRACTORIES, AND MISCELLANEOUS MATERIALS(1)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Agate (natural) | | 90 | 3-4 | 100 | - | None |
| Agate (polished) | Buffalo Meter | ↓ | 3 | 100 | - | None |
| Al-Si-Mag Porcelain | American Lava | | 2 | 17.5 | - | None |
| Alumina (bonded) | General Electric | | 4 | — | - | Destroyed |
| Alundum LA 116 | Norton | | 2 | 19.1 | - | None |
| Bonded Alumina Filter(3) | | | 4 | — | - | |
| Bonded Alundum MR(3) | | | 4 | — | - | |
| Boron Nitride | | | 4 | — | - | |
| Carboloy 44-A | General Electric | | 4 | 100 | 0 | None |
| Carboloy 55-A | General Electric | | 4 | 100 | 0 | Etched |
| Carboloy 78 | General Electric | | 4 | 100 | 0 | None |
| Carboloy 999 | General Electric | | 4 | 100 | 0 | None |
| Ceramic AB-2 | Coors Porcelain | | 2 | 8.5 | - | None |
| Ceramic Al-200 | Coors Porcelain | | 2 | 12.6 | - | None |
| Charcoal | | | 4 | — | - | Ignited |
| Crystalon (SiC) | Norton | | 4 | 100 | - | None |
| Glass, Pyrex(3) | | | 1 | — | - | |
| Glass, Soft(3) | | | 2 | — | - | |
| Graphitar No. 30 | Lee | | 4 | — | - | Dissolved at room temperature |
| Graphite P-5A6(3) | Vickers, Inc. | | 4 | — | - | None |
| Graphite P-5A6, Silver Impregnated | Pure Bond | | 4 | 100 | - | None |
| Graphite P-55, Copper Impregnated | Pure Bond | | 4 | 100 | - | None |

TABLE 4.16

(Concluded)

| Material | Source | $H_2O_2$, weight percent | Class | Percent AOL per Week at 151 F | Percent Stability(2) After Test | Effect on Material |
|---|---|---|---|---|---|---|
| Graphite P-59L, Copper Impregnated | Pure Bond | 90 | 4 | 100 | - | None |
| Graphite P-692 | Pure Bond | ↓ | 4 | Excessive | - | None |
| Karbate | National Carbon Div. | | 4 | 100 | 0 | None |
| KT Silicon Carbide | Carborundum | | 2 | 1.2 | 95.5 | None |
| Norbide | Norton | | 2 | 15.6 | - | None |
| Porcelain (white, chemical)(3) | | | 2 | — | - | |
| Pyroceram(3) | Corning Glass | | 1 | — | - | None |
| Synthetic Sapphire (polished) | Linde | | 1 | 0.8 | - | None |
| Zirconium Silicate | Selas Corp. | | 2 | 7.6 | 97 | None |

(1) Data taken from Ref. 4.25 unless otherwise noted

(2) Footnote 2, Table 4.4

(3) Reference 4.40

# TABLE 4.17

## RESULTS OF EVALUATION OF PROTECTIVE COATINGS FOR 90 W/O HYDROGEN PEROXIDE SERVICE(1, 2)

| Material | Source | Class | Percent AOL per Week at 151 F | Applications | Remarks |
|---|---|---|---|---|---|
| Recommended Coatings for Long Time Contact and Splash Resistance to 90 w/o $H_2O_2$ | | | | | |
| Teflon | | 1 | | Dispersion-coated thermoplastic | In Al 1060, 5-gallon container tests, $H_2O_2$ concentration loss was 35.5 to 54.9 percent from 90.4 percent in 52 weeks |
| Teflon (TFE) | Dielectrix | 1 | - | Dispersion coating | Difficult to obtain nonpermeable coating |
| Teflon (TFE) | Dielectrix | 1 | - | Bladder | Tends to be brittle; multithin layers are rewarding |
| Kel-F | M. W. Kellogg | 1 | - | Dispersion coating (Uniform coatings possible) | In Al 1060, 5-gallon container tests, $H_2O_2$ concentration loss was 0.7 percent in 39 weeks, and 22.9 percent in 79 weeks from 90.0 percent |
| Kel-F on 1060 Al | Metal Cladding, Inc. | 1 | 0.0 | Spray coating only (uniform coatings possible) | No effect on sample; 95 percent stability(2) after test |
| Kel-F on 5254 Al | Metal Cladding, Inc. | 1 | 4.6 | Spray coating only (uniform coatings possible) | No effect on sample; 96 percent stability(2) after test |
| Kel-F on 5652 | Metal Cladding, Inc. | 1 | 3.4 | Spray coating only (uniform coatings possible) | No effect on sample; 92.2 percent stability(2) after test |
| Omni (Viton A) | David Clark | 2 | 2.9<br>0.5(3) | Glass or Teflon cloth impregnated with Viton A | No effect upon exposure to 90-percent $H_2O_2$ for 7 days at 66 C (151 F) |
| Glass Lining (clear, light grey) | Pfaudler Corp. | 1 | 2.4 | Formed glass lining | No effect upon material |
| Glass Lining (cobalt-colored glass) | Pfaudler Corp. | 1 | 3.0 | Formed glass lining | No effect upon material |
| Kanegin (electroless nickel upon mild steel) | Keystone Chromium | 2 | - | Plating | Very slight bronzing after elevated $H_2O_2$ service |
| Kanegin Coated and Tin-Plated Metals | Keystone Chromium | 2 | 9 | Plating | No effect upon material |

## TABLE 4.17
(Continued)

| Material | Source | Class | Percent AOL per Week at 151 F | Applications | Remarks |
|---|---|---|---|---|---|
| Recommended Coatings for Splash-Resistance Service to 90 w/o $H_2O_2$ | | | | | |
| Omni (Viton A) | David Clark | 2 | - | Glass, Dacron, or Teflon cloth impregnated with Viton | Curtains, equipment covers |
| Teflon (TFE sheet) | DuPont | 1 | - | Films | Drop cloths, curtains, covers for equipment |
| Viton A | DuPont | 2 | - | Sheet form | Curtains, cover cloths, etc. |
| Metallic Aluminum (nonvolatile carrier) | Various suppliers | - | - | Paint | Excellent field experience for painting metal surfaces |
| Aluminum Foil | Various suppliers | 1-2 | - | Foil and film | Coverings for various items |
| Plastic Metal No. 22 (plastic paint) | National Engineering Products | 2 | - | Applied as ordinary paint | One small blister in 48 hours; three small blisters in 9 days (most favorable for splash resistance) |
| Mylar (plastic) | DuPont | 1 | - | Film | Coverings, splash shields |
| Scotch Pak (plastic) | Various suppliers | 1 | - | Film | Coverings, splash shields |
| Kanegin (electroless nickel) | Keystone Chromium | 2 | - | Plating | Excellent coating for mild steel and other metals) |
| Tin-Plated Kanegin | Keystone Chromium | 2 | - | Plating | Very low $H_2O_2$ loss upon $H_2O_2$ contact |
| Tygon Paint 7286 TP-81-Clear | | - | - | Applied as ordinary paint | Blistered in 24 hours; no other effects noted |
| Tygon Paint 71253 TY-107B | U.S. Stoneware | - | - | Applied as ordinary paint | Blistered in 24 hours |
| Corrosite No. 521 | Corrosite Corp. | - | - | Applied as ordinary paint | Blistered in 24 hours |
| Corrosite No. 551 | Corrosite Corp. | - | - | Applied as ordinary paint | Blistered in 24 hours |
| Corrosite No. 581 | Corrosite Corp. | - | - | Applied as ordinary paint | Blistered in 24 hours |

## TABLE 4.17
(Continued)

| Material | Source | Class | Percent AGL per Week at 151 F | Applications | Remarks |
|---|---|---|---|---|---|
| Saran Rubber Q-1875 | Dow Chemical | - | - |  | Softened and blistered in 1 week; specially applied by manufacturer |
| MV—Type No. 150 | Gregg | - | - |  | Blistered in 48 hours |
| Amercoat No. 1262 | American Pipe & Construction | - | - |  | Blistered in 43 hours |
| Heilex | Heil Process | - | - |  | One small blister in 24 hours; applied by fabricator |
| P-5, Co-Polymer | Watson Standard | - | - | Applied as ordinary paint | Blistered in 24 hours |
| Neolac Gray No. 8588 | Chamberlain Engineering | - | - | Applied as ordinary paint | Blistered in 24 hours |
| Steelcote Stainless | Steelcote Mfg. | - | - | Applied as ordinary paint | Small blisters overnight |

## TABLE 4.17
## (Concluded)

| Material | Source | Results | Remarks |
|---|---|---|---|
| Coatings Not Recommended for 90 Percent $H_2O_2$ Service | | | |
| Geon Latex 31X | B. F. Goodrich | Blistered in 24 hours | Difficulty encountered in application |
| Flexcoat No. 1 Black | Bison Chemicals | Blistered in 16 hours | Blisters encountered in vapor phase |
| Lithgow LC-600 (grey) | Lithgow | Blistered in 24 hours | Applied by manufacturer |
| Amercoat Red | American Pipe & Construction | Blistered in 7 hours | |
| Prufcoat Medium Grey | Prufcoat Labs | Blistered in 24 hours | Applied by manufacturer |
| Lithgow LC-600 (brown) | Lithgow | Small blisters in 7 hours | Applied by manufacturer |
| Veloform F-10 CPP304 | Firestone Rubber | Blistered heavily in 16 hours | Applied by fabricator |
| Cordo S-255 A | Cordo Chemical | Coating blistered in 12 hours | Applied by dipping |
| Cordo Plastic Coating (E-1 Resin + H-26 Activator) | Cordo Chemical | Excessive $H_2O_2$ decomposition and blister formation | Applied by laboratory per instructions |
| Chromalloy | — | High rate of $H_2O_2$ decomposition and chrome leaching | Applied by manufacturer to low-carbon steel samples |
| Unichrome Drum Lining B-124-17 | United Chromium | Heavy blisters in 20 hours at 30 C; heavy blisters in 3 hours at 66 C | Applied by manufacturer |
| Ucilon System E Coating | United Chromium | | |
| EX 63B Paint | American Paint | | |
| Sealer EC 801 with Accelerator | Minnesota Mining & Mfg | | |
| Penton Lining on 1060 Aluminum | Buffalo Lining & Fabricating | | |

(1) Data taken from Ref. 4.25
(2) Data taken from Ref. 4.29
(3) Percent AOL/month at 86 F

NOTE: The aluminum alloys all show good splash resistance. Any nonflammable plastics or metals listed in the previous tables having Class 1 through 3 are suitable for use as splash resistant materials.

## TABLE 4.18

## EVALUATION OF CLOTHING MATERIALS FOR CONTACT WITH 90 W/O HYDROGEN PEROXIDE(1)

| Sample | Source | Percent AOL per Month at 86 F | Percent AOL per Week at 151 F | Inflammability Drip Tests | | Remarks |
|---|---|---|---|---|---|---|
| | | | | Clean | Soiled | |
| Permeable | | | | | | |
| Dacron | | | | | | |
| Monofilament | U.S. Rubber Co. | 1.0 | 12.1 | No effect | No effect(2) | Apparently no damage |
| Heavy Pile | G. W. Borg Co. | 0.5 | 13.0 | No effect | No effect(2) | Apparently no damage |
| Staple Fabric | Travis Fabrics, Inc. | 0.8 | 13.4 | No effect | No effect(2) | Apparently no damage |
| Saran | | | | | | |
| Monofilament | Saran Yarns Co. | 0.5 | 6.0 | No effect | No effect(2) | Apparently no damage |
| Dacron-Wool | | | | | | |
| 55 to 45 percent | Deering Milliken | 0.7 | 7.1 | No effect | No effect | Weakened |
| Dynel | Burlington Mills | - | - | No effect | Burned | Partially dissolved at 66 C (151 F) |
| Saran (staple) | Saran Yarns Co. | 1.3 | 4.0 | No effect | Burned | Partially dissolved at 66 C (151 F) |
| Vinyon "N" | Milburn Co. | 1.9 | 4.0 | No effect | Burned | Partially dissolved at 66 C (151 F) |
| Impermeable | | | | | | |
| Polyvinylchloride | Milburn Co. | 0.2 | 3.6 | Not tested | | Hardens on prolonged contact at 66 C (151 F); bleaches |
| Flexigrip Zipper (vinyl) | Flexigrip, Inc. | 1.0 | 4.8 | No effect | Distorts | Hardens on prolonged contact at 66 C (151 F) |

(1) Data taken from Ref. 4.25

(2) Some Dacron samples may burn upon contact with 90 percent $H_2O_2$ when soiled with catalyst.

## TABLE 4.18a

## CLOTHING MATERIALS NOT SUITABLE FOR USE WHEN HANDLING 90 W/O HYDROGEN PEROXIDE(1)

| Sample | Effect of Sample on $H_2O_2$ | Effect of $H_2O_2$ on Sample |
|---|---|---|
| Permeable | | |
| Cotton, Drill | Moderate decomposition | Burns readily when soiled |
| Cotton, Rayon (50-50) | Moderate decomposition | Burns readily when soiled |
| Dacron, Viscose (50-50) | Moderate decomposition | Weakens considerably |
| Leather | — | Burns readily |
| Linen, Bleached | Moderate decomposition | Burns readily |
| Linen, Unbleached | Moderate decomposition | Burns readily when soiled |
| Rayon | Moderate decomposition | Burns readily when soiled |
| Silk, Degummed Fiber | — | Dissolved |
| Wool | Moderate decomposition | Weaks considerably; crumbles when touched |
| Impermeable | | |
| Aluminized Cotton Duck | Moderate decomposition | Burns readily when soiled |

(1) Data taken from Ref. 4.25

## TABLE 4.19

## COMPATIBILITY OF VARIOUS METALS WITH 98 W/O HYDROGEN PEROXIDE AT HIGH TEMPERATURES(1)

(Exposure at 270 F for 1 Hour)

| Material | Weight Change During Test(2), gram | $H_2O_2$ Concentration Change, percent | Appearance After Test(3) |
|---|---|---|---|
| Inconel 718(5) | -0.0003 | 11.7 | Light bronzing of the metal |
| 304 Stainless Steel(4) | None | 14.5 | Heavily bronzed |
| 304 Stainless Steel(5) | Not measured | -- | Sample of $H_2O_2$ decomposed violently upon reaching 270 F. No change in specimen appearance. |
| 316 Stainless Steel(4) | -0.0008 | 6.8 | Heavily bronzed |
| 316 Stainless Steel(4) | +0.0013 | 1.2 | No change in specimen appearance |
| 347 Stainless Steel(5) | -0.0002 | 11.2 | Lightly bronzed |
| 347 Stainless Steel(5) | +0.0003 | 1.3 | No change in specimen appearance |
| Hastelloy-C(4) | -0.0014 | 9.0 | Slightly bronzed |
| Hastelloy-X(4) | -0.0036 | 51.8 | No apparent change |
| Equipment Test (Pyrex) | No metal sample | 0.6 | No change in specimen appearance |

## TABLE 4.19

(Concluded)

(1) Data taken from Ref. 4.29.

(2) Weight changes of less than 0.004 gram are not considered significant.

(3) All specimens were examined at 100X after testing. In no case was there any discernible difference in the surfaces of the blanks and the treated specimens other than the reported color change.

(4) The specimens were passivated by treatment for 4 hours in 70-percent $HNO_3$ at room temperature, washed with tap water, rinsed with distilled water, blotted dry with filter paper, and then oven-dried at 220 F.

(5) The specimens were passivated by treatment for 2 hours in 2-percent $Na_2Cr_2O_7$ solution at room temperature, washed with water, immersed in a 20-percent $HNO_3$ solution, rinsed with distilled water, and then oven-dried at 220 F.

## TABLE 4.20

## COMPATIBILITY OF 90-PERCENT HYDROGEN PEROXIDE WITH 1060 AND 1100 ALUMINUM ALLOYS(1)

| Material Form(2) | Surface Condition | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|
| | | Temperature, F | Time, days | AOL | Stability | |
| 1060 Alloy | Unanodized RMS 96 | 110 | 10 | 0.2 | 92.3 | No effect |
| 1060 Alloy, H12 Temper | Unanodized RMS 89 | 110 | 10 | 0.2 | 92.4 | No effect |
| 1060 Alloy | Anodized RMS 96 | 110 | 10 | 0.3 | 97.2 | No effect |
| 1060 Alloy, H12 Temper | Anodized RMS 89 | 110 | 10 | 0.3 | 97.5 | No effect |
| 1060 Alloy | Unanodized | 75 | 10 | 0.6 | 98.8 | No effect |
| 1060 Alloy | Unanodized | 40 | 10 | 0.7 | 99.0 | Discolored |
| 1100 Alloy | Unanodized RMS 20 | 110 | 10 | 1.4 | 95.2 | White coating |
| 1100 Alloy | Anodized RMS 20 | 110 | 10 | 2.0 | 96.7 | Grey coating |

(1) Data taken from Ref. 4.10, 4.12, and 4.13.

(2) Passivation procedure CVA10-62a; no surface treatment; surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.21

## COMPATIBILITY OF 90 W/O HYDROGEN PEROXIDE WITH 6061-T6 ALUMINUM SHEET(1)(2)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Percent | | Exposure | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | AOL | Stability | Temperature, F | Time, days | |
| Unanodized RMS 11-14 | CVA 10-62a | None | 5.4 | 94.2 | 151 | 7 | Frosty sheen |
| Unanodized RMS 47 | North American LA 0110-003 | None | 3.1 | 93.8 | 151 | 7 | Spotty, dull |
| Unanodized RMS 65 | North American LA 0110-003 | None | 2.9 | 96.2 | 151 | 7 | Spotty, dull |
| Unanodized RMS 91 | North American LA 0110-003 | None | 2.3 | 97.3 | 151 | 7 | Spotty, dull |
| Unanodized RMS 207 | North American LA 0110-003 | None | 2.3 | 97.0 | 151 | 7 | Spotty, dull |
| Unanodized RMS 351 | North American LA 0110-003 | None | 3.4 | 96.3 | 151 | 7 | Spotty, dull |
| Unanodized | North American LA 0110-003 | None | 2.9 | 92.4 | 151 | 7 | No effect |
| Unanodized | CVA 10-62a | 1 AOL cycle exposure | 1.8 | 96.9 | 151 | 7 | Dull discoloration |
| Unanodized | CVA 10-62a | 2 AOL cycles exposure | 0.5 | 98.5 | 151 | 7 | Light spotting |
| Unanodized | CVA 10-62a | "Farrelok" 2 AOL cycles | 1.7 | 95.5 | 151 | 7 | No effect |

(1) Data taken from Ref. 4.14, 4.15.

(2) Thickness = 0.063 in.; surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.21
(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Percent |  | Exposure |  | Exposure Response |
|---|---|---|---|---|---|---|---|
|  |  |  | AOL | Stability | Temperature, F | Time, days |  |
| Unanodized | FMC Bulletin 104 | 1 AOL cycle<br>7 days at 151 F | 1.5 | 95.7 | 151 | 7 | Spotted |
| Unanodized | FMC Bulletin 104 | 2 AOL cycles<br>7 days at 151 F | 1.6 | 97.2 | 151 | 7 | Spotted, frosted |
| Unanodized | North American LA 0110-003 | None | 2.9 | 92.4 | 151 | 7 | No effect |
| Unanodized | North American LA 0110-003 | 1 AOL cycle<br>7 days at 151 F | 1.3 | 97.9 | 151 | 7 | Dull grey color |
| Unanodized | North American LA 0110-003 | 2 AOL cycles<br>7 days at 151 F | 1.0 | 98.3 | 151 | 7 | No effect |
| Unanodized | North American LA 0110-003 | None | 12.0 | 86.0 | 151 | 7 | No effect |
| Unanodized RMS 21 | FMC Bulletin 104 | None | 1.1 | 97.3 | 110 | 10 | No effect |
| Unanodized RMS 21 | North American LA 0110-003 | None | 0.9 | 97.7 | 110 | 10 | No effect |
| Unanodized RMS 21 | Walter Kidde 520007 | None | 1.5 | 97.7 | 110 | 10 | No effect |
| Unanodized RMS 21 | McDonnell 13002 | None | 2.2 | 92.9 | 110 | 10 | White deposit |
| Unanodized RMS 21 | CVA 10-62a | None | 2.3 | 97.4 | 110 | 10 | White deposit |

TABLE 4.21

(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Percent | | Exposure | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | AOL | Stability | Temperature, F | Time, days | |
| Unanodized<br>RMS 66 | CVA 10-62a | None | 2.6 | 82.4 | 110 | 10 | No effect |
| Unanodized<br>RMS 100 | CVA 10-62a | None | 2.4 | 85.4 | 110 | 10 | No effect |
| Anodized<br>RMS 13-18 | CVA 10-62a | None | 6.2 | 91.7 | 151 | 7 | Frosty, spotty |
| Anodized<br>RMS 7 | North American<br>LA 0110-003 | None | 0.7 | 97.7 | 151 | 7 | Uniformly dulled |
| Anodized<br>RMS 44 | North American<br>LA 0110-003 | None | 0.9 | 97.5 | 151 | 7 | Uniformly dulled |
| Anodized<br>RMS 87 | North American<br>LA 0110-003 | None | 1.2 | 97.7 | 151 | 7 | Uniformly dulled |
| Anodized<br>RMS 202 | North American<br>LA 0110-003 | None | 1.1 | 97.8 | 151 | 7 | Uniformly dulled |
| Anodized<br>RMS 380 | North American<br>LA 0110-003 | None | 1.1 | 97.8 | 151 | 7 | Uniformly dulled |
| Anodized | CVA 10-62a | None | 2.9 | 96.8 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | 1 AOL cycle<br>7 days at 151 F | 2.1 | 97.6 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | 2 AOL cycles<br>7 days at 151 F | 1.5 | 98.2 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | "Farrellok" | 64.6 | 0.0 | 151 | 7 | No effect |

TABLE 4.21
(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Percent | | Exposure | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | AOL | Stability | Temperature, F | Time, days | |
| Anodized | CVA 10-62a | "Farrellok"<br>1 AOL cycle<br>7 days at 151 F | 7.3 | 0.0 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | "Farrellok"<br>2 AOL cycles<br>7 days at 151 F | 1.4 | 95.4 | 151 | 7 | No effect |
| Anodized | North American LA 0110-003 | None | 2.7 | 97.2 | 151 | 7 | No effect |
| Anodized | North American LA 0110-003 | 1 AOL cycle<br>7 days at 151 F | 1.7 | 97.7 | 151 | 7 | No effect |
| Anodized | North American LA 0110-003 | 2 AOL cycles<br>7 days at 151 F | 1.4 | 98.0 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | 2 weeks storage in $N_2$ gas | 2.1 | 95.3 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | 2 weeks storage in polyethylene at 160 F | 2.6 | 93.8 | 151 | 7 | No effect |
| Anodized | CVA 10-62a | 2 weeks storage in 100 percent RH at 160 F | 5.1 | 90.3 | 151 | 7 | No effect |
| Anodized<br>*S/V Ratio 0.38 $in.^{-1}$ | North American LA 0110-003 | None | 1.8 | 76.9 | 110 | 10 | Spotty, frosted surface |

## TABLE 4.21
(Concluded)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Percent |  | Exposure |  | Exposure Response |
|---|---|---|---|---|---|---|---|
|  |  |  | AOL | Stability | Temperature, F | Time, days |  |
| **Anodized S/V Ratio 0.76 in.$^{-1}$** | North American LA 0110-003 | None | 3.5 | 67.3 | 110 | 10 | Frosted surface |
| **Anodized S/V Ratio 1.15 in.$^{-1}$** | North American LA 0110-003 | None | 5.6 | 43.8 | 110 | 10 | Frosted surface |
| **Anodized S/V Ratio 1.53 in.$^{-1}$** | North American LA 0110-003 | None | 7.8 | 26.8 | 110 | 10 | Spotty, frosted surface |
| **Anodized S/V Ratio 1.91 in.$^{-1}$** | North American LA 0110-003 | None | 7.8 | 0.0 | 110 | 10 | Frosted surface |
| **Anodized RMS 66** | CVA 10-62a | None | 5.5 | 64.4 | 110 | 10 | No effect |
| **Anodized RMS 100** | CVA 10-62a | None | 3.8 | 80.8 | 110 | 10 | No effect |

## TABLE 4.22

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH 304 STAINLESS STEEL(1)

| Material Form (2) | Surface Condition | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| Sheet | RMS 7 | 35-percent $H_2O_2$(3) | 151 | 7 | 9.0 | 86.8 | Spotty bronzing |
| Sheet | RMS 45 | 35-percent $H_2O_2$(3) | 151 | 7 | 12.3 | 81.9 | Spotty bronzing |
| Sheet | RMS 66 | 35-percent $H_2O_2$(3) | 151 | 7 | 10.0 | 85.9 | Spotty bronzing |
| Sheet | RMS 174 | 35-percent $H_2O_2$(3) | 151 | 7 | 10.7 | 83.4 | Spotty bronzing |
| Sheet | RMS 256 | 35-percent $H_2O_2$(3) | 151 | 7 | 11.4 | 80.1 | Spotty bronzing |
| Sheet | RMS 5-8 | None | 151 | 7 | 6.5 | 95.9 | Slight bronzing |
| Annealed Sheet | RMS 14 | None | 110 | 10 | 4.6 | 90.3 | Mottled bronzing |
| Annealed Sheet | RMS 14 | 35-percent $H_2O_2$(3) | 110 | 10 | 3.7 | 90.1 | Light bronzing |

(1) Data taken from Ref. 4.14 and 4.15

(2) Passivation procedure CVA 10-62a; surface/volume ratio = 0.38 $in.^{-1}$

(3) Posttreatment was in 35-percent hydrogen peroxide inhibited with 0.03-percent phosphoric acid

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH 316L STAINLESS STEEL(1)(2)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| Sheet Stock t = 0.063 | | | | | | | |
| RMS 48 | CVA 10-62a | None | 110 | 10 | 4.2 | 85.5 | Spotty bronze |
| RMS 80 | CVA 10-62a | None | 110 | 10 | 3.6 | 87.1 | Spotty bronze |
| RMS 48 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 2.2 | 83.3 | Spotty bronze |
| RMS 80 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 2.0 | 86.1 | Spotty bronze |
| RMS 13 | FMC Bulletin 104 | None | 110 | 10 | 5.4 | 95.7 | Slightly bronzed |
| RMS 13 | North American LA 0110-003 | None | 110 | 10 | 4.6 | 96.7 | Slightly bronzed |
| RMS 13 | Walter Kidde 520007 | None | 110 | 10 | 7.0 | 95.2 | Slightly bronzed |
| RMS 13 | McDonnell A/C 13002 | None | 110 | 10 | 7.8 | 95.4 | Slightly bronzed |
| RMS 13 | CVA 10-62a | None | 110 | 10 | 7.5 | 95.1 | Slightly bronzed |
| Emery Paper Buffed | CVA 10-62a | 35-percent $H_2O_2$ | 75 | 10 | 1.4 | 97.6 | Uniformly bronzed |
| Emery Paper Buffed | CVA 10-62a | 35-percent $H_2O_2$ | 40 | 10 | 1.2 | 99.0 | Lightly bronzed |

## TABLE 4.23

(Concluded)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure |  | Percent |  | Exposure Response |
|---|---|---|---|---|---|---|---|
|  |  |  | Temperature, F | Time, days | AOL | Stability |  |
| Tubing |  |  |  |  |  |  |  |
| RMS 8 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 3.3 | 95.5 | Uniformly bronzed |
| RMS 8 | Walter Kidde 520007 | None | 110 | 10 | 4.1 | 93.6 | Uniformly bronzed |
| RMS 8 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 7 | 2.3 | 95.5 | Lightly bronzed |
| RMS 8 | Walter Kidde 520007 | None | 110 | 7 | 3.0 | 92.8 | Lightly bronzed |
| RMS 8 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 5 | 1.1 | 97.3 | Lightly bronzed |
| RMS 8 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 3 | 0.6 | 98.8 | Lightly bronzed |
| RMS 8 | Walter Kidde 520007 | None | 110 | 3 | 1.1 | 97.6 | Lightly bronzed |

(1) Data taken from Ref. 4.11, 4.12, and 4.18

(2) Sheet stock; surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.24

## COMPATIBILITY OF 90 v/o HYDROGEN PEROXIDE WITH 321 STAINLESS STEEL(1)(2)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| 0.063-Inch Sheet Stock | | | | | | | |
| Emery Paper Buffed | CVA 10-62a | None | 151 | 7 | 10.3 | 87.5 | Spotty bronze |
| Emery Paper Buffed | CVA 10-62a | 1 AOL cycle<br>7 days at 151 F | 151 | 7 | 3.7 | 97.8 | Spotty bronze |
| Emery Paper Buffed | CVA 10-62a | 2 AOL cycles<br>7 days at 151 F | 151 | 7 | 3.6 | 98.6 | Blue-bronze |
| Emery Paper Buffed | CVA 10-62a | 35-percent $H_2O_2$ | 151 | 7 | 7.0 | 93.1 | No effect |
| Emery Paper Buffed | CVA 10-62a | 35-percent $H_2O_2$,<br>1 AOL cycle<br>7 days at 151 F | 151 | 7 | 3.1 | 97.8 | Light bronze |
| Emery Paper Buffed | CVA 10-62a | 35-percent $H_2O_2$;<br>2 AOL cycles<br>7 days at 151 F | 151 | 7 | 2.6 | 98.6 | Light bronze |
| Emery Paper Buffed | CVA 10-62a | "Farrellok" | 151 | 7 | 14.6 | 76.6 | Uniform bronze |
| Emery Paper Buffed | CVA 10-62a | "Farrellok,"<br>1 AOL cycle<br>7 days at 151 F | 151 | 7 | 4.4 | 97.6 | Uniform bronze |

TABLE 4.24

(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure |  | Percent |  | Exposure Response |
|---|---|---|---|---|---|---|---|
|  |  |  | Temperature, F | Time, days | AOL | Stability |  |
| 0.063-Inch Sheet Stock |  |  |  |  |  |  |  |
| Emery Paper Buffed | CVA 10-62a | "Farrellok" +<br>2 AOL cycles<br>7 days at 151 F | 151 | 7 | 3.8 | 98.3 | Orange-bronze |
| Emery Paper Buffed | North American LA 0110-003 | None | 151 | 7 | 18.5 | 59.1 | Uniform bronze |
| Emery Paper Buffed | North American LA 0110-003 | 1 AOL cycle<br>7 days at 151 F | 151 | 7 | 6.4 | 96.5 | Spotty bronze |
| Emery Paper Buffed | North American LA 0110-003 | 2 AOL cycles<br>7 days at 151 F | 151 | 7 | 4.7 | 97.8 | Brown-bronze |
| Emery Paper Buffed | CVA 10-62a | 2 weeks storage in dry $N_2$ gas | 151 | 7 | 5.2 | 94.7 | Spotty bronze |
| Emery Paper Buffed | CVA 10-62a | 2 weeks storage polyethylene bag at 160 F | 151 | 7 | 4.8 | 94.1 | Uniform bronze |
| Emery Paper Buffed | CVA 10-62a | 2 weeks storage 100-percent RH at 160 F | 151 | 7 | 4.8 | 94.9 | Uniform bronze |
| RMS 4-6 | CVA 10-62a | None | 151 | 7 | 7.9 | 94.3 | Light bronze |
| RMS 96 | CVA 10-62a | None | 110 | 10 | 2.9 | 85.7 | Bronzed |
| RMS 50 | CVA 10-62a | None | 110 | 10 | 3.6 | 83.2 | Irregular bronze |
| RMS 96 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 1.7 | 86.9 | Spotty bronze |

## TABLE 4.24

(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| 0.063-Inch Sheet Stock | | | | | | | |
| RMS 50 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 2.9 | 82.8 | Spotty bronze |
| Buffed, S/V Ratio 0.38 in.$^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 10.0 | 55.5 | Severely bronzed |
| Buffed, S/V Ratio 0.76 in.$^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 20.6 | 11.6 | Severely bronzed |
| Buffed, S/V Ratio 1.15 in.$^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 35.2 | 0.0 | Severely bronzed |
| Buffed, S/V Ratio 1.53 in.$^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 51.6 | 0.0 | Severely bronzed |
| Buffed. S/V Ratio 1.91 in.$^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 88.2 | 0.0 | Severely bronzed |

TABLE 4.24

(Continued)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| 0.25-Inch Tubing | | | | | | | |
| Emery Paper Buffed | Detergent clean | None | 110 | 10 | 2.9 | 90.2 | Yellow-bronze |
| Emery Paper Buffed | LTV 308-20-3 | None | 110 | 10 | 2.7 | 93.5 | Faint yellow |
| Emery Paper Buffed | LTV 308-20-3 $HNO_3$ Sol. 75 F | Oven-baked at 750 F | 110 | 10 | 1.4 | 94.3 | Mottled tan-blue |
| Emery Paper Buffed | Detergent clean | Oven-baked at 750 F | 110 | 10 | 2.6 | 89.4 | Iridescent straw-copper |
| Emery Paper Buffed | LTV 308-20-3 | Oven-baked at 600 F | 110 | 10 | 5.0 | 74.7 | Iridescent gray-bronze |
| Emery Paper Buffed | LTV 308-20-3 | Oven-baked at 700 F | 110 | 10 | 3.3 | 81.9 | Iridescent gray-bronze |
| Emery Paper Buffed | LTV 308-20-3 | Oven-baked at 750 F | 110 | 10 | 2.2 | 88.2 | Iridescent gray-orange |
| Emery Paper Buffed | LTV 308-20-3 | Oven-baked at 800 F | 110 | 10 | 0.7 | 97.6 | Light pink-straw color |
| RMS 12 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 10 | 2.4 | 95.1 | Slightly bronzed |
| RMS 12 | Walter Kidde 520007 | None | 110 | 10 | 2.8 | 94.8 | Slightly bronzed |
| Buffed, S/V Ratio 1.91 $in.^{-1}$ | LTV 308-20-3 | None | 110 | 10 | 16.4 | 0.0 | Light bronzing |

TABLE 4.24

(Concluded)

| Surface Condition | Passivation Procedure | Surface Posttreatment | Exposure | | Percent | | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | AOL | Stability | |
| 0.25-Inch Tubing | | | | | | | |
| Buffed, S/V Ratio 1.91 in.$^{-1}$ | North American LA 0110-003 | None | 110 | 10 | 22.5 | 0.0 | Severely bronzed |
| RMS 12 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 7 | 1.8 | 95.5 | Slightly bronzed |
| RMS 12 | Walter Kidde 520007 | None | 110 | 7 | 2.2 | 96.9 | Slightly bronzed |
| RMS 12 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 5 | 1.3 | 96.0 | Lightly bronzed |
| RMS 12 | Walter Kidde 520007 | None | 110 | 5 | 1.4 | 96.6 | Lightly bronzed |
| RMS 12 | CVA 10-62a | 35-percent $H_2O_2$ | 110 | 3 | 0.7 | 98.3 | No effect |
| RMS 12 | Walter Kidde 520007 | None | 110 | 3 | 1.1 | 97.6 | No effect |

(1) Data taken from Ref. 4.13, 4.14, and 4.15

(2) Surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.25

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH SELECTED STAINLESS STEEL ALLOYS(1) (2)

| Stainless-Steel Alloy | Surface Condition | Passivation Procedure | Surface Posttreatment | Percent AOL | Percent Stability | Exposure | | Exposure Response |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Temperature, F | Time, days | |
| 17-H PH<br>Sheet | RMS 7-8 | CVA 10-62a | None | 55.7 | 0.0 | 151 | 7 | No effect |
| 17-4 PH<br>Sheet,<br>HT R-900 | RMS 87 | Walter Kidde 520007 | None | 10.7 | 65.3 | 110 | 10 | No effect |
| 17-4 PH<br>Sheet,<br>HT R-900 | RMS 40 | Walter Kidde 520007 | None | 13.0 | 30.3 | 110 | 10 | No effect |
| 17-4 PH<br>Sheet,<br>HT R-900 | RMS 113 | Walter Kidde 520007 | None | 19.7 | 21.2 | 110 | 10 | Darkened, spotty |
| 17-4 PH<br>Sheet<br>HT R-900 | RMS 113 | Walter Kidde 520007 | None | 18.9 | 24.5 | 110 | 10 | Heavily bronzed |
| 17-7 PH<br>Sheet,<br>HT TH-1050 | RMS 58 | CVA 10-62a | 35-percent $H_2O_2$ | 15.8 | 24.8 | 110 | 10 | Heavily bronzed |
| 17-7 PH<br>Sheet,<br>HT TH-1050 | RMS 57 | CVA 10-62a | None | 13.3 | 58.5 | 110 | 10 | Heavily bronzed |

(1) Data taken from Ref. 4.15

(2) Surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.25
(Concluded)

| Stainless-Steel Alloy | Surface Condition | Passivation Procedure | Surface Posttreatment | Percent AOL | Percent Stability | Exposure | | Exposure Response |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Temperature, F | Time, days | |
| 302 Cold Drawn Wire | RMS 94 | CVA 10–62a | 35-percent $H_2O_2$ | 4.3 | 92.8 | 110 | 10 | Slightly bronzed |
| 302 Cold Drawn Wire | RMS 94 | CVA 10–62a | None | 3.7 | 90.1 | 110 | 10 | Severely bronzed |
| 347 Sheet | RMS 88 | CVA 10–62a | None | 3.4 | 86.5 | 110 | 10 | Bronzed |
| 347 Sheet | RMS 88 | CVA 10–62a | 35-percent $H_2O_2$ | 2.2 | 83.0 | 110 | 10 | Bronzed |
| 347 Sheet | RMS 39 | CVA 10–62a | None | 4.0 | 84.9 | 110 | 10 | Bronzed |
| 347 Sheet | RMS 39 | CVA 10–62a | 35-percent $H_2O_2$ | 3.5 | 83.6 | 110 | 10 | Dull bronze |

## TABLE 4.26

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH VICONE 185 ELASTOMER(1) (2)

| Passivation Procedure | Surface Posttreatment | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|
| | | Temperature F | Time, days | | | |
| North American LA 0110-003 | None | 160 | 7 | 2.5 | 98.9 | Bleached |
| CVA 10-64a | None | 110 | 10 | 0.9 | 92.0 | Bleached |
| CVA 10-64a | 5-percent $HNO_3$ | 110 | 10 | 0.9 | 93.6 | Bleached |
| FMC Bulletin 104 | None | 110 | 10 | 0.4 | 99.4 | Bleached |
| North American LA 0110-003 | None | 110 | 10 | 0.9 | 99.5 | Bleached |
| Walter Kidde 520007 | None | 110 | 10 | 0.2 | 99.4 | Bleached |
| McDonnell A/C 13002 | None | 110 | 10 | 0.5 | 99.4 | Bleached |
| CVA 10-64a | None | 110 | 10 | 0.3 | 99.4 | Bleached |
| CVA 10-64a | 5-percent $HNO_3$ | 75 | 10 | 0.8 | 98.9 | Bleached |
| CVA 10-64a | 5-percent $HNO_3$ | 40 | 10 | 0.8 | 98.7 | Bleached |

(1) Data taken from Ref. 4.12 and 4.16
(2) 0.063-inch sheet stock; surface condition as fabricated

## TABLE 4.27

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH SILASTIC 9711 ELASTOMER SHEET(1) (2)

| Passivation Procedure | Surface Posttreatment | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|
| | | Temperature, F | Time, days | | | |
| North American LA 0110-003 | None | 160 | 7 | 6.5 | 98.8 | Slight blister |
| CVA 10-64a | None | 151 | 7 | 5.3 | 99.2 | No effect |
| CVA 10-64a | 1 AOL cycle<br>7 days at 151 F | 151 | 7 | 5.8 | 98.9 | Dimpled, spotty |
| CVA 10-64a | 2 AOL cycles<br>7 days at 151 F | 151 | 7 | 5.5 | 99.1 | Opaque blisters |
| CVA 10-64a | "Farrellok" | 151 | 7 | 3.4 | 99.2 | No effect |
| CVA 10-64a | "Farrellok"<br>1 AOL cycle<br>7 days at 151 F | 151 | 7 | 4.1 | 99.2 | Spotty |
| CVA 10-64a | "Farrellok" +<br>2 AOL cycles<br>7 days at 151 F | 151 | 7 | 4.1 | 99.1 | Opaque blisters |
| FMC Bulletin 104 | None | | | 4.8 | 99.2 | No effect |
| FMC Bulletin 104 | 1 AOL cycle<br>7 days at 151 F | 151 | 7 | 4.8 | 99.2 | Dimpled, spotty |
| FMC Bulletin 104 | 2 AOL cycles<br>7 days at 151 F | 151 | 7 | 4.6 | 99.2 | Opaque blisters |
| Walter Kidde 520007 | None | 151 | 7 | 5.2 | 99.4 | No effect |

(1) Data taken from Ref. 4.16 and 4.17

(2) Sheet thickness = 0.063 inch; surface/volume ratio (S/V) = 0.38 in.$^{-1}$ except where otherwise noted

TABLE 4.27

(Continued)

| Passivation Procedure | Surface Posttreatment | Exposure |  | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|
|  |  | Temperature, F | Time, days |  |  |  |
| Walter Kidde 520007 | 1 AOL cycle<br>7 days at 151 F | 151 | 7 | 5.5 | 99.0 | Spotty |
| Walter Kidde 520007 | 2 AOL cycles<br>7 days at 151 F | 151 | 7 | 5.2 | 98.6 | Opaque Blisters |
| CVA 10-64a | 2 weeks storage in dry $N_2$ gas | 151 | 7 | 5.7 | 99.0 | No effect |
| CVA 10-64a | 2 weeks storage polyethylene bag at 160 F | 151 | 7 | 5.7 | 99.0 | No effect |
| CVA 10-64a | 2 weeks storage 100-percent RH at 160 F | 151 | 7 | 5.2 | 98.9 | No effect |
| CVA 10-64a | None | 151 | 7 | 4.3 | 98.8 | No effect |
| CVA 10-64a | None | 151 | 7 | 3.7 | 97.4 | Bleached |
| CVA 10-64a | 5-percent $HNO_3$ | 110 | 10 | 2.8 | 96.9 | Bleached |
| North American LA 0110-003 | None | 110 | 10 | 2.9 | 99.2 | Bleached |
| Walter Kidde 520007 | None | 110 | 10 | 1.7 | 99.4 | No effect |
| Walter Kidde 520007 (S/V = 0.76/in.) | None | 110 | 10 | 3.2 | 99.3 | No effect |

## TABLE 4.27
(Concluded)

| Passivation Procedure | Surface Posttreatment | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|
| | | Temperature, F | Time, days | | | |
| Walter Kidde 520007 (S/V = 1.15/in.) | None | 110 | 10 | 5.3 | 99.2 | No effect |
| Walter Kidde 520007 (S/V = 1.53/in.) | None | 110 | 10 | 6.9 | 98.0 | No effect |
| Walter Kidde 520007 (S/V = 1.91/in.) | None | 110 | 10 | 7.9 | 99.1 | No effect |

## TABLE 4.28

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH SELECTED VITON ELASTOMERIC MATERIALS(1) (2)

| Material Form | Passivation Procedure | Surface Posttreatment | Exposure |  | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|---|
|  |  |  | Temperature, F | Time, days |  |  |  |
| Fluorel 2141 1/16-Inch Sheet | North American LA 0110-003 | None | 160 | 7 | 4.3 | 98.2 | Blistered, swelled |
| Fluorel 2141 1/16-Inch Sheet | North American LA 0110-003 | None | 110 | 10 | 1.1 | 98.8 | No effect |
| Parker V359-7 Batch 04107 | CVA 10-64a | None | 151 | 7 | 11.5 | 91.9 | Blistered, exudate |
| Parker 77-545 Batch 03888 | CVA 10-64a | None | 151 | 7 | 5.9 | 95.6 | Blistered, distorted |
| Stillman SR-27-770 | CVA 10-64a | None | 151 | 7 | 2.4 | 98.6 | Light blister |
| Viton A Parker V359-7 | CVA 10-64a | None | 110 | 10 | 2.5 | 95.0 | Bleached black to grey |
| Viton A Parker V359-7 | CVA 10-64a | 5-percent $HNO_3$ | 110 | 10 | 2.4 | 85.8 | Bleached black to grey |

(1) Data taken from Ref. 4.16 and 4.17
(2) Surface condition as fabricated; surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.29

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH SELECTED PLASTICS(1)

| Material Form(2) | Passivation Procedure | Surface Posttreatment | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | | | |
| Aclar 22C 5-Mil Sheet | North American LA 0110-003 | None | 160 | 7 | 0.5 | 98.7 | No effect |
| Aclar 22C 2-Mil Sheet | CVA 10-64a | None | 110 | 10 | 0.5 | 92.4 | No effect |
| Aclar 22C 2-Mil Sheet | CVA 10-64a | 5-percent $HNO_3$ | 110 | 10 | 0.1 | 91.5 | No effect |
| Aclar 22C 5-Mil Sheet | FMC Bulletin 104 | None | 110 | 10 | 0.0 | 99.3 | No effect |
| Aclar 22C 5-Mil Sheet | North American LA 0110-003 | None | 110 | 10 | 0.0 | 99.2 | No effect |
| Aclar 22C 5-Mil Sheet | Walter Kidde 520007 | None | 110 | 10 | 0.2 | 99.4 | No effect |
| Aclar 22C 5-Mil Sheet | McDonnell A/C 13002 | None | 110 | 10 | 0.0 | 99.2 | No effect |
| Aclar 22C 5-Mil Sheet | CVA 10-64a | None | 110 | 10 | 0.0 | 99.5 | No effect |

(1) Data taken from Ref. 4.17
(2) Surface/volume ratio = 0.38 in.$^{-1}$

## TABLE 4.29
(Concluded)

| Material Form$^{(2)}$ | Passivation Procedure | Surface Posttreatment | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature F | Time, days | | | |
| Aclar 22C 20-Mil Sheet | North American LA 0110-003 | None | 110 | 10 | 0.1 | 99.1 | No effect |
| Aclar 33C 5-Mil Sheet | CVA 10-64a | None | 110 | 10 | 1.2 | 98.7 | No effect |
| Aclar 33C 5-Mil Sheet | CVA 10-64a | 5-percent $HNO_3$ | 110 | 10 | 2.1 | 97.9 | No effect |
| "Fluorogold" Polytetra-fluoroethylene | CVA 10-64a | None | 151 | 7 | 2.7 | 98.8 | Bleached gold to white |

# TABLE 4.30

## COMPATIBILITY OF 90 w/o HYDROGEN PEROXIDE WITH SELECTED COMPOSITE MATERIALS(1) (2)

| Composite | Surface Condition | Passivation Procedure | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | | | |
| 6061-T6 Al | Unanodized | North American<br>LA 0110-003 | 160 | 7 | 10.6 | 87.2 | No effect |
| + | | | | | | | |
| Aclar 22C | As fabricated | | | | | | No effect |
| 6061-T6 Al | Unanodized | North American<br>LA 0110-003 | 160 | 7 | 10.2 | 92.9 | Silastic adhered to aluminum |
| + | | | | | | | |
| Silastic 9711 | As fabricated | | | | | | |
| 6061-T6 Al | Unanodized | North American<br>LA 0110-003 | 160 | 7 | 13.2 | 83.0 | Slight adhesion, Al-Vicone |
| + | | | | | | | |
| Vicone 185 | As fabricated | | | | | | |
| 6061-T6 Al | Unanodized | North American<br>LA 0110-003 | 160 | 7 | 10.2 | 90.6 | Al etched, Fluorel blistered |
| + | | | | | | | |
| Fluorel 2141 | As fabricated | | | | | | |
| 1060 Al | Anodized | FMC Bulletin<br>104 | 151 | 7 | 3.3 | 95.4 | Frosted Al surface |
| + | | | | | | | |
| 6061-T6 Al | Anodized | | | | | | |
| 6061-T6 Al | Anodized | FMC Bulletin<br>104 | 151 | 7 | 14.1 | 78.4 | White oxide |
| + | | | | | | | |
| 321 SS | Buffed | | | | | | Bronzed severely |
| 6061-T6 Al | Anodized | FMC Bulletin<br>104 | 151 | 7 | 14.0 | 30.6 | White oxide |
| + | | | | | | | |
| 316L SS | Buffed | | | | | | Bronzed |

(1) Data taken from Ref. 4.11
(2) Surface/volume ratio = 0.38 in.$^{-1}$

TABLE 4.30

(Concluded)

| Composite | Surface Condition | Passivation Procedure | Exposure | | Percent AOL | Percent Stability | Exposure Response |
|---|---|---|---|---|---|---|---|
| | | | Temperature, F | Time, days | | | |
| 321 SS | Buffed | FMC Bulletin 104 | 151 | 7 | 24.0 | 45.2 | Severely bronzed |
| + | | | | | | | |
| 316L SS | Buffed | | | | | | |
| 1060 Al | Anodized | FMC Bulletin 104 | 110 | 10 | 0.4 | 98.3 | No effect |
| + | | | | | | | |
| 6061-T6 Al | Anodized | | | | | | No effect |
| 6061-T6 Al | Anodized | FMC Bulletin 104 | 110 | 10 | 3.7 | 89.8 | Thin oxide |
| + | | | | | | | |
| 321 SS | Buffed | | | | | | Bronzed |
| 6061-T6 Al | Anodized | FMC Bulletin 104 | 110 | 10 | 2.4 | 91.5 | Thin oxide |
| + | | | | | | | |
| 316L SS | Buffed | | | | | | Bronzed |
| 321 SS | Buffed | FMC Bulletin 104 | 110 | 10 | 4.9 | 85.6 | Severely bronzed |
| + | | | | | | | |
| 316L SS | Buffed | | | | | | |

TABLE 4.31

HETEROGENEOUS DECOMPOSITION RATE OF HYDROGEN PEROXIDE
AS A FUNCTION OF SURFACE PREPARATION(1)

| $H_2O_2$, w/o | Surface |  | S/V $cm^{-1}$ | Decomposition Rate at 212 F |  |  |
|---|---|---|---|---|---|---|
|  | Type | Preparation(2) |  | Overall $day^{-1}$ | Blank(3) $day^{-1}$ | $k_2$,(5) cm/day |
| 90(4) | 1260 Aluminum | a,b,h | 1.90 | 0.0626 | 0.0009 | 0.032 |
| 90 | 1260 Aluminum | a,b,g,h | 2.29 | 0.0309 | 0.0144 | 0.0072 |
| 90 | 1260 Aluminum | a,b,i | 1.71 | 0.0168 | 0.0008 | 0.0094 |
| 90 | 1260 Aluminum | a,b,g,i | 2.18 | 0.0164 | 0.0042 | 0.0056 |
| 90 | 1260 Aluminum | a,b,j | 2.06 | 0.0148 | 0.0009 | 0.0067 |
| 90 | 1260 Aluminum | a,b,j,g | 2.66 | 0.0093 | 0.0048 | 0.0017 |
| 90 | 1260 Aluminum | a,b,k | 1.65 | 0.0135 | 0.0009 | 0.0077 |
| 90 | 1260 Aluminum | a,b,g,k | 2.19 | 0.0098 | 0.0053 | 0.0021 |
| 90 | 1260 Aluminum | q | 2.01 | 0.0459 | 0.0051 | 0.020 |
| 90 | 1260 Aluminum | g,q | 2.08 | 0.0325 | 0.0111 | 0.0103 |
| 90 | 301-T Stainless Steel | a,c,j | 1.85 | 3.84 | 0.0019 | 2.07 |
| 90 | 301-T Stainless Steel | a,l | 2.15 | 3.03 | 0.0011 | 1.41 |
| 90 | 301-T Stainless Steel | a,c,m | 2.25 | 5.47 | 0.0009 | 2.42 |
| 90 | 2014 Aluminum | a,b,e,f | 1.01 | 0.150 | 0.0066 | 0.141 |
| 90 | 2014 Aluminum | a,b,e,f,g | 0.95 | 0.0156 | 0.0139 | 0.0018 |
| 90 | 2219 Aluminum | a,b,e,f | 0.95 | 1.8 | 0.008 | 1.9 |
| 90 | 2219 Aluminum | a,b,e,f,g | 1.02 | 0.196 | 0.142 | 0.053 |

## TABLE 4.31

(Continued)

| $H_2O_2$, w/o | Surface |  | S/V cm$^{-1}$ | Decomposition Rate at 212 F |  |  |
|---|---|---|---|---|---|---|
|  | Type | Preparation |  | Overall day$^{-1}$ | Blank day$^{-1}$ | $k_2$,$^{(5)}$ cm/day |
| 90 | 7039 Aluminum | a | 2.29 | 0.343 | 0.0010 | 0.149 |
| 90 | 7039 Aluminum | a,g | 2.97 | 0.0856 | 0.0127 | 0.024 |
| 90 | 7039 Aluminum | a,b,e,f | 2.49 | 0.0709 | 0.0008 | 0.028 |
| 90 | 7039 Aluminum | a,b,e,f,g | 4.53 | 0.0723 | 0.0090 | 0.0140 |
| 90 | 7039 Aluminum | a,b,e,f | 1.07 | 0.0562 | 0.0063 | 0.047 |
| 90 | 7039 Aluminum | a,b,e,f,g | 1.05 | 0.0204 | 0.0063 | 0.0134 |
| 90 | 7039 Aluminum | a,b,e,f,g | 2.32 | 0.0364 | 0.0013 | 0.0151 |
| 98$^{(6)}$ | 7039 Aluminum | a,b,e,f,g | 4.30 | 0.0682 | 0.0314 | 0.0086 |
| 90 | 7039 Aluminum | a,b,e,f,g | 4.24 | 0.0589 | 0.0063 | 0.0124 |
| 98 | 7039 Aluminum | a,b,e,f,g | 4.39 | 0.0960 | 0.0050 | 0.0207 |
| 98 | 7039 Aluminum | a,b,e,f,g | 4.67 | 0.124 | 0.006 | 0.0252 |
| 90 | 1260 Aluminum | a,b,e,f,g | 2.07 | 0.0066 | 0.0032 | 0.0016 |
| 98 | 1260 Aluminum | a,b,e,f,g | 1.97 | 0.0108 | 0.0024 | 0.0043 |
| 98 | 1260 Aluminum | a,b,e,f,g | 2.22 | 0.0098 | 0.0025 | 0.0033 |
| 90 | 5052 Aluminum | a,b,e,f,g | 2.93 | 0.0124 | 0.0065 | 0.0020 |
| 98 | 5052 Aluminum | a,b,e,f,g | 2.22 | 0.0168 | 0.0024 | 0.0065 |
| 98 | 5052 Aluminum | a,b,e,f,g | 2.97 | 0.0145 | 0.0047 | 0.0033 |
| 90 | Kel-F | f | 3.75 | 0.0191 | 0.0011 | 0.0048 |
| 90 | Kel-F | f,g | 4.68 | 0.0202 | 0.0015 | 0.0040 |
| 90 | Teflon FEP | f | 6.02 | 0.0717 | 0.0027 | 0.0115 |
| 90 | Teflon FEP | f,g | 6.97 | 0.0783 | 0.0011 | 0.0111 |
| 90 | Tin on 5052 Aluminum | s | 2.00 | 0.0536 | 0.0009 | 0.026 |
| 90 | Tin on 5052 Aluminum | g,s | 3.05 | 0.0397 | 0.0126 | 0.0089 |
| 90$^{(6)}$ | Tin on 5052 Aluminum | s,t | 1.77 | 0.0154 | 0.0068 | 0.0049 |
| 90$^{(6)}$ | Tin on 5052 Aluminum | g,s,t | 2.33 | 0.0210 | 0.0015 | 0.0084 |

## TABLE 4.31
(Continued)

| $H_2O_2$, w/o | Surface | | S/V $cm^{-1}$ | Decomposition Rate at 212 F | | |
|---|---|---|---|---|---|---|
| | Type | Preparation | | Overall $day^{-1}$ | Blank $day^{-1}$ | $k_2$,(5) cm/day |
| 90(7) | Tin on 1260 Aluminum | u | 2.61 | 0.0541 | 0.0041 | 0.0191 |
| 90(7) | Tin on 1260 Aluminum | g,u | 2.62 | 0.0712 | 0.0395 | 0.0121 |
| 90(7) | Tin on 1260 Aluminum | u | 2.15 | 0.0315 | 0.0047 | 0.0124 |
| 90(7) | Tin on 1260 Aluminum | g,u | 2.22 | 0.0397 | 0.0261 | 0.0061 |
| | | | | Decomposition Rate at 176 F | | |
| 98 | 301-T Stainless Steel | a,g | 1.68 | 1.37 | 0.000 | 0.82 |
| 98 | 301-T Stainless Steel | a,g | 2.10 | 1.31 | 0.004 | 0.62 |
| 90 | 301-T Stainless Steel | a,c,e,f,g | 1.83 | 1.12 | 0.001 | 0.61 |
| 90 | 301-T Stainless Steel | a,c,e,f,g | 1.83 | 1.29 | 0.659 | 0.34 |
| 90 | 347 Stainless Steel | a,c,e,f,g | 1.72 | 0.944 | 0.001 | 0.55 |
| 90 | 347 Stainless Steel | a,c,e,f,g | 1.72 | 1.38 | 0.544 | 0.48 |
| 90 | AM355 Stainless Steel | a,c,e,f | 1.74 | 1.13 | 0.000 | 0.64 |
| 90 | AM355 Stainless Steel | a,c,e,f,g | 2.39 | 2.15 | 0.146 | 0.84 |
| 90 | Almar 18-250 | a,c,e,f | 1.85 | 0.074 | 0.001 | 0.039 |
| 90 | Almar 18-250 | a,c,e,f,g | 2.15 | 0.095 | 0.006 | 0.041 |
| 90 | Almar 18-250 | a,c,e,f,g | 1.95 | 0.187 | 0.006 | 0.093 |
| 98 | Almar 18-250 | a,c,e,f,g | 2.11 | 0.189 | 0.004 | 0.088 |
| 90 | Almar 18-250 | a,c,e,f,g | 2.14 | 0.086 | 0.005 | 0.038 |
| 98 | Almar 18-250 | a,c,e,f,g | 2.05 | 0.112 | 0.002 | 0.054 |
| 90 | 301-T Stainless Steel | a,c,j | 1.85 | 1.68 | 0.000 | 0.91 |
| 90 | 301-T Stainless Steel | a,c,g,j | 2.24 | 1.63 | 0.029 | 0.72 |
| 90 | 301-T Stainless Steel | a,g,l | 2.76 | 1.21 | 0.088 | 0.41 |
| 90 | 301-T Stainless Steel | a,c,m | 2.25 | 1.49 | 0.000 | 0.66 |
| 90 | 301-T Stainless Steel | a,c,g,m | 2.76 | 3.11 | 0.243 | 1.04 |
| 90 | 301-T Stainless Steel | n,p | 2.15 | 1.16 | 0.001 | 0.54 |

TABLE 4.31

(Concluded)

| $H_2O_2$, w o | Surface | | S/V cm$^{-1}$ | Decomposition Rate at 77 F | | |
|---|---|---|---|---|---|---|
| | Type | Preparation | | Overall day$^{-1}$ | Blank day$^{-1}$ | $k_2$,(5) cm/day |
| 90 | 347 Stainless Steel | a,c,e,f,g | 1.72 | 0.00588 | 0.00182 | 0.00236 |
| | | | | Decomposition Rate at 32 F | | |
| 90 | 301-T Stainless Steel | a,c,e,f,g | 1.83 | 0.00035 | 0.00010 | 0.00014 |

(1)Data taken from Ref. 4.9

(2)Surface preparation according to Table 4.31a

(3)For samples without treatment g, the blank is determined before addition of the test sample. With treatment g after repeated replacement of $H_2O_2$, the blank is determined after test and removal of the sample. The blank includes the homogeneous decomposition by contaminants and the heterogeneous decomposition due to the vessel walls, including any contaminants absorved there.

(4)90 w/o $H_2O_2$ containing $3.4 \times 10^{-5}$ mg/l $Na_2Sn(OH)_6$ and $6.9 \times 10^{-5}$ mg/l $HNO_3$ stabilizer

(5)$K_2$ represents a specific rate constant for an assumed first order reaction at the liquid-surface interface

(6)98 w/o $H_2O_2$ containing $8.4 \times 10^{-6}$ mg/l tin stabilizer

(7)99 w/o $H_2O_2$ containing no stabilizer

## TABLE 4.31a

## PROCEDURES USED FOR SURFACE PREPARATION IN TABLE 4.31

| Note | Preparation Procedure |
|---|---|
| a | Sample degreased in aromatic solvent followed by a rinse in acetone, all at room temperature |
| b | Sample submerged in 1-percent NaOH for 10 minutes at room temperature |
| c | Sample submerged in 10-percent NaOH for 16 hours at room temperature |
| d | Sample submerged in 1-percent $HNO_3$ for 5 minutes at room temperature |
| e | Sample submerged in 35-percent $HNO_3$ for 16 hours at room temperature |
| f | Sample submerged in HP-90 until used for test, at room temperature |
| g | Sample submerged in stabilized HP-90 at the temperature of the test for 1- to 16-hour periods, followed by repeat treatments with fresh HP-90 until steady-state conditions appear to be achieved |
| h | Sample submerged in fused stearic acid for 1 hour at 80 to 100 C immediately after treatment by Procedure b |
| i | Sample submerged in 2-percent ethylene-diaminetetraacetic acid in 30-percent $H_2SO_4$ for 30 minutes at 80 to 90 C |
| j | Sample submerged in 1-percent disodium ethylenediaminetetraacetic acid in 35-percent $HNO_3$ |
| k | Sample submerged in fused phthalic anhydride for 1 hour at 140 to 150 C immediately after treatment by Procedure b |
| l | Sample submerged in Viscasil 100,000, then wiped dry with absorbent tissue |
| m | Sample submerged in 85-percent $H_3PO_4$ for 16 hours at room temperature |

## TABLE 4.31a
(Concluded)

| Note | Preparation Procedure |
|---|---|
| n | Sample submerged in 35-percent $HNO_3$ for 1 hour at 50 to 70 C |
| p | Sample submerged in 1-percent Viscasil in benzene, dried, resubmerged, and dried |
| q | Sample anodized in 25-percent $H_3PO_4$ at 1 amp/sq decimeter for 6 minutes at room temperature |
| s | Samples submerged in 2-percent NaOH for 2 hours, then in 2-percent $HNO_3$ for 10 minutes, then zincated. Samples zincated in 16-percent $Na_2ZnO_2$ - 40-percent NaOH solution for 30 seconds at room temperature. Samples were then rinsed well and submerged in 2-percent $HNO_3$ for 1 minute. Samples were then zincated again, rinsed, and submerged in 2-percent $HNO_3$ for 1 minute again. Samples were then electroplated by submerging in 6.4-percent stannous sulfate, 5.0-percent sulfamic acid, 0.5-percent dihydroxydiphenyl sulfone solution with the current on and maintained for 6 minutes at room temperature at 0.022 amp/cm$^2$ (20 amp/sq ft). Samples were then rinsed well and submerged in HP-90 for 20 hours. |
| t | Samples previously plated by procedure s were given an additional tin plate by submerging in 5.0-percent stannous sulfate, 5.0-percent sulfuric acid, 5.0-percent sodium sulfate, 0.4-percent gelatin, 0.2-percent m-cresol solution with the current on and maintained for 6 minutes at room temperature at 0.022 amp/cm$^2$. Samples were then rinsed well and submerged in HP-90 for 20 hours. |
| u | Samples were treated as in procedure s through the first zincating step. Samples were then zinc electroplated in 0.05-percent zinc chloride, 0.05-percent sodium cyanide, 1-percent sodium hydroxide solution for 1 minute at room temperature at 0.022 amp/cm$^2$. Samples were then rinsed and submerged in 2-percent $HNO_3$ for 1 minute and then tin electroplated as in s. The tin plate was then fused in a furnace at 265 C and then tin electroplated a second time. Samples were then rinsed well and submerged in HP-90 for 20 hours. |

TABLE 4.32

COMPARISON OF THE VARIOUS METHODS OF TANK TEMPERATURE MEASUREMENT IN ORDER OF INCREASING COST (REF.4.64)

| Methods | Advantages | Disadvantages | Approximate Cost |
|---|---|---|---|
| 1. Bare hand on tank surface | A. Low cost<br>B. Unlimited number of sensing points | A. Poor accuracy | |
| 2. Temperature-sensitive paint on tank surface | A. Low cost<br>B. Large areas could be covered | A. Limited number of sensitive temperatures<br>B. Adversely affected by $H_2S$, $SO_2$ and $NH_3$ | \$25 to \$50 |
| 3. Spot surface temperature consisting of bimetallic dial thermometer with sensitive part in aluminum block affixed to lower section of tank surface and insulated (used by Shell Chemical without alarm) | A. Low cost<br>B. Actual temperature indication<br>C. Linear temperature scale<br>D. Not affected by high vapor space temperature | A. Some ambient temperature effects | \$50 to \$75 |
| 4. Same as No. 3 but installed in thermal well below liquid level | A. Relatively inexpensive<br>B. Measures actual liquid temperature<br>C. Linear temperature scale<br>D. Not affected by high vapor space temperature<br>E. Not affected by ambient temperature | A. Nozzle required | \$75 to \$100 |
| 5. Spot surface or thermal well installation using gas-filled thermal system with or without alarm contacts | Same as 3 and 4 | Same as 3 and 4 | \$200 to \$350 |
| 6. Surface temperature consisting of gas-filled dial thermometer with sensitive part in contact | A. Nozzle not required<br>B. Measures average surface temperature<br>C. Linear temperature scale | A. Same ambient effects<br>B. Vapor space temperature would affect temperature indication at low liquid | \$300 to \$400 |

|  |  |  |  |
|---|---|---|---|
| 5. Spot surface or thermal well installation using gas-filled thermal system with or without alarm contacts | Same as 3 and 4 | Same as 3 and 4 | $200 to $350 |
| 6. Surface temperature consisting of gas-filled dial thermometer with sensitive part in contact with a section of the tank from horizontal centerline to bottom of the tank. Insulation applied. | A. Nozzle not required<br>B. Measures average surface temperature<br>C. Linear temperature scale | A. Same ambient effects<br>B. Vapor space temperature would affect temperature indication at low liquid level | $300 to $400 |
| 7. Surface temperature (Belly-Band type) recorder consisting of vapor tension capillary and insulated | A. Nozzle not required<br>B. Contacts large surface area<br>C. Permanent temperature record | A. Thermal system tends to record warmest temperature along capillary<br>1. Would record vapor space temperature any time vapor is warmer than liquid<br>B. Cost<br>C. Temperature scale not linear and very difficult to read in lower range<br>D. Good surface contact required<br>E. Some ambient effect | $400 to $500 |
| 8. Same as 7 except using gas-filled capillary system | Same as 7 plus<br>D. Linear temperature scale<br>E. Indicates average surface temperature | A. Would average vapor space and liquid surface temperature<br>B. Good surface contact required<br>C. Some ambient effect<br>D. Cost | $300 to $500 |
| 9. Weston Average Resistance Tank Temperature System consisting of an indicator switch to dial in the proper resistance corresponding to the liquid level | A. Up to six liquid levels<br>B. Average temperatures below liquid level | A. Cost<br>B. Maintenance<br>C. Must enter tank with probe<br>D. Must know liquid level | $1,000+ |
| 10. Multi-Point Temperature Recorder with or without alarm contact. (Used by Shell Chemical without alarm.) | A. Could also record ambient temperature<br>B. Permanent visual record of all temperatures<br>C. Linear scale | A. Cost<br>B. Maintenance | $2,000 to $2,500 |

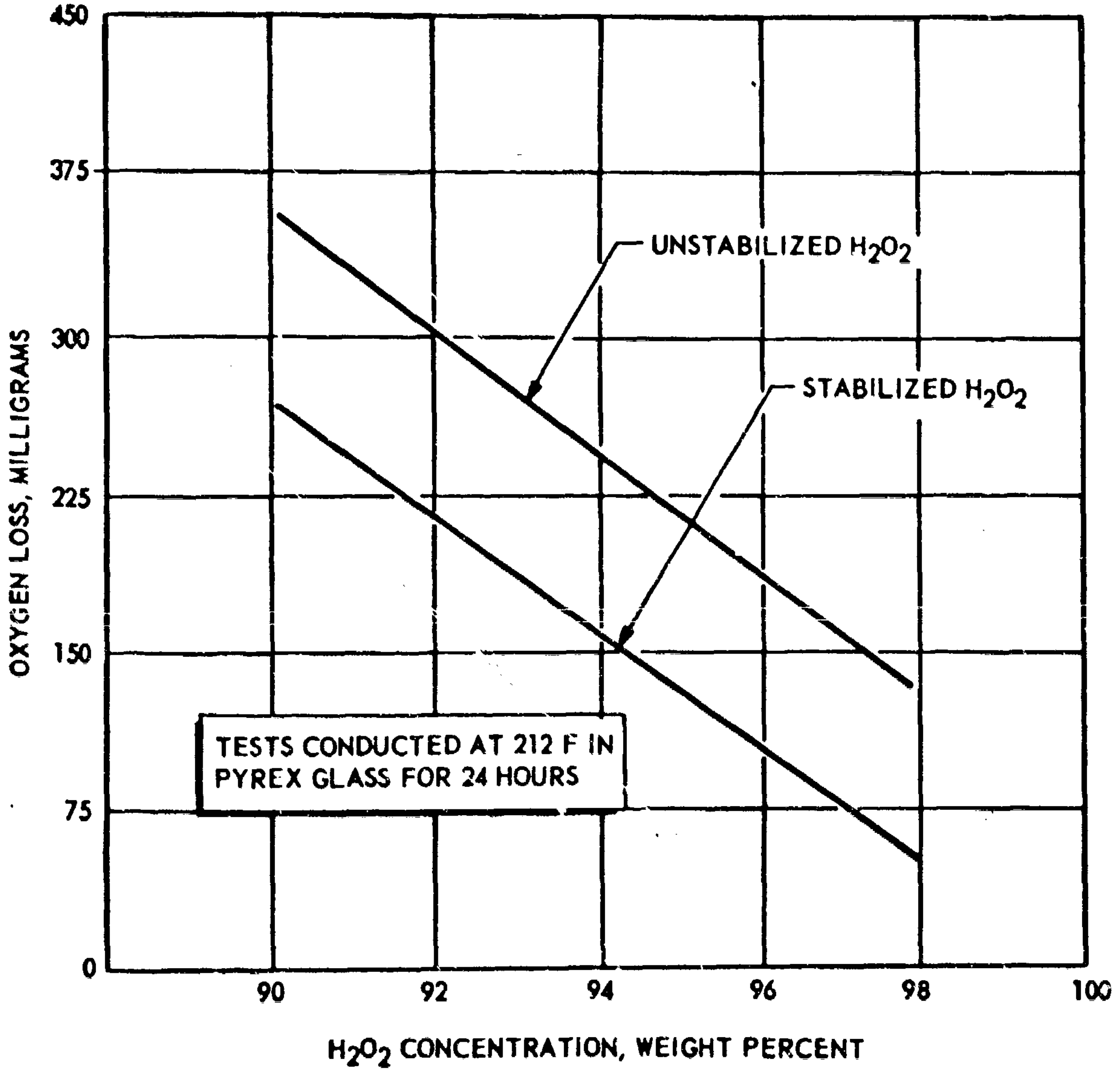


Figure 4.1. Stability of Hydrogen Peroxide as a Function of Concentration (Ref. 4.2)

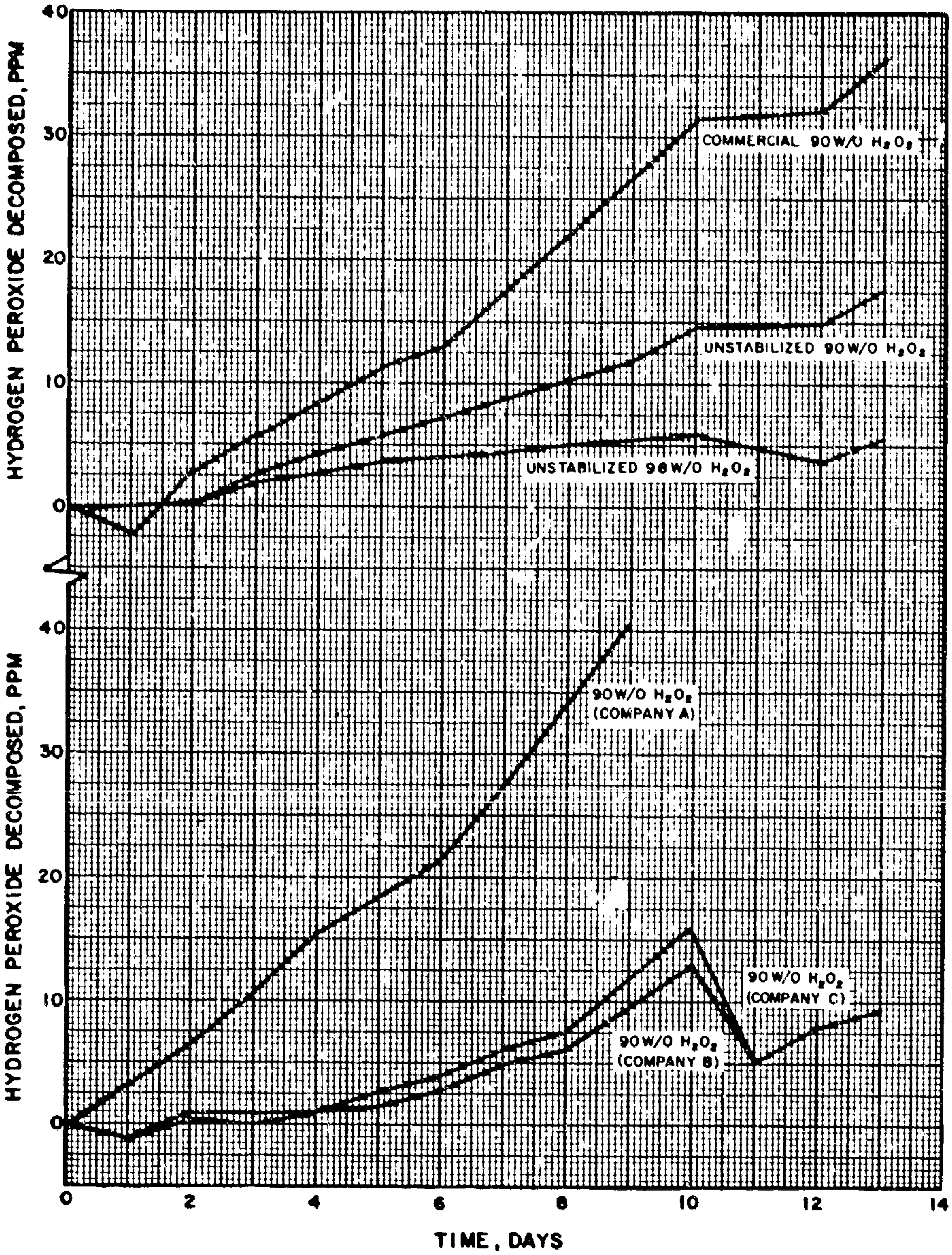


Figure 4.2. Typical Decomposition Rates for Various Hydrogen Peroxide Samples at 32 F (Ref. 4.6)

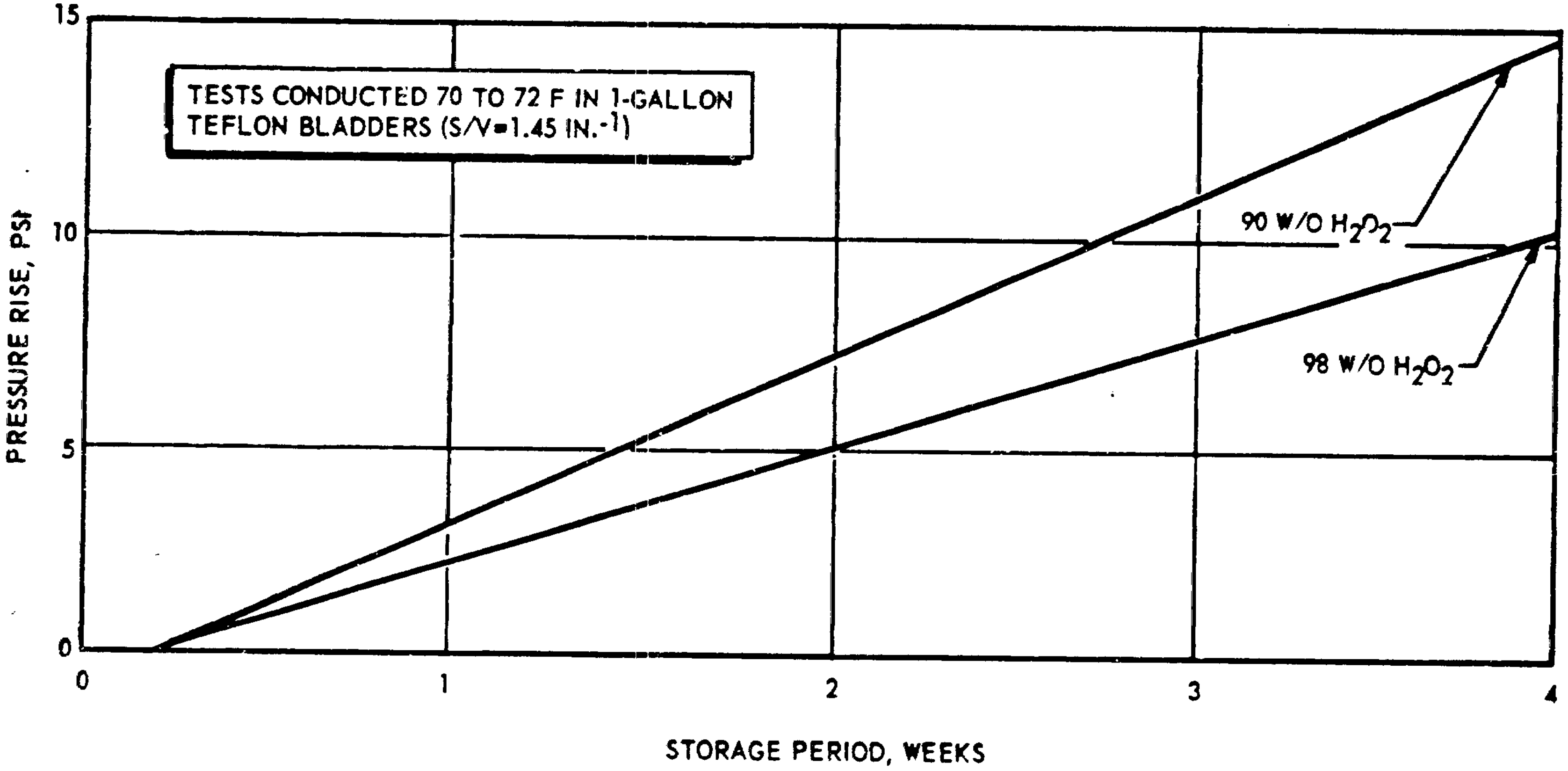


Figure 4.3. Results of Sealed Storage Tests With Unstabilized 90 w/o and 98 w/o $H_2O_2$ (Ref. 4.7)

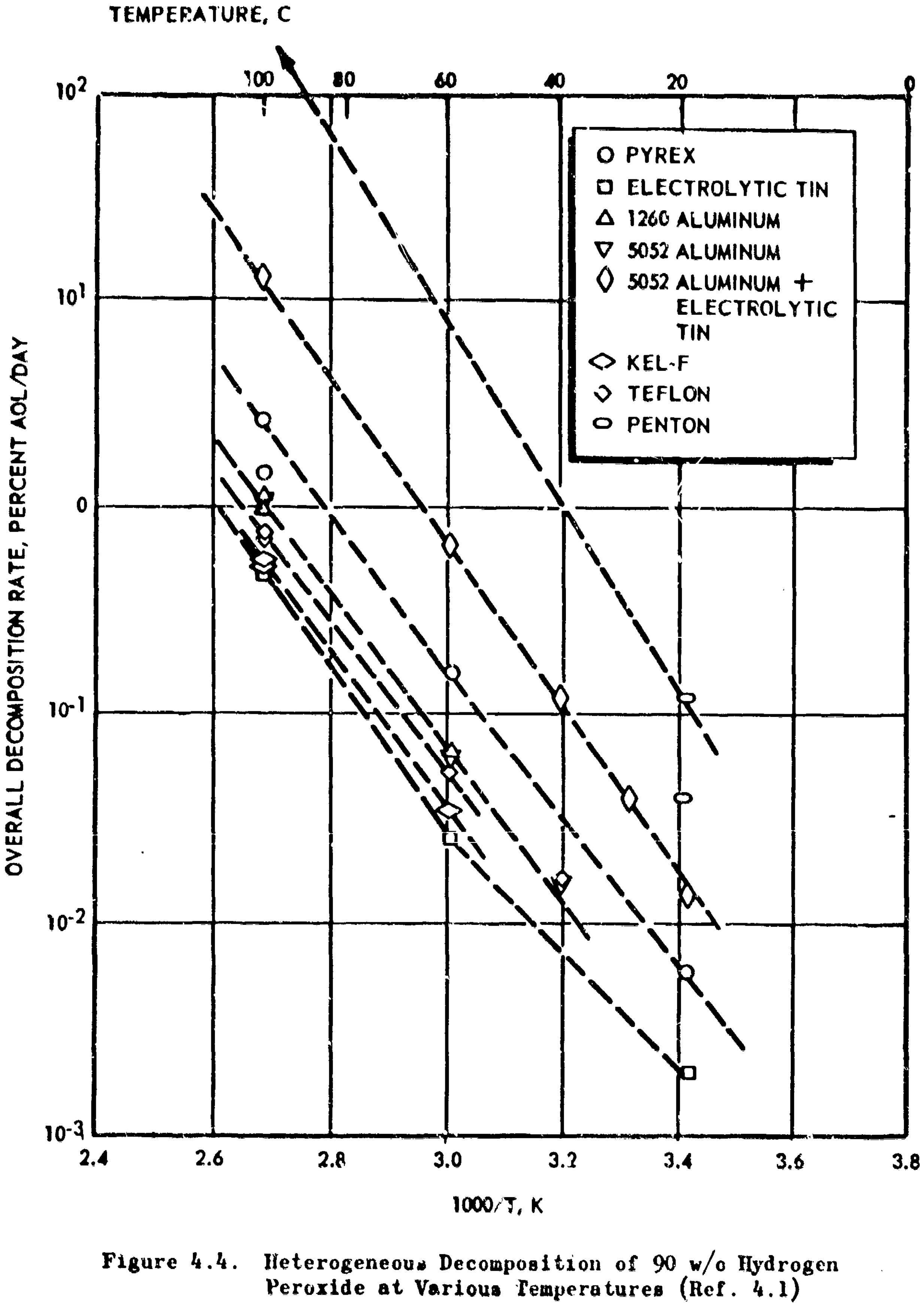
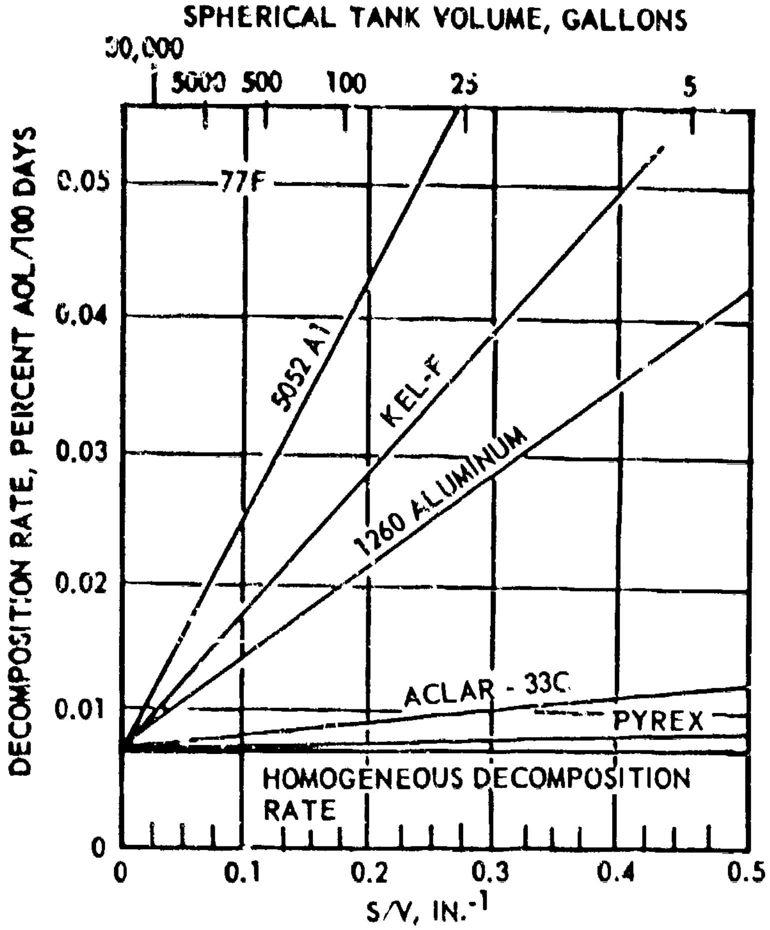
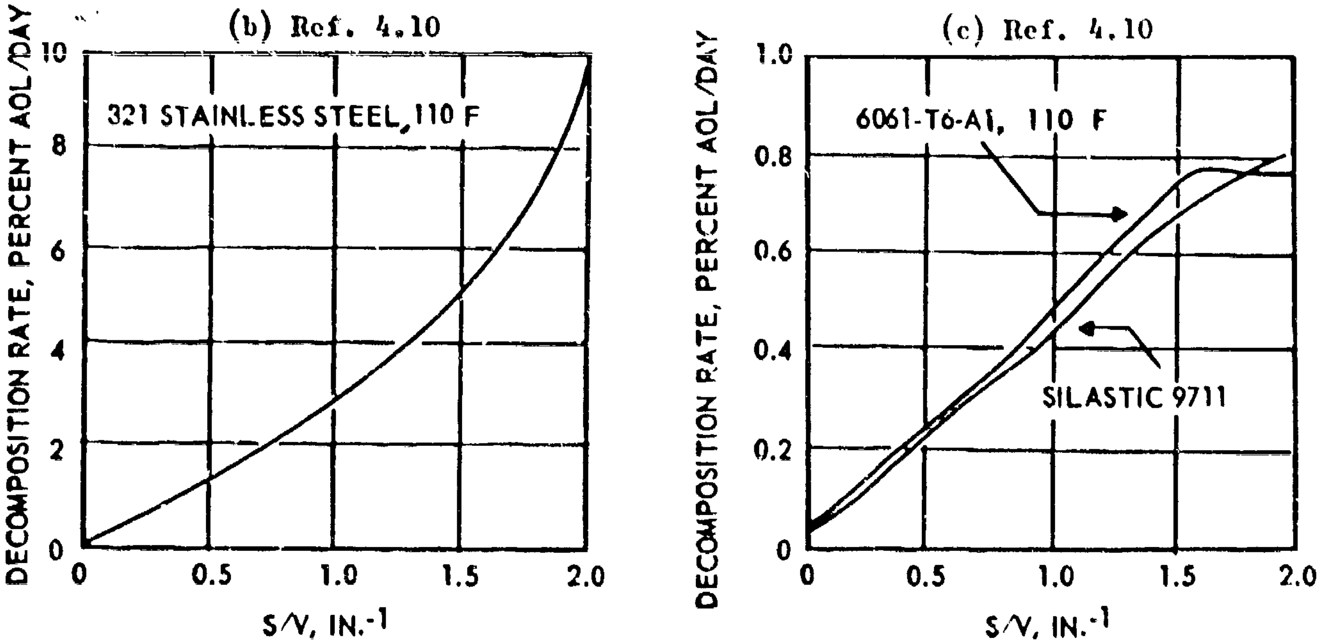


Figure 4.4. Heterogeneous Decomposition of 90 w/o Hydrogen Peroxide at Various Temperatures (Ref. 4.1)

(a) Ref. 4.1




(b) Ref. 4.10

(c) Ref. 4.10

Figure 4.5. Decomposition Rates of 90 Weight Percent Hydrogen Peroxide-Water Solutions as a Function of Surface-to-Volume Ratio

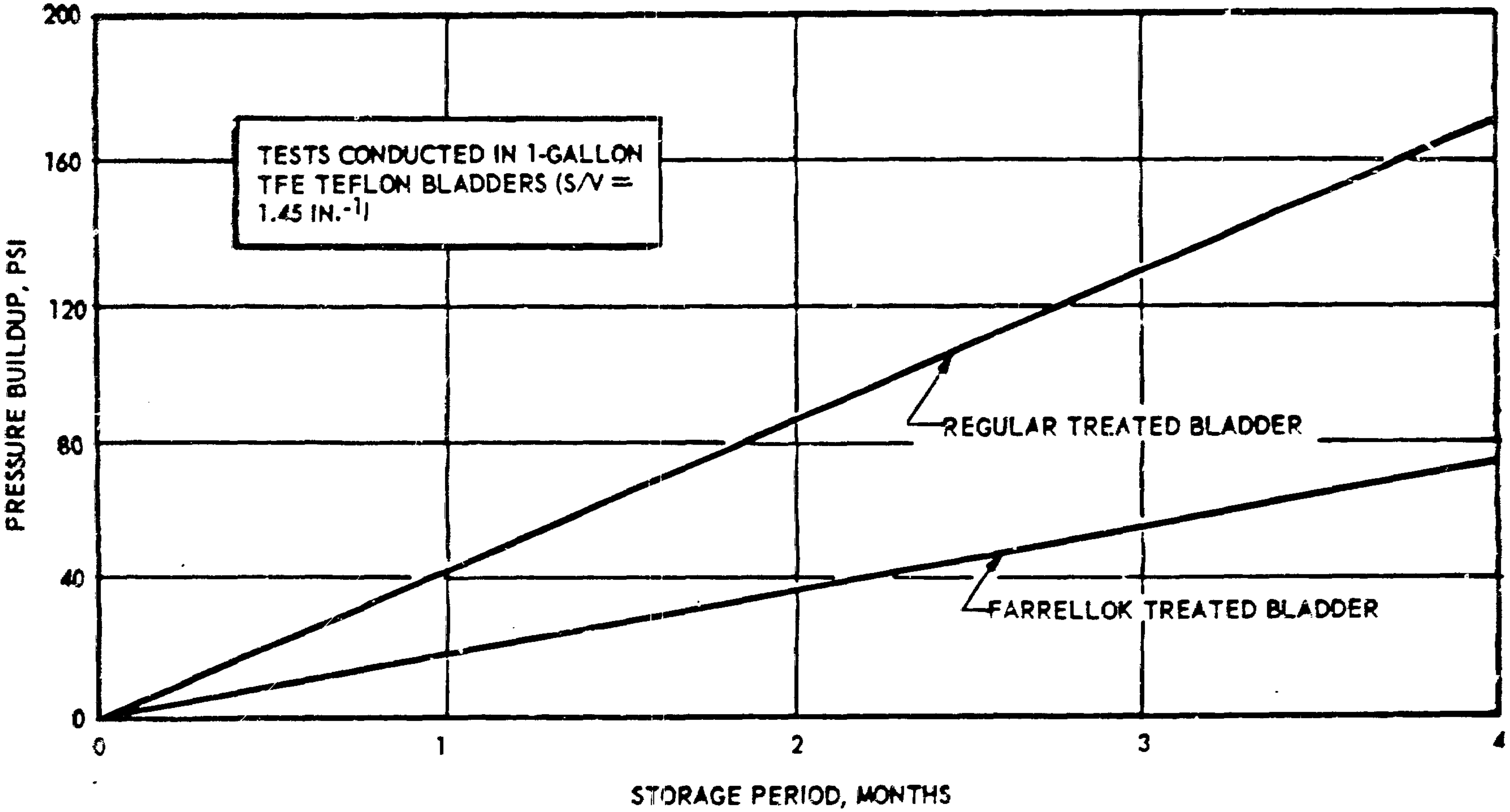


Figure 4.6. Results of Sealed Storage Tests at 72 F With Unstabilized 98 Weight Percent $H_2O_2$ in Bladders Treated by Various Techniques (Ref. 4.7)

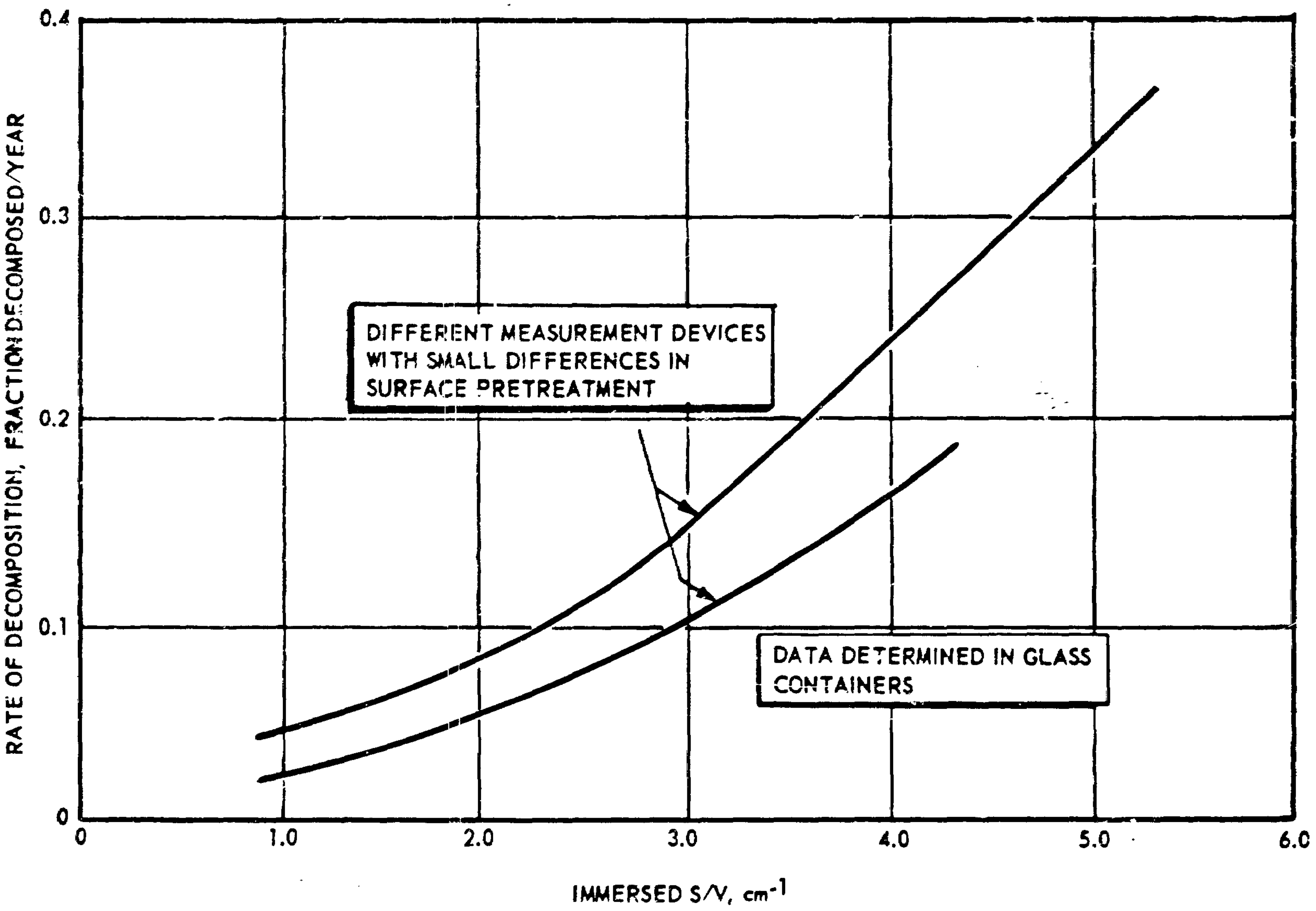


Figure 4.7. Effect of Surface to Volume Ratio on the Decomposition Rate of 99 + Weight Percent Hydrogen Peroxide During Storage (Ref. 4.5)

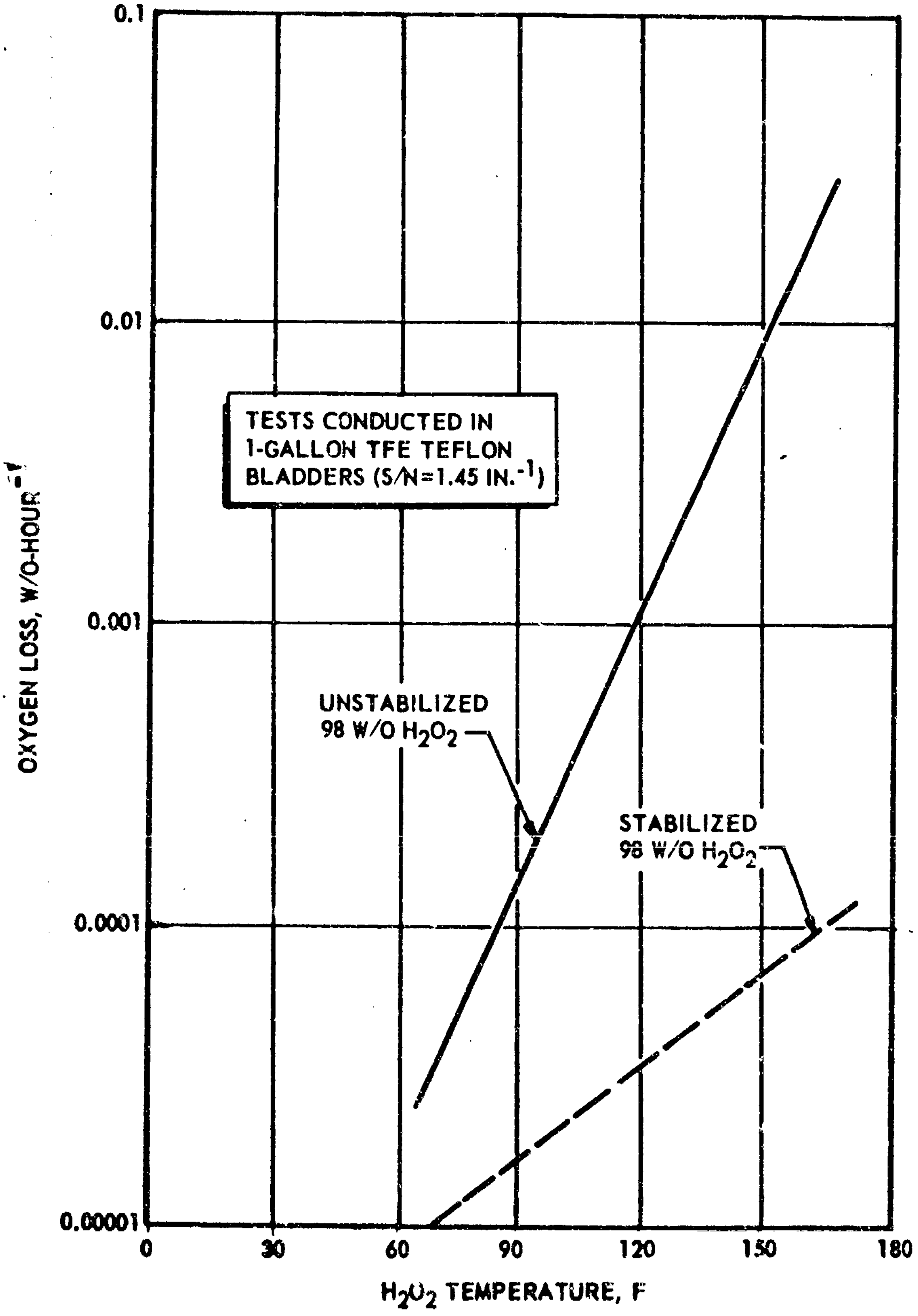


Figure 4.8. Effect of Stabilisation of 98 Weight Percent $H_2O_2$ as a Function of Temperature (Ref. 4.7)

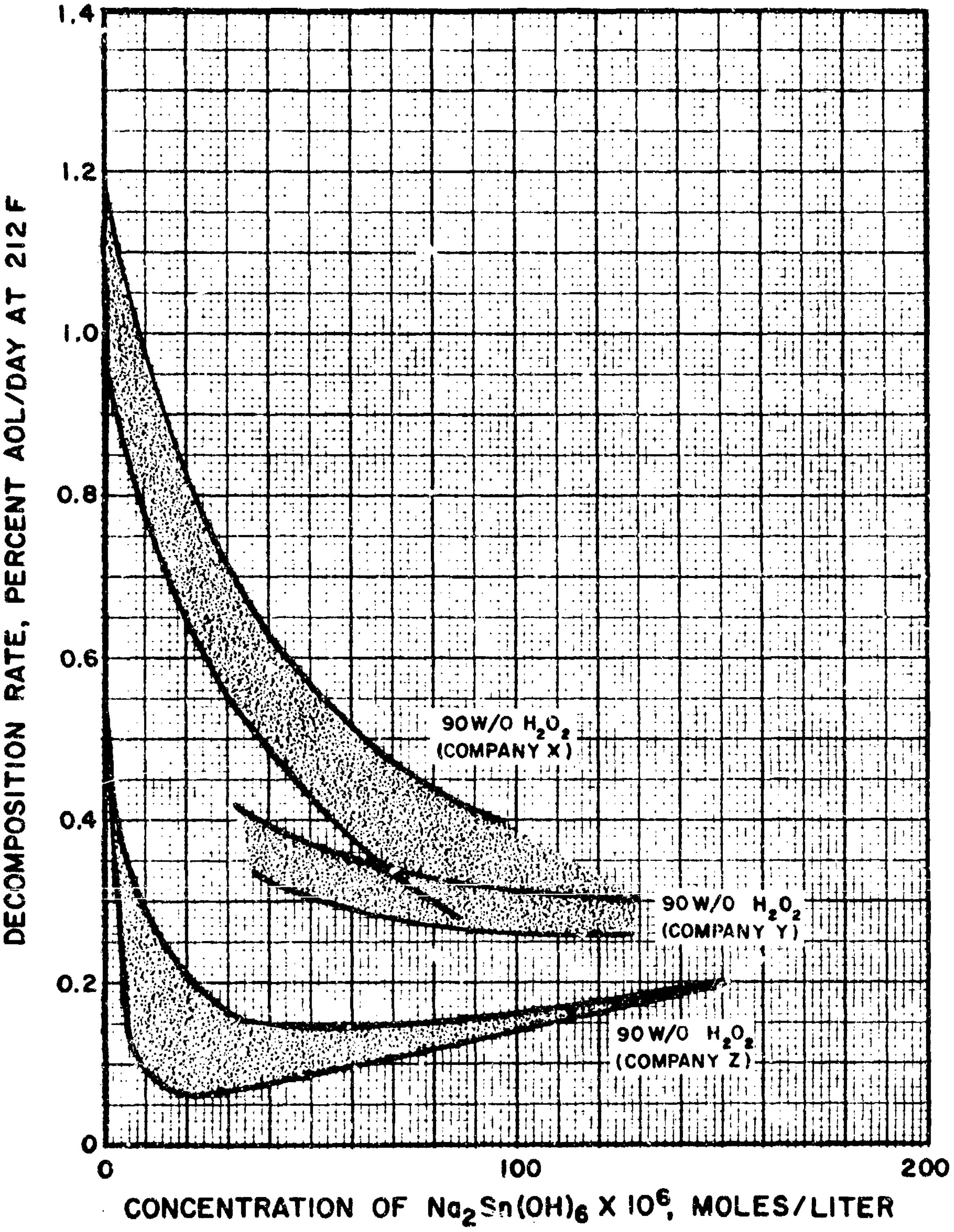


Figure 4.9. Effect of Stabilization of 90 w/o $H_2O_2$ as a Function of Stabilizer Concentration at 212 F (Ref. 4.8)

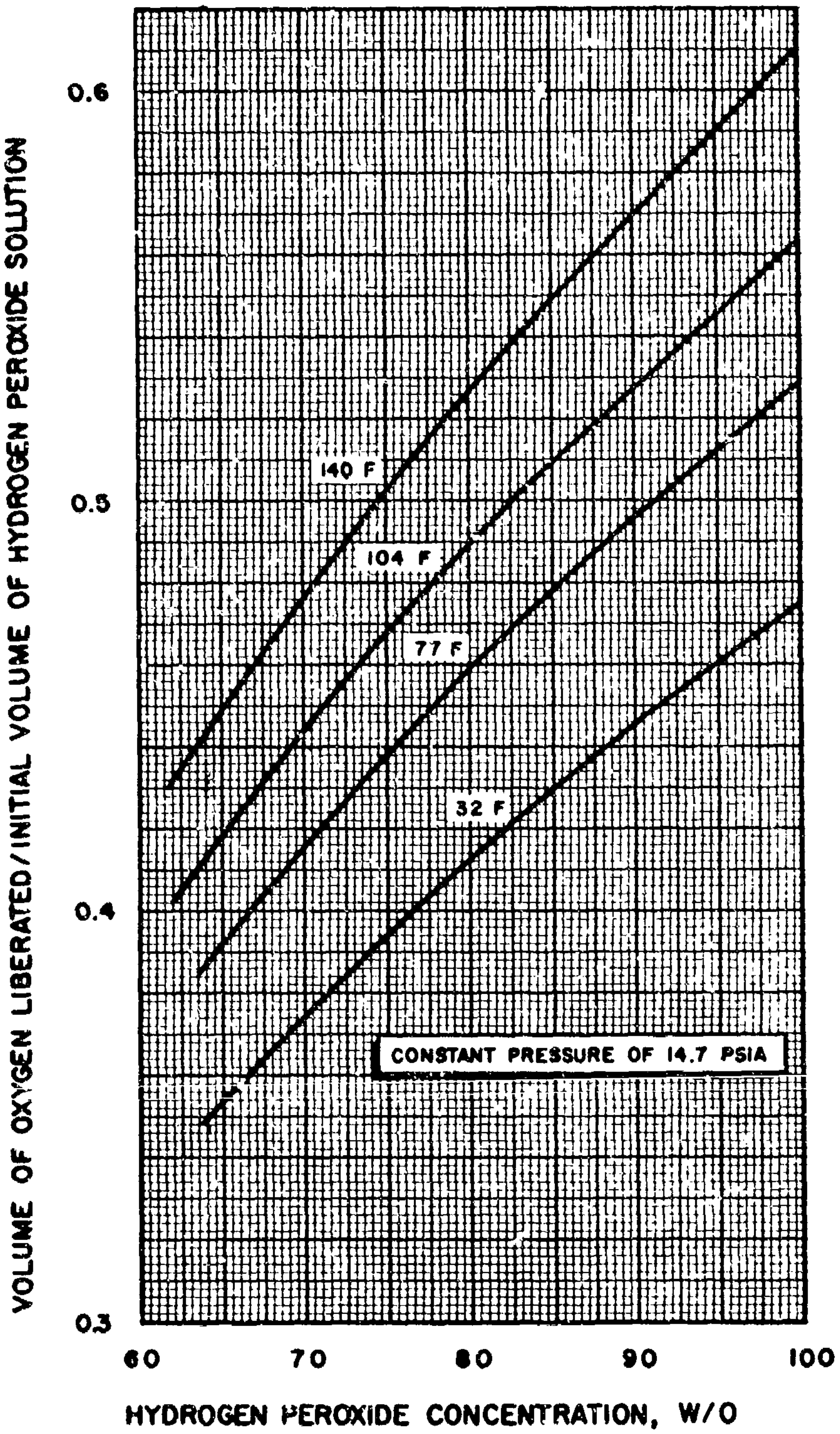


Figure 4.10. Volume of Oxygen Liberated per Year From the Decomposition of Hydrogen Peroxide at a Rate of 0.1 Percent AOL/Year

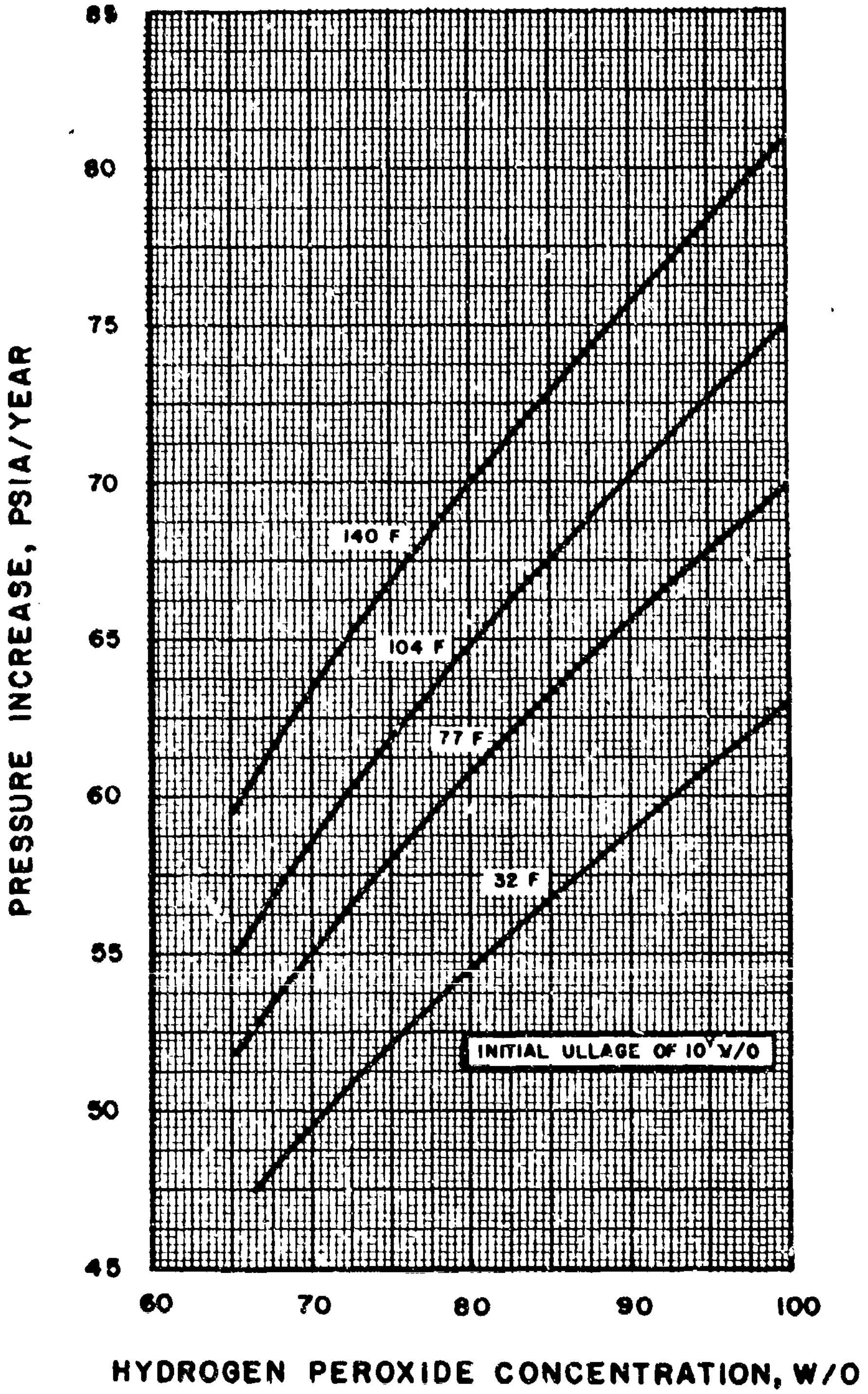


Figure 4.11. Pressure Increase in a Sealed Container Resulting From Hydrogen Peroxide Decomposition at a Rate of 0.1 Percent AOL/Year

# SECTION 5: TRANSPORTATION

## 5.1 SHIPPING CONTAINERS AND VEHICLES

Approved hydrogen-peroxide shipping containers are available in the following capacities (Ref. 5.1, 5.2):

Reagent quantities: 1 pint (3/4 pound) (I.C.C. Regulation 73.266)

Drum quantities: 30 gallons (300 pounds) (I.C.C. Regulation 42D)

Tank cars: 4000, 6000, and 8000 gallons (I.C.C. Regulation 103-A-AL-W)

Tank trucks: 2000 and 4000 gallons (I.C.C. Regulation MC 310-$H_2O_2$)

Portable tanks: any desirable size (I.C.C. Special Permit)

All hydrogen peroxide storage or shipping containers are equipped with a dustproof vent to release oxygen produced from decomposition and to prevent the possibility of contamination.

### 5.1.1 Reagent Quantity Containers

Reagent quantity containers are glass bottles with dustproof vents on top. For concentrations above 52 w/o $H_2O_2$, the glass container capacity should not exceed 1 quart (Ref. 5.3). When packing these containers for shipping, I.C.C. Regulation 73.266, Specifications 15A, 15B, 15C, 16A, and 19A apply (Ref. 5.2). The applicable reagent bottles must be packed in a metal container vented at the bottom and packed in another metal container vented at top. Cushioning material shall be used between the bottle and inner container and between the inner and outer metal containers. Cushioning material shall be vermiculite or the equivalent in an amount at least 10 times the volume of the solution shipped, and shall be wet with at least 10-percent water by volume to which a stabilizing agent has been added (Ref. 5.2). These containers should then be crated in a wooden box.

### 5.1.2 Drums

There are two types of drums available for shipping concentrated hydrogen peroxide. One is a double-head drum suitable for all freight shipment, and the other is a single-head drum suitable only for full-carload and full-truckload shipments. The vent on the double-head drum opens into the compartment between the two heads. This compartment will trap any $H_2O_2$ lost through splashing or leakage (Ref. 5.4, 5.5).

Both types of drums are fabricated according to I.C.C. Specification 42D (Ref. 5.2). Each of these drums is made of high-purity aluminum with a vented closure in the top head. The rated capacity does not exceed 30 gallons, and side openings are not permitted. The closure is sealed to prevent removal in transit. The top head should be plainly marked "KEEP THIS END UP" or "KEEP PLUG UP TO PREVENT SPILLAGE." For shipments other than carload or truckload lots loaded by consignor and unloaded by consignee, the drums must be of a design and venting arrangement approved by the Bureau of Explosives.

The approximate tare weight of a single compartment drum is 42 pounds, and that of a double compartment drum is 50 pounds. The net filling weights of 70 and 90 percent hydrogen peroxide are 280 and 300 pounds, respectively. These weights correspond to about 26 or 27 gallons of liquid in the drum. The volume will vary with temperature (Ref. 5.4).

### 5.1.3 Tank Cars

Tank cars suitable for hydrogen peroxide use are available in 4000-, 6000-, and 8000-gallon capacities. These cars, constructed according to I.C.C. Specification 103A-AL-W (Ref. 5.2), are cylindrical, fusion-welded aluminum tanks with a dome containing a manhole, a vent with a porous-stone filter to exclude dust, an unloading dip-pipe, a fill connection, and a bursting disk designed to blow out a 45-psig pressure. The temperature of the hydrogen peroxide is measured by a thermometer or thermocouple carried in a protective aluminum tube inside the tank or fastened to the tank's outside wall below the liquid level; the outside thermometer or thermocouple is insulated with glass wool (Ref. 5.1). All fittings, gaging, venting, loading, discharging, and air-inlet devices are constructed of materials compatible with hydrogen peroxide. Venting devices are of a type approved by the Bureau of Explosives.

### 5.1.4 Tank Trucks

I.C.C. Specification MC-310-$H_2O_2$ (Ref. 5.2) applies to shipment by tank trucks with 2000- to 4000-gallon capacity. These trucks, which have been specially constructed for hydrogen peroxide service, are equipped with complete unloading facilities, including a connecting hose and fittings for attachment to the consignee's storage system (Ref. 5.1, 5.4).

### 5.1.5 Portable Tanks

Portable tanks, commonly of 500- and 1300-gallon capacity, are subject to I.C.C. Special Permits. These tanks, which can be filled at the plant and used as storage vessels at the user's site, offer many advantages, particularly for remote, overseas, or temporary sites.

## 5.2 SHIPPING REGULATIONS

For shipping, the I.C.C. has classified concentrated $H_2O_2$ as a corrosive, "white label," liquid. Each container must be clearly marked "THIS SIDE UP" or "KEEP PLUG UP TO AVOID SPILLAGE." In addition, each container must carry the specification marking and number and the statement of the contents. "FOR HYDROGEN PEROXIDE USE ONLY" must be stenciled above the specification markings.

### 5.2.1 Commercial Air (Federal Aviation Agency)

When hydrogen peroxide is shipped by commercial air travel, the Official Air Transport of Restricted Articles, Tariff and Civil Air Regulations No. 49 regulates packaging and handling information.

### 5.2.2 Military Air (Department of Defense)

Regulations noted in AFM 71-4, Packaging and Handling of Dangerous Materials for Transportation by Military Aircraft, and NAVWEPS 15-03-500 govern all hydrogen peroxide shipments by military aircraft.

### 5.2.3 Waterways (U.S. Coast Guard)

Hydrogen peroxide shipments on Coast Guard-controlled waterways are controlled by I.C.C. Regulations and U.S. Coast Guard Regulations NAV-CG-108, which note packaging and handling information.

## 5.3 OPERATION AND MAINTENANCE OF EQUIPMENT

### 5.3.1 Drums

To prevent spillage through the venting device, drums containing hydrogen peroxide should not be tilted or rolled during loading, transfer, or handling; they must be moved and stored in an upright position.

Siphoning or pumping are the recommended methods for emptying drums. The siphoning system is used when small quantities of hydrogen peroxide are involved. A siphon known commercially as the Model D Golden Thief Vacuum Pump (manufactured by the W&W Manufacturing Co., Box 9311, Chicago, Illinois) or its equivalent is usually used for transferring or sampling of small quantities of liquid. Although the vacuum portion of the noted device contains aluminum alloys unsuitable for peroxide use, the only part that contacts the solution is a compatible plastic tube. This siphon can be used for sampling tanks as well as drums and can deliver liquid from a considerable height. The plastic tubing and the sampling pump should be properly cleaned and passivated before use. Suitable cleaning and packaging between use times is also required. A combination of glass and plastic tubing is also possible in a siphon arrangement. Pouring or gas pressurization should be avoided in emptying drums containing hydrogen peroxide. (Gas pressurization can introduce contaminants or overpressurize the drum.) (Ref. 5.4).

Although direct pouring is not a recommended technique, a special hydrogen peroxide drum valve suitable for attachment to the standard 30-gallon drum is available from the Shell Chemical Company. This valve enables a direct pour from the drum and is suitable for short use times only (1 to 2 days) (Ref. 5.4).

After being emptied, the drum (and compartments) should be completely flushed with clean water and drained. The bung cap should be replaced immediately and tightened securely. All pipelines and hoses should be drained when transfers are complete.

When emptying a drum by pumping or vacuum, a trap should be placed in the suction line to prevent feedback of the hydrogen peroxide into the container after withdrawal.

### 5.3.2 Tank Cars and Trucks

Tank cars and tank trucks may be unloaded by either pumping or pressurization with clean, dry, hydrocarbon-free nitrogen gas. The use of a self-priming pump is quite common and is particularly desirable when fast delivery under pressure is required. The majority of the pumps are a centrifugal design, although air-driven reciprocating pumps are also available. Pump unloading is recommended for both tank cars and trucks.

The pressure fed system (sometimes called the ejector system) is a method of feeding by gas pressurization and should not be used on drums or smaller containers. There are mixed feelings about pumping by this technique. In addition to the possibility of overpressurization that exists with this technique, it is felt by some organizations that the possible introduction of water or oil with the pressurant gas and/or the insertion of the pump inlet line into the supply tank offers the possibility of vehicle container contamination. Thus if this unloading system is used, it is recommended that the compressed air or nitrogen used for pressurization be filtered for entrained solids as well as water (water-pumped gas is preferred to oil-pumped gas), and its pressure carefully controlled.

The standard tank car compressed gas fitting has been designed for nitrogen. The gas pressurization line should be equipped with a suitable pressure reduction valve, a safety relief valve (set for approximately 15 psig), and a pressure gage. A pressure of 5 to 10 psig is normally sufficient to unload a 4000-gallon tank car in 2 hours. This will consume about 6- to 10-cu ft/min nitrogen. Pressures in excess of 15 psig should not be used. The compressed-gas feed line should be blown out before introduction into the hydrogen peroxide supply. Details of the unloading procedures should be obtained from the particular hydrogen peroxide manufacturer that supplies the tank car.

Tank truck unloading is normally handled by the hydrogen peroxide producer or his carrier. Each tank comes equipped with the necessary fittings, a hose, and a pump designed for hydrogen peroxide service. Trained drivers and/or other qualified personnel representing the producer are present to make the necessary connections for the unloading operation. After unloading a tank with pressure, the vent shall be opened at once. When pressure transfer is used on tanks, a line shall be attached to the safety vent and extended to the ground so that the vent may be quickly opened to stop the flow in an emergency. The tank should not be flushed after emptying unless it is to be entered for inspection or repair.

When either the tank car or truck have been emptied, the outside of the tank and the ground should be washed thoroughly wherever spillage of the hydrogen peroxide could have occurred during the unloading. All lines, hoses, and the pump should be drained free of hydrogen peroxide and flushed with clean water. All lines and hoses should then be covered with aluminum blind flanges or polyethylene bags to prevent contamination from dust (Ref. 5.4).

### 5.3.3 Handling

When transporting hydrogen peroxide, the following handling procedures and safety precautions should be followed:

1. At least two trained operators should always be assigned to any operation involving the handling, transfer, or storage of hydrogen peroxide.

2. Drivers and operators involved in deliveries of hydrogen peroxide should be instructed to identify the material as hydrogen peroxide of the correct concentration and grade. Carelessly calling it by another name such as "acid" may result in its being unloaded into the wrong tank with possible serious consequences.

3. Leaking pipes, hoses, pumps, etc., from concentrated hydrogen peroxide tank trucks or tank cars are fire hazards. The presence of combustible materials, especially wood, paper, or cotton waste, at the filling or unloading site, should be avoided. Spilled hydrogen peroxide should be immediately removed by flushing with copious quantities of water.

4. Operators unloading hydrogen peroxide should wear protective clothing and use only the designated equipment.

5. There should be water hoses, showers, and eye fountains in the immediate vicinity of the unloading area. The location and proper function of this equipment should be checked before beginning operation.

6. Sampling of hydrogen peroxide, if necessary, should be done only under very carefully controlled conditions and only by authorized personnel. All samples should be discarded after use and never returned to the storage container.

7. Sampling devices or any other material should not be inserted into a hydrogen peroxide container. Samples should be taken by pumping or draining from system feed lines.

8. If, for some reason, it is necessary to put some instrument, device, sampler, etc., into a hydrogen peroxide solution, the device must undergo the appropriate cleaning and passivation procedure. With each addition of a foreign body to hydrogen peroxide, the chance of contamination is increased.

9. Freezing may cause localized concentrations of contaminants which, on thawing, may result in accelerated decomposition.

10. Freezing will cause concentration gradients to develop as the material thaws. Thorough agitation is required to ensure uniform concentration of the solution. Hydrogen peroxide solutions are difficult to freeze, and supercooling of 70 to 90 F is not uncommon. Handling, vibration, or motion of any kind should be avoided during possible supercooling periods to avoid freezing and subsequent concentration stratification.

11. Pressure vents should be shielded so that the possibility of dust return or other contamination is minimized.

12. Routine inspection of storage facilities should include hosing down storage containers as well as the storage area at regular intervals to minimize the accumulation of dust, dirt, debris, etc.

13. The outside of storage containers should be thoroughly cleaned before removal of outlet covers. This may be accomplished by means of an air hose, a water hose, or a combination of these.

14. Cleaning of the threaded sections before connection of the mating parts should be carefully done to minimize the possibility of contamination.

15. In the opening of a pipe line or similar item that has previously been used in transferring hydrogen peroxide, it should always be assumed that there may be some hydrogen peroxide left in the line, and a supply of water should be available.

14. Storage of equipment such as transfer hoses should provide for venting any pressure built up from decomposition of residual peroxide. All drained materials should be diluted and discarded.

## 5.4 REFERENCES

5.1 United States Government, Office of the Director of Defense Research and Engineering, Washington, D.C., *The Handling and Storage of Liquid Propellants*, January 1963.

5.2 General Services Administration, National Archives and Records Service, Federal Register Division, *Code of Federal Regulations*, Title 49, Chapter I, "Interstate Commerce Commission," Parts 71 to 90, revised 1956.

5.3 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, *Hydrogen Peroxide*, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, 1955.

5.4 Shell Chemical Company, New York, New York, *Concentrated Hydrogen Peroxide, $H_2O_2$. Properties, Uses, Storage, Handling*, 2nd Edition, Report No. SC: 62-23, 1962.

5.5 McCormick, James C., Buffalo, New York, *Hydrogen Peroxide Rocket Manual*, F.M.C. Corporation, 1965.

# SECTION 6: SAFETY

## 6.1 HAZARDS

The potential safety hazards in dealing with hydrogen peroxide fall into the following general categories: detonation and/or explosion, uncontrolled decomposition, fires, and personnel injury. While these hazards may sound ominous, it must be remembered that similar hazards exist for various other compounds which are in widespread use and are safely handled by industry. If operating personnel are armed with knowledge of the potential hazards and how to avoid them, there is no reason why concentrated hydrogen peroxide cannot be safely employed in commercial processes.

### 6.1.1 Physiological Effects

6.1.1.1 Vapor Inhalation. Hydrogen peroxide solutions and vapors are nontoxic, but they are irritating to body tissue. This irritation can vary from mild to severe, depending upon the concentration of hydrogen peroxide. Concentrated hydrogen peroxide has little odor unless deliberately inhaled. The sensation is then somewhat like that produced by ozone or the halogens (Ref. 6.1).

Inhalation of hydrogen peroxide vapors causes irritation and inflammation of the respiratory tract and may result in burning of the nose and throat, running of the nose, and coughing. Prolonged breathing can produce swelling of the respiratory membranes or accumulation of fluid in the sinuses and lungs. Short-time exposure will not cause lasting harm, but a physician should be notified in extreme exposure cases (Ref. 6.2. and 6.3). The toxicity level for 90 w/o hydrogen peroxide is expressed as a threshold limit value (TLV) of 1 ppm (1.4 mg/cu m) (Ref. 6.4

and 6.5). The TLV represents the average concentration over a normal work day to which the average human can be safely exposed on a daily basis without adverse effects.

The vapors can also irritate the eyes, producing burning, redness, and watering. The effect is short-lived except in extreme or continuous exposure. When hydrogen peroxide contacts the eyes, the eyes should be flushed immediately with water.

6.1.1.2 Cutaneous Exposure. The vapors, mists, and solutions of hydrogen peroxide are very irritating to body tissues. When the liquid touches the skin, there is a burning sensation and the areas affected are bleached. If contact is brief, the effects will usually disappear within 2 or 3 hours. Continued exposure, however, will result in slight water blister formation which should heal quickly. Contact of the hydrogen peroxide with the more sensitive parts of the body, such as the thighs, neck, or under the fingernails, will cause more severe effects than contact with the hands. If hydrogen peroxide contacts the skin, the area affected should be flooded immediately with large quantities of water (Ref. 6.2 and 6.3). If the irritation does not subside after flushing with water and burns persist, a physician should be notified.

Various experiments have been conducted with animals to show the effect of hydrogen peroxide on skin surfaces. With rabbits, it was observed that 90 w/o hydrogen peroxide applied to the skin was absorbed and caused death by gas embolism (rabbits are susceptible to embolism, however). Cats, guinea pigs, rats, pigs, and dogs, although much less susceptible to embolism, showed a greater reaction on the skin (Ref. 6.1). (There were no results showing possible lethal effects of $H_2O_2$ on these animals, however.)

In studies on human skin, 90 w/o hydrogen peroxide on the palms and fingertips, where the keratin is thick and nerve endings are abundant, causes strong prickling and formation of opaque white patches. This is extremely painful under the fingernails. "On other skin areas where the keratin is thinner, irritation occurs, but with less itching and the white appearance is confined to a few areas at the base of hairs. There is no evidence of penetration deeper than the first layer of skin, or stratum corneum, and all these effects disappear without trace" (Ref. 6.1, page 426).

6.1.1.3 Ingestion. If hydrogen peroxide is swallowed, e.g., during pipetting, it may cause bleeding and severe distention of the stomach due to the liberation of oxygen. In some cases, injection or ingestion of hydrogen peroxide can be fatal, depending upon the amount and concentration. Intravenous injections of dilute hydrogen peroxide solutions are more lethal than concentrated solutions, since the dilute solutions are able to penetrate the system more deeply before decomposition and blocking of the circulation occur (Ref. 6.1).

In the mouth, an effervescence occurs as the hydrogen peroxide decomposes, giving a prickling sensation. At high concentrations, the effects in the mouth are heightened, to the point of painfulness, to say nothing of the hazard of burns; and such contact is to be avoided.

### 6.1.2 Fire Hazards

Hydrogen peroxide by itself is not flammable, but solutions of high concentration may react with combustible materials and generate enough heat to cause ignition. When involved in a fire, hydrogen peroxide actively supports combustion by liberating oxygen, and this results in a "flare" fire that may terminate in explosion. Elimination of air, however, does not control or put out the fire. Hot, concentrated, liquid hydrogen peroxide (> 65 w/o), once ignited, will "burn" rapidly as a continuous, hot, nearly invisible vapor decomposition flame close to the surface of the liquid. Such a decomposition flame will continue without an external source of heat until the liquid is entirely consumed, unless the liquid concentration is reduced or the liquid is cooled sufficiently to extinguish the flame (Ref. 6.2).

Hydrogen peroxide solutions greater than 65 w/o can release enough energy to heat the decomposition products to a relatively high temperature (1382 F for 90 w/o solutions). Ignition of nearly inflammable material may then be expected. Solutions of less than 65 w/o may also cause fires due to the fact that upon exposure to air, water in the solution may evaporate faster than the peroxide, increasing the concentration of the latter. Naturally, the lower the initial concentration, the less likely this would happen (Ref. 6.2).

Fires can be started easily by dampening combustible materials with hydrogen peroxide solutions stronger than about 70 w/o, provided that the proper catalyst is present. In the absence of catalysts, many materials such as clean cotton or wood may not even react with 90 w/o hydrogen peroxide. (The absence of any catalytic material, however, is rather unlikely according to Ref. 6.6.) Secondary fires may also occur. Consumption of the hydrogen peroxide does not necessarily eliminate the fire. If the ignition temperature limit of any fuel-air mixture in the immediate vicinity has been achieved, combustion of these materials will continue. This may, however, occur at a considerably different burning rate.

An empirical test was devised (Ref. 6.7) to compare the flammability hazard of the various concentrations of propellant-grade hydrogen peroxide. A spill test was developed using a green felt of 90-percent wool and 10-percent vegetable fiber. (Numerous other organic materials were tried, but this was the first material to give reproducible results.) The test simply consists of placing two drops of concentrated hydrogen peroxide on the piece of felt and measuring the time to visible flame. The ignition time decreases with increasing concentration as shown in Fig. 6.1.

Ignition (i.e., initiation of rapid decomposition) limits have been determined for hydrogen peroxide vapor (Ref. 6.8 and 6.9) for pressures above atmospheric; these data are presented in Fig. 6.2. The ignition limits of hydrogen peroxide are actually the ignition limits of the vapor and are, therefore, a function of the vapor-phase composition. In turn, this vapor-phase compsition is a function of the liquid temperature and the total pressure on the system. The ignition limits are not sharply defined but are general areas, as illustrated by the positive and negative test results shown in Fig. 6.2.

General areas where the vapor phase in contact with the liquid phase has reached the probable ignition level are shown in Fig. 6.3 (Ref. 6.10).

### 6.1.3 Explosion Hazards

Although hydrogen peroxide solutions are not ordinarily classed as explosives (see Section 4.4.1.1.2), certain conditions can exist in which a detonation or an explosive-like release of energy can occur. Typically, most "explosions" involving hydrogen peroxide are a result of decomposition of the hydrogen peroxide, which may occur as a result of gross contamination and/or excessive temperature rise of the hydrogen peroxide. The decomposition reaction produces large amounts of heat (which further accelerates the decomposition reaction) and gas with subsequent effects of gas overpressurization in any confining areas. The "explosion" usually results from the rupture of the confining surface and release of the gas pressure.

Normally, this decomposition process is relatively slow, and the final pressure release is preceeded by a slow thermal and pressure buildup. However, there are also conditions in which the decomposition process reaches an explosive rate. Although such conditions are usually associated with the vapor phase, separation of the cause-effect relationship between the liquid and vapor phases is difficult. In addition to the normal liquid-vapor equilibrium, the entrapment of vapor (and a subsequent vapor-phase decomposition within the liquid phase) is always possible with a material that decomposes so readily into liquid and gaseous products.

6.1.3.1 Vapor-Phase Hazards. When the concentration of hydrogen peroxide in the vapor phase exceeds 26 mole percent (40 w/o) at atmospheric pressure, an explosive decomposition reaction is possible (Ref. 6.8 and 6.9). This limit is increased with decreasing pressures (43 w/o at 200 mm Hg and 70 w/o at 40 mm Hg) and decreased with pressures above ambient. Ignition of these concentrations may occur as a result of a spark, contact with a catalytic surface, or contact with a heat source in excess of 300 F.

During vapor detonation velocity measurements (Ref. 6.8), a detonation velocity of 6700 ft/sec was recorded at atmospheric pressure in a minimum concentration of 50 w/o hydrogen peroxide. No detonations were observed in hydrogen peroxide vapor at total pressures of 42.6 and 99.5 psia. Measurements of detonation velocities in higher concentrations at atmospheric pressure were generally unobtainable because of spontaneous decomposition or premature ignition of the test gases.

Under ordinary storage and handling conditions, explosive vapor concentrations are not reached. However, when heated under atmospheric pressure to temperatures of ~ 264 F, liquid concentrations above 75 w/o will produce vapor concentrations in the explosive range. These explosive regions correspond to the ignitable regions shown in Fig. 6.3 as a function of liquid composition, liquid temperature, and pressure.

6.1.3.2 Liquid-Phase Hazards. Although earlier experimental efforts, particularly those of the Germans, had indicated that liquid hydrogen peroxide solutions with concentrations greater than 88 w/o could be detonated, more recent efforts have demonstrated the absence of shock sensitivity in the liquid phase below concentrations of 95 w/o. However, there are still more conflicts in the data obtained from a variety of shock sensitivity tests on hydrogen peroxide concentrations greater than 95 w/o. Consequently, these higher concentrations are still considered (Ref. 6.11) potentially explosive under certain conditions. In addition, concentrated hydrogen peroxide solutions are thermally sensitive (see Section 6.1.3.1) although the direct participation of the liquid phase in detonations involving the heated vapor phase is questionable.

The validity of positive results from some types of sensitivity tests used in the early efforts on the hydrogen peroxide liquid phase are questionable (Ref. 6.12) for the following reasons:

1. Shock sensitivity in earlier work was usually done by setting off relatively large explosive charges in the hydrogen peroxide. This technique is questionable because the mixture of organic vapors from the explosive charge may have initiated the reaction, and the heat liberated by the explosive charge may vaporize enough hydrogen peroxide to result in a vapor explosion.
2. Thermal tests in early work were limited to open containers. Because of localized heating and distillation effects, it was not known what concentration of hydrogen proxide was actually involved in the explosion.
3. Subsequent sensitivity tests (Ref. 6.9) on the vapor phase above a hydrogen peroxide liquid phase of 90 w/o indicated that none of the detonations found in this concentration range involved the liquid phase.

The results of various experimental efforts, which have involved three primary areas of sensitivity testing (thermal sensitivity, shock sensitivity, and detonation propagation), are summarized in the following paragraphs to provide a guide to the potential explosion hazards of the hydrogen peroxide liquid phase.

6.1.3.2.1 <u>Thermal Sensitivity</u>. To expand previously available liquid-phase thermal sensitivity data (summarized in Table 6.1) thermal sensitivity tests were conducted by duPont (Ref. 6.12) on hydrogen peroxide in open and in closed containers. The open-container tests (at atmospheric pressure) showed that the vapor above 90 w/o liquid hydrogen peroxide exploded at 248 to 284 F. The liquid did not explode but decomposed rapidly, producing temperatures up to 752 F. Similarly tested 98-percent hydrogen peroxide vapor exploded at 212 to 248 F and gave evidence of liquid participation in the reaction. Results from tests on 35-percent hydrogen peroxide were similar to those with 90-percent hydrogen peroxide. In sealed glass bulbs, 90-percent hydrogen peroxide exploded at 320 to 356 F and the liquid was involved in the reaction; however, the explosions were attributed to pressure buildup from relatively slow decomposition. A low-order explosion was produced with 95 and 98 w/o hydrogen percxide at 248 to 284 F. The results of representative tests from these efforts are reprinted in Tables 6.2 through 6.4.

In a further effort to determine liquid-phase participation in vapor-phase detonations resulting from thermal sensitivity, field tests (Ref. 6.12) were conducted using larger quantities of material. These tests, which eliminated the possibility of complete vaporization of the liquid, consisted of placing approximately 2 gallons of concentrated hydrogen peroxide in old, well-used "Albone" (35 w/o stabilized $H_2O_2$) drums. These drums were placed in a pit with remote heat contol and temperature recording systems. The drums were heated at a controlled rate, and the temperature-time profile of each was recorded. The following results were reported on the five tests run:

1. Two gallons of 90 w/o hydrogen peroxide. The drum started belching foam at 271 F. Much liquid was dispersed, but the stainless-steel container was undamaged.
2. Two gallons of 95 w/o hydrogen peroxide. Vapor ignited at 268 F and burned with several white puffs with no resulting damage to the stainless-steel container.
3. Two gallons of 35 w/o hydrogen peroxide. Vapors ignited at 248 F. Burning continued for 30 seconds. Both ends of the drum were bulging and the thermocouple had been ejected from the drum during the test.
4. Two gallons of 95 w/o hydrogen peroxide. Vapors ignited at 295 F and burned for 3 minutes. The drum was undamaged.
5. Two gallons of 95.2 w/o hydrogen peroxide. At 289.4, the drum ruptured, spewing high-strength liquid hydrogen peroxide. The maximum pressure recorded was 75 psi.

It was concluded (Ref. 6.12) as a result of these tests and the other available data that in concentrations up to 95 w/o the liquid, or at least a good part of the liquid, does not participate (except to form more vapor from heat feedback) when vapor-phase burning or explosion occurs. This is true even though the adjoining vapor temperature exceeds 572 F. However, concentrated liquid hydrogen peroxide is susceptible to overheating, which makes possible the formation of vapor within the liquid phase and consequent "belching." Thermal hazards increase for liquid hydrogen peroxide concentrations above 95 w/o, even though direct participation by the liquid phase in resulting detonations is questionable.

6.1.3.2.2 Shock Sensitivity. Hydrogen peroxide and hydrogen peroxide-water solutions are considered non-impact sensitive in both the solid state (low-temperature studies) and the liquid state up to 212 F (Ref. 6.2, 6.4, 6.6, 6.12, and 6.13). No impact sensitivity was noted (Ref. 6.13) for 98 w/o hydrogen peroxide at 212 F and an impact height of 300 kg-cm.

Hydrogen peroxide grades of 90 and 98 w/o $H_2O_2$ have been subjected to adiabatic compression test loading rates of 231,000 lb/sec at 70 to 72 F and 160 F with no effect on the hydrogen peroxide. Loading rates of 3,000,000 lb/sec at 70 to 90 F have been achieved on 90 w/o hydrogen peroxide with no adverse effects (Ref. 6.3).

Shock tests with No. 20 PETN boosters set off in 30-gallon aluminum drums, and tests with 15 grams of Hercomite dynamite exploded in the same quantity at 70 to 72 F and 160 F showed no propellant detonation for 90 and greater w/o hydrogen peroxide solutions (Ref. 6.3).

Card gap tests, using an apparatus in which 30 gms of liquid sample was separated from a 30 gm tetryl charge by a thin (5 to 10 mils) aluminum membrane, indicated no evidence of detonation in 90, 95, and 98 w/o hydrogen peroxide (Ref. 6.12). The results of these tests are shown in Table 6.5, and are similar to those resulting from earlier tests conducted by the Navy (Ref. 6.3) to demonstrate the relative insensitivity of 90, 95.5, and 99.5 w/o hydrogen peroxide at ambient temperatures and 160 F.

Other types of shock sensitivity tests have also been conducted on 90, 95, and ~ 100 w/o hydrogen peroxide (Ref. 6.12 and Table 6.6). Although some of these data do indicate shock sensitivity in hydrogen peroxide concentrations above 95 w/o, the data are suspect (Ref. 6.12) because of potential vapor-phase detonation and contamination contributions.

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Although it is generally concluded that hydrogen peroxide solutions are not normally shock sensitive, it should be noted that hydrogen peroxide with additives (or contaminants) capable of being oxidized are highly impact sensitive. This sensitivity theoretically depends upon the concentration and type of additive and, in actual practice, upon the sample size and the method and type of impact. Various mixtures involving hydrogen peroxide of various concentrations with minimum (< 10 percent) quantities of organic materials such as ethylene glycol, ethyl alcohol, benzene, etc. have been found to be particularly hazardous (Ref. 6.11). These mixtures will detonate violently when subjected to the slightest mechanical shock with detonation velocities approaching those of nitroglycerine, TNT, RDX, etc.

6.1.3.2.3 Detonation Propagation. Under normal usage, it seems impossible to obtain a propagating detonation in hydrogen peroxide-water solutions. The only tests where a propagating detonation has been observed were under conditions of extreme confinement with an exceptionally heavy booster charge. Although these conditions are not likely to be encountered in any normal storage or handling condition, studies by the Navy (Ref. 6.11) have demonstrated some conditions at which hydrogen peroxide concentrations above 95 w/o will propagate a detonation.

In another study (Ref. 6.3) propagation tests were conducted on 98-percent hydrogen peroxide by placing explosives (having energy rates of 1,860,000,000 ft-lb per second and pressure generation rates of 576,000 atmospheres which develop within 12.5 microseconds) in a 1.5-inch schedule-80 stainless-steel pipe. The pipe was connected to an aluminum drum containing 250 pounds of hydrogen peroxide. Although a detonation was set off in the pipe, the hydrogen peroxide was unaffected.

Similar results were obtained (Ref. 6.3) by the Bureau of Mines in tests on 99 w/o hydrogen peroxide contained in 0.5-inch tubing. A large booster charge was located in 1-inch tubing of hydrogen peroxide, which was connected to the smaller tubing. The detonation of the booster charge, which detonated the material in the 1-inch tube, failed to propagate into the hydrogen peroxide in the smaller tubing.

6.1.3.3 Explosion Potential Criteria. A criterion (Ref. 6.14) has been developed for the estimation of the potential explosive and detonation hazard of hydrogen peroxide systems. This involves the calculation of what is called the "critical excess energy" of the system and is the heat of reaction for the formation of all gaseous products from all compounds in the mixture. Before continuing with the correlation procedure, a discussion of balancing combustion-explosion type reactions seem appropriate. Briefly, these are the rules for balancing these reactions:

1. Carbon is first oxidized to CO
2. If additional oxygen remains, form water
3. If additional oxygen remains, oxidize CO to $CO_2$

Addition of readily oxidizable metals to this system would introduce a step between 1 and 2; however, there are a number of qualifications to this procedure so that the reliability of this technique as a hazard criterion for metals is questionable.

After balancing the equation with the particular ratio of ingredients which are of interest, the heat of reaction is computed, assuming that all of the reaction products are in the vapor form. Heats of formation of the reactants in their actual form (solid,, liquid, or gas) and of the end products in their gaseous form, all based at 298 K, are used for this computation. A heat of reaction in excess of 450 cal/gm implies a possible explosive hazard for that particular mixture. A heat of reaction in excess of 900 cal/gm predicts a possible detonation hazard. These "critical energy" values were selected after a very careful study of experimental data accumulated from explosive and detonation tests on mixtures of organic compounds with concentrated hydrogen peroxide. A heat of reaction can be computed for a number of compositions and the compositions for the "critical excess energy" values of 450 and 900 cal/gm determined. These computed compositions may then be plotted to map out hazard areas in the use of mixtures of these materials. It should be noted, however, that these values are not infallible. Mixtures should always be tested experimentally before actual handling operations begin.

Expressions, which may be solved by pure mathematics, have also been generated for the determination of the critical energy compositions (Ref. 6.15). However, for those handbook users who are willing to balance the chemical equation, the following heats of formation of the common products of combustion are given. The heats of formation of various concentrated hydrogen peroxide solutions are shown in Fig. 2.12 to 2.13a and are discussed in Section 2.2.3.1 of this report.

$CO$ -26.417 kcal/mol at 293 K; molecular weight = 28.01

$H_2O$ -57.80 kcal/mol at 298 K; molecular weight = 18.016

$CO_2$ -94.315 kcal/mol at 298 K; molecular weight = 44.010

Heats of formation or heats of combustion (from which heats of formation can be computed) of a large variety of organic compounds are available in practically all chemical handbooks.

In the computation of systems where the components are not mutually soluble or are not soluble in all proportions, consideration should be given to the possible existence of hazardous concentrations at liquid-phase interfaces. The solubility of a large number of compounds in hydrogen peroxide is given in Table 4.14a, Section 4. This method of evaluation is not really appropriate for immiscible systems.

Despite the apparent success of the correlation methods, a safety hazard evaluation must always be obtained for a new system whenever the safety of personnel or equipment is concerned. These methods should only be used to define limits for experimental test design.

The explosive regions in systems of hydrogen peroxide and organic compounds surround the composition ratios of $H_2O_2$/organic compound which lead to complete reaction to carbon dioxide and water. Explosions are generally unobtainable if the final solution contains less than approximately 30 w/o hydrogen peroxide.

The sensitivity of these explosive mixtures toward explosion is of the same order of magnitude as that for molten TNT or nitroglycerine. Oxygen-deficient mixtures or water-rich mixtures are less sensitive (to mechanical impact, for example) than oxygen-balanced or oxygen-rich mixtures. Explosions can be initiated by mechanical shock, explosive shock, heat, electric discharges, hot surfaces, etc.

The following factors should not be overlooked in the investigation of a new system:

1. The possibility of reaction, such as the formation of performic acid in the system containing formic acid. In this case, the explosive region increases in area as a function of time because performic acid is generated at a measurable rate.

2. The addition of a new species such as sulfuric acid, which at high $H_2SO_4/H_2O$ ratios caused the autodetonation of compositions which had yielded negative impact test results. This is usually a time-dependent reaction.

3. Immiscible systems can explode at interfaces. Increased dispersion may cause an immiscible system to be as dangerous as a miscible system.

4. Solids such as ion exchange resins, or plastics such as polyvinyl-chloride, can explode when saturated with concentrated hydrogen peroxide.

5. The first impact tests on a new system should probably be made at high hydrogen peroxide concentrations and low organic compound concentrations since this region is where the detonation limit is closest to the limit determined via impact test or cap-in-pipe test. For this same reason, definitive positive tests (as opposed to doubtful tests as often obtained with oxygen-deficient mixtures) will be obtained in this region (Ref. 6.14)

## 6.2 HAZARD PREVENTION

As described in the Hazards Section (6.1), spills and leakage of hydrogen peroxide can result in hazards to both personnel and facilities. The best possible means of avoiding these hazards is to eliminate or minimize the potential cause factors. Effective reduction of leakage, spills, contamination, and other potentially hazardous situations can be best accomplished by the use of properly designed equipment and thoroughly trained personnel.

## 6.2.1 System Integrity

The importance of the design integrity of propellant storage, transfer, and handling systems cannot be overemphasized. The systems should be reliable, operationally flexible, and easy to maintain. Some of the suggested design criteria that should be incorporated in a system are:

1. The system must be constructed of materials which are definitely known to be compatible with hydrogen peroxide.
2. The system will be designed and operated in such a manner as to prevent contamination of the system with known reactive materials.
3. The number of mechanical joints will be reduced to a minimum, thus reducing the probability of propellant leakage.
4. The system will be designed to safely withstand the maximum operating pressure.
5. The transfer lines will be free of liquid traps.
6. An inert-gas (moisture-free) system must be provided to purge the transfer lines without the necessity of dumping the residual hydrogen peroxide or disconnecting any system joints.
7. The system components must be reliable, compatible with hydrogen peroxide, and properly serviced (cleaned and passivated).
8. Sufficient remotely activated control equipment must be provided to isolate portions of the system during emergencies or component replacement.

The continual observation of an operational system for possible malfunctions can prevent serious propellant spills.

## 6.2.2 Trained Personnel

Properly trained personnel are required to handle propellant-grade hydrogen peroxide. All personnel concerned with the handling, storage, or transfer of hydrogen peroxide should be thoroughly familiar with the following:

1. The nature and properties of propellant-grade hydrogen peroxide
2. Compatible materials of construction and the necessity of essential passivation techniques
3. Operation of the transfer and storage system
4. Toxicity and physiological effects of hydrogen peroxide
5. Operation and use of safety equipment and clothing
6. Fire and spill prevention techniques
7. Fire and spill control measures
8. Disposal and decontamination techniques
9. Local operating procedures and regulations
10. First aid techniques

No person should be allowed to handle hydrogen peroxide unless thoroughly familiar with the previously listed items and should be confident that the propellant can be handled safely with the equipment and facilities available. In addition, all operations should be controlled by a procedures checklist, which has been prepared and thoroughly checked by personnel most familiar with the potential problem areas. As further safeguards, close supervision should be maintained to ensure adherence to safety practices, and all operations involving the handling of hydrogen peroxide should be performed by groups of two or more persons.

## 6.3 HAZARD CONTROL

### 6.3.1 Facility Safety Equipment

Equipment for facility protection should consist of a water deluge system and fire hoses (chemical fire extinguishers are not to be used on hydrogen peroxide fires). This equipment should be strategically located and easily accessible. Other facility items to be provided for personnel protection include safety showers, eye wash fountains, and appropriately located first aid kits.

All operating personnel should be thoroughly familiar with the location and operation of each piece of safety equipment. The operating condition of the equipment must be verified periodically.

### 6.3.2 Spill Control

A propellant spill can be most efficiently controlled by performing the following steps in the order listed:

1. Stop the propellant-handling operations
2. Isolate the propellant tanks from the transfer lines by closing the necessary valves (by remote control if possible)
3. Locate the source of the spill
4. Isolate the components affected by closing the necessary valves
5. Dispose of the spilled propellant

The performance of the first four steps should be automatic and can be performed in a very short time.

The disposition of the spilled propellant should not be too difficult, especially when propellant handling is performed during satisfactory weather conditions and the first four steps listed previously are quickly executed.

Hydrogen peroxide spills can best be controlled by deluging the spilled propellant with large quantities of water. After the spill is controlled, the entire area must be thoroughly cleaned to prevent the possibility of fire.

### 6.3.3 Fire and Explosion Control

Since most wooden flooring, straw, rags, clothing, leather, etc., contain enough catalytic material to cause rapid ignition with 90-percent hydrogen peroxide, proper precautions should be taken with this fact in mind. Storage areas for concentrated solutions should be of fireproof construction, and provision should be made for the flushing and draining of spillage.

Fires involving hydrogen peroxide should be controlled with water, because it dilutes the hydrogen peroxide and reduces the intensity of flare burning. The prompt application of copious amounts of water dilutes and cools, eliminating or minimizing the possibility of violent reaction. CHEMICAL FIRE EXTINGUISHERS SHOULD NOT BE USED.

To gain control, at least two parts of water for each part of hydrogen peroxide present should be applied. Because containers may burst, creating a fragmentation hazard, fighting these fires with hand lines is dangerous; therefore, prefire arrangements (i.e., the provision of fixed systems, etc.) should be made. In a hydrogen peroxide-fuel fire, every possible effort should be exerted to stop the flow of both fuel and hydrogen peroxide. If a fire breaks out nearby, containers of 90-percent hydrogen peroxide should be kept below 230 F to prevent vapor-phase explosions. A temperature-actuated sprinkler system on the storage tanks could be employed as a further precaution.

To prevent an explosion, hydrogen peroxide should be stored at a temperature low enough to prevent excessive gas formation due to decomposition. (A temperature below 145 F is recommended for long-term storage as noted in Ref. 6.4). Hydrogen peroxide that has become contaminated or shows an abnormal temperature rise should be diluted and disposed of. Phosphoric acid ($H_3PO_4$) may be added as an emergency stabilizer to reduce decomposition (Ref. 6.4) before disposal.

## 6.4 PERSONNEL PROTECTION

### 6.4.1 Personnel Safety Equipment

The main personnel hazard in handling concentrated hydrogen peroxide is probably not from the contact of peroxide with the skin but the danger of burns caused by ignition of clothing. Protective clothing is necessary for all personnel handling concentrated hydrogen peroxide. Ordinary fabrics made of cotton, rayon, leather, or wool should not be used, because these are apt to ignite when splashed with hydrogen peroxide. Unnoticed splashes on ordinary clothing may cause fire sometime after the occurrence. Conventional permeable clothing of Dacron, Dynel, or Orlon, when used with eye goggles, gloves, and boots, normally gives adequate protection. For full body protection, vinyl coveralls or aprons of Koroseal or Neoprene should be used. The clothing must cover all parts of the operator's body and must be adjusted so as to prevent drainage into the gloves or boots. Permeable clothing wet with peroxide must be flushed with water and removed promptly, and the affected body parts must be thoroughly washed.

The hands and feet are always subject to contamination during the handling of liquid propellants or associated equipment. Gloves and boots will keep hydrogen peroxide from touching the skin. (Leather reacts quite readily with hydrogen peroxide, however.) The gloves used should protect against hydrogen peroxide and also should allow free movement of the fingers. The vinyl-coated gloves, Type R-1, Mil-G-4244 (Ref. 6.16) meet these requirements. Surgical rubber gloves or lightweight Neoprene gloves are suitable for handling small parts. Since boots of the approved protective materials are not commercially available, an overboot, designed to be worn over regular safety footwear and high enough to fit comfortably under the protective trousers, is suitable. Boots made of natural or reclaimed rubber or GR-S may be used with reasonable safety if any contamination is washed off quickly. The boots should be frequently inspected to detect flaws which might result in personal injury. Severe foot burns can result from splashes on ordinary shoes.

Respiratory protection against vapors is not ordinarily required. Respirators approved for protection against hydrogen peroxide mists, however, should be available for use where exposure to the aerosol or mist is possible (Ref. 6.17 and 6.18).

In selection of protective clothing for $H_2O_2$ handling, the degree of hazard involved and the workers' comfort and agility must be considered. Overdressing and use of protective accessories when not warranted can actually be hazardous. A hood and full suit of impermeable clothing is only required where danger of gross spillage or spray directly on the worker is involved. In a pump transfer operation of hydrogen peroxide above 50 w/o, at least one man should be fully outfitted with impermeable clothing if detachable equipment such as a hose is being used. For handling hydrogen peroxide in drum quantities and in pump transfers in a permanent piping system, the permeable uniform worn with face shield, or eye goggles, rubber gloves, apron, and boots or rubbers will be sufficient. When wearing permeable Dacron or Dynel shirts and trousers, it is good practice to wear Dacron or Dynel underwear and socks. Goggles which afford complete eye protection should be worn during all handling and transfer operations. Water must always be available and two persons must always be present when high-strength hydrogen peroxide is handled even if protective clothing is worn.

Protective clothing and accessories recommended for personnel handling propellant-grade hydrogen peroxide are listed in Table 6.7.

## 6.4.2 First Aid

IF HYDROGEN PEROXIDE CONTACTS THE SKIN. Flood the area involved with water. If burns are present, refer to a physician.

IF HYDROGEN PEROXIDE CONTACTS THE EYES. Flush immediately and freely with water for at least 10 to 15 minutes; or if water is not available, saliva can be used to absorb the hydrogen peroxide and decrease the effect upon the tender eye membrane (Ref. 6.3). This should be done if even minute quantities of solution have entered the eyes. For any case of exposure involving the eyes, refer to an eye specialist.

IF HYDROGEN PEROXIDE IS SWALLOWED. Encourage vomiting. Give lukewarm water freely and encourage belching if there is evidence of distention. Call a physician.

IF HYDROGEN PEROXIDE VAPOR OR MIST IS INHALED. Remove victim immediately from further exposu . If irritation of the nose and throat is severe, refer to physician.

## 6.4.3 Medical Treatment

IN CASES OF EXTREME EXPOSURE OR CONTACT, OR PERSISTING IRRITATION, A PHYSICIAN SHOULD BE NOTIFIED.

## 6.5 REFERENCES

6.1 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, Hydrogen Peroxide, A. C. S. Monograph 128, Reinhold Publishing Corporation, New Yor, New York, 1955.

6.2 Shell Chemical Company, New York, New York, Concentrated Hydrogen Peroxide. $H_2O_2$. Properties, Uses, Storage Handling, 2nd Edition, Report No. SC: 62-23, 1962.

6.3 McCormick, J. C., F.M.C. Corporation, Buffalo, New York, Hydrogen Peroxide Rocket Manual, 1965.

6.4 United States Government, Office of the Director of Defense Research and Engineering, Washington, D.C., The Handling and Storage of Liquid Propellants, January 1963.

6.5 Sax, N. I., Dangerous Properties of Industrial Materials, Reinhold Publishing Corporation, New York, New York, 1957.

6.6 Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide," Ind. Eng. Chem., 39, 1536-43 (1947).

6.7 Explosives Research and Development Establishment, Waltham Abbey, England, Some Properties of 100 per cent Hydrogen Peroxide.

6.8 Monger, J., H. J. Baumgartner, G. C. Hood, and C. E. Sanborn, "Detonations in Hydrogen Peroxide Vapor," J. Chem. Eng. Data, 9(1), 124-7 (1964).

6.9 Satterfield, C. N., F. Feakes, and N. Sekler, "Ignition Limits of Hydrogen Peroxide Vapor at Pressures above Atmospheric," J. Chem. Eng. Data, 4, 131 (1959).

6.10 Laporte Chemicals Ltd., Luton, England, Hydrogen Peroxide Data Manual, 1960.

6.11 Naval Ordnance Laboratory, White Oak, Maryland, Report NOLTR 63-12.

6.12 E.I. duPont de Nemours & Company, Inc., Wilmington, Delaware, A Report for North American Aviation, Inc., Rocketdyne Division, October 1958.

6.13 Bloom, R., Jr., and N. J. Brunsvold, "Anhydrous Hydrogen Peroxide as a Propellant," *Chem. Eng. Progress*, *53*, 541 (1957).

6.14 Shell Chemical Company, New York, New York, *Concentrated Hydrogen Peroxide. Summary of Research Data on Safety Limitations*, Report No. SC: 59-44R, 1959.

6.15 Shell Development Company, Emeryville, California, *Hydrogen Peroxide by Oxidation of Isopropyl Alcohol. XVI. Vapor Explosions and Miscellaneous Explosion Test Data*, Technical Report 7-60, January 1960.

6.16 Private communication, J. C. McCormick, F.M.C. Corporation, Buffalo, New York, to M. T. Constantine, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California.

6.17 "Military Specification, Gloves, Protective, Acid Resistant, Vinyl Coated Cotton, Type R-1," Mil-G-4244A(AF), 6 May 1954.

6.18 "Respiratory Protective Devices," AFP161-1-1, 20 August 1962.

6.19 "Respiratory Protective Devices," TB MED-223.

6.20 F. M. C. Corporation, New York, New York, *Materials of Construction for Equipment in Use With Hydrogen Peroxide*, BECCO Bulletin 104, 1966 Revision.

TABLE 6.1

90- TO 100-PERCENT HYDROGEN PEROXIDE THERMAL SENSITIVITY DATA*

| Liquid Systems: | | | | |
|---|---|---|---|---|
| Conditions of Test | Temperature, F | 90 percent | 95 percent | 98 to 100 percent |
| Glass Vials in Wood Metal Bath 0.1 to 0.2 milliliter $H_2O_2$ | | Exploded at 302+ F | Slow explosion | Explodes at 270+ F |
| Aluminum Tube, Nichrome-Wound, 5 milliliters $H_2O_2$ | 383<br>302 | Rapid decomposition | Slow explosion | Detonates |
| Melting Point Block—Aluminum and Glass Inserts | | All decompose and explode at temperatures of 284 F and up | | |
| Stainless-Steel Bomb | | All slowly explode at temperatures above 248 F | | |

| Vapor Systems: | | $H_2O_2$ in Liquid, w/o | |
|---|---|---|---|
| Conditions of Test | | 90 | 100 |
| Boiling Liquid in Glass at Atmospheric Pressure | | Vapor Explodes at 284 to 302 F. Liquid rapidly decomposes. | Vapor and liquid explode at 307 F |

*Data taken from work of various investigators and summarized in Ref. 6.12. These data, which were not referenced or otherwise detailed with regard to additional test parameters and techniques, are included as a general summary of the data preceeding the efforts reported in Ref. 6.12.

## TABLE 6.2

## THERMAL TESTS ON 90- TO 98-PERCENT $H_2O_2$ IN CLOSED CONTAINERS*

In Sealed Glass Bulbs 90-Percent $H_2O_2$ Only:

| $H_2O_2$, grams | Starting Temperature, F | Explosion Temperature, F | Time Heated, minutes | Remarks |
|---|---|---|---|---|
| 0.438 | 356.0 | 374.0 | 5 | Tests indicate liquid $H_2O_2$ does not detonate even at its boiling point. The explosion is probably due to relatively slow decomposition. |
| 0.096 | 368.6 | 404.6 | 2 | |
| 0.461 | 348.8 | 404.6 | 3 | |
| 0.165 | 294.8 | 347.0 | 135 | |
| 0.235 | 336.2 | 345.2 | 4 | |
| 0.096 | 311.0 | 321.8 | 11 | |

In a Passivated Stainless-Steel Bomb
With an Aluminum Liner:

| $H_2O_2$, w/o | Quantity, milliliters | Temperature, at Start, F | Temperature, Final, F | Pressure Rise, psi/sec | Reaction Time, seconds |
|---|---|---|---|---|---|
| 90 | 30 | 275.0 | 519.8 | 1400 | 7.6 |
| 95 | 30 | 269.6 | 559.4 | 5450 | 1.6 |
| 98 | 30 | 287.6 | 609.8 | 9020 | 2.2 |

NOTE: These tests indicate that none of the $H_2O_2$ detonates, but 98 percent is sharply more hazardous.

*Ref. 6.12

TABLE 6.3

THERMAL-DECOMPOSITION TESTS OF HYDROGEN PEROXIDE*
(250-cc Round-Bottom Glass Flask)

| Test No. | $H_2O_2$ Concentration, percent | Volume Charged, cc | Temperature Recorded | Initial Explosion Temperature, F | $T_{max}$, F | $\Delta T$, F | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | 90 | 15 | Vapor | 266 | >572 | >306 | Vapor explosion |
| 2 | 90 | 15 | Vapor | 284 | 377.6 | 93.6 | Vapor explosion |
| 3 | 90 | 15 | Vapor | 287.6 | 370.4 | 82.8 | Vapor explosion |
| 4 | 90 | 15 | Vapor | 260.6 | 917.6 | 657.0 | Vapor explosion |
| 5 | 90 | 15 | Vapor | 255.2 | 465.8 | 210.6 | Vapor explosion |
| 6 | 90 | 12 | Vapor | 267.8 | 645.8 | 378 | Vapor explosion |
| 7 | 95 | 12 | Vapor | 235.4 | 458.6 | 223.2 | Vapor explosion |
| 8 | 95 | 12 | Liquid | 284.0 | 633.2 | 349.2 | Vapor explosion |
| 9 | 95 | 12 | Liquid | — | — | — | Vapor explosion; blew thermocouple out |
| 10 | 95** | 12 | Liquid | 276.8 | 305.6 | 28.8 | Vapor explosion |
| 11 | 95** | 12 | Vapor | 147.2 | 179.6 | 32.4 | Vapor explosion; blew thermocouple out |
| 12 | 95** | 12 | Liquid | 264.2 | 858.2 | 594 | Vapor explosion; two reports audible |
| 13 | 95** | 12 | Vapor | 276.8 | 392.0 | 115.2 | Vapor explosion; two reports audible |
| 14 | 98 | 12 | Liquid | 212 | 282.2 | 70.2 | Vapor explosion |
| 15 | 98 | 12 | Liquid | 203.0 | 309.2 | 106.2 | Vapor explosion |
| 16 | 98 | 12 | Vapor | 136.4 | 314.6 | 178.2 | Vapor explosion; glass vessel ruptured |
| 17 | 98** | 12 | Liquid | 296.6 | — | — | Vapor explosion; no temperature record |
| 18 | 98** | 12 | Liquid | 212 | — | — | Vapor explosion; glass vessel ruptured |

*Ref. 6.12

**Flask opening covered with aluminum sheet

TABLE 6.4

### THERMAL-DECOMPOSITION TESTS OF HYDROGEN PEROXIDE*

(265-cc Closed Vessel)

| Test No. | $H_2O_2$ Concentration, w/o | Volume Charged, cc | Initial Explosion Temperature, F | $T_{max}$, F | $\Delta T$, F | $P_{max}$, psig | $(dp/dt)_{max}$, psi/sec | Time to $P_{max}$, seconds | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 90 | 15 | 287.6 | 377.6 | 90 | — | — | — | No pressure record available |
| 2 | 90 | 15 | 262.4 | 388.4 | 126 | 660 | — | — | No pressure rate or time |
| 3 | 90 | 15 | 248.0 | 464 | 216 | 1000 | 1050 | 1.7 | |
| 4 | 90 | 25 | 280.4 | 528.8 | 248.4 | — | — | — | No pressure record available |
| 5 | 90 | 25 | 275.0 | 518 | 243 | 1450 | 1360 | 7.6 | |
| 6 | 95 | 15 | 284.0 | 485.6 | 201.6 | — | — | — | No pressure record available |
| 7 | 95 | 15 | 284.0 | 440.6 | 156.6 | 800 | 510 | > 3.5 | |
| 8 | 95 | 25 | 294.8 | 536.0 | 241.2 | 1260 | — | — | No pressure rate or time |
| 9 | 95 | 25 | 269.6 | 559.4 | 289.8 | 2500 | 5450 | 1.6 | |
| 10 | 98 | 15 | 280.4 | 465.8 | 185.4 | 1000 | 1290 | 2.85 | |
| 11 | 98 | 25 | 287.6 | 609.8 | 322.2 | 3100 | 9020 | > 2.2 | |

*Ref. 6.12

## TABLE 6.5

## SHOCK-SENSITIVITY TESTS OF HYDROGEN PEROXIDE*

(Modified Card-Gap Apparatus)

| Test No. | Liquid Under Test | Volume Charged, cc | Tetryl Charge Weight, grams | Disk Thickness, mils | Results |
|---|---|---|---|---|---|
| 1 | Water | 40 | 14 | 10 | Fragmented apparatus; no apparent damage to "crusher" |
| 2 | 90-percent $H_2O_2$ | 40 | 14 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 3 | 95-percent $H_2O_2$ | 40 | 14 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 4 | 98-percent $H_2O_2$ | 40 | 14 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 5 | 98-percent $H_2O_2$ | 40 | 33 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 6 | 95-percent $H_2O_2$ | 40 | 33 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 7 | 90-percent $H_2O_2$ | 40 | 33 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 8 | 90-percent $H_2O_2$ | 40 | 14 | 10 | Fragmented apparatus; no apparent damage to crusher |
| 9 | 98-percent $H_2O_2$ | 40 | 33 | 5 | Fragmented apparatus; no apparent damage to crusher |

*Ref. 6.12

## TABLE 6.6

## 90- TO 100-PERCENT HYDROGEN PEROXIDE SHOCK SENSITIVITY DATA*

| | $H_2O_2$, w/o | | |
|---|---|---|---|
| | 90 | 95 | 100 |
| Impact Tests | ← No explosions → | | |
| Rifle Fire | ← No explosions → | | |
| No. 6 and 8 Blasting Caps Alone | ← No detonations → | | |
| No. 6 and 8 Blasting Caps With Pentaerythritol | Incomplete | detonation → | Complete |
| Ballistic Mortar | 40 percent of TNT | 80 percent of TNT | |
| Lead Block Enlargement | 5 cc/gm | 7 cc/gm | 9 to 12 cc/gm |
| Explosion Velocity Aluminum Pipe | $<100$ meter/sec | 4500 meter/sec | 6200 meter/sec |
| Closed Steel Tubes, 175 milliliters $H_2O_2$ + 50 grams Penthrite Primed With Fulminate | No Detonation | Detonated | — |

*Data taken from work of various investigators and summarized in Ref. 6.12. These data, which are not referenced or otherwise detailed with regard to additional test parameters and techniques, are included as a general summary of the efforts preceding the data reported in Ref. 6.12.

# TABLE 6.7

## PROTECTIVE CLOTHING AND ACCESSORIES RECOMMENDED FOR PERSONNEL HANDLING CONCENTRATED HYDROGEN PEROXIDE*

| Item | Description | Source |
|---|---|---|
| Shirts, Trousers | Dacron fabric, Polystyrene buttons, no front or side pockets, no cuffs | Worklon, Inc., N.Y., N.Y. |
| | Dynel Fabric | Mine Safety Appl. Co. |
| | 100-percent Dynel Chem-Weave, medium weight | Chem-Wear, Inc., Darien, Conn. |
| Belts | Vinyl plastic, with plastic buckle | Numerous commercial sources |
| Undershirts | Dacron | Alamac Knitting Mills, N.Y., N.Y., Special lot, minimum order, 10 dozen |
| | Dacron-cotton (can be ignited if soiled) | Carmi-Ainsbrooke Corp., Carmi, Illinois |
| Shorts | Dacron | Carmi-Ainsbrooke Corp.<br>Manhattan Shirt Co., N.Y., N.Y. |
| Socks | Knit Dacron, no elastic, white<br>Dynel fabric | Holston Mfg. Co., Knoxville, Tenn.<br>Numerous commercial sources |
| Shoes | 6-inch Neoprene Coated, No. 990 steel toe | Iron Age Div., Childs & Co., Inc., Pittsburgh, Pa. |
| Rubbers | Full, Neoprene with tongue | Numerous commercial sources |
| Boots | Neoprene, knee length | Numerous commercial sources |
| Goggles | No. 93 AV large nose, clear Willson Monogoggle | Willson Products, Inc., Reading, Pa. |
| | Model 293607 SAF-I-CHEM, Series 29 clear lens | U.S. Safety Service Co. Kansas City, Mo. |
| Face Shield | No. 324 clear Sellstrom face shield | Watson Co., Buffalo, N.Y. |
| Gloves | Sureseal, gauntlet, Vinyl or Neoprene, No. 116 lightweight for laboratory use. No. 136 medium weight for work use | Surety Rubber Co. Carrollton, Ohio |
| Apron | 8-mil vinyl plastic. Surgeon's type, extra long, overlapping in back, ties in front. | Milburn Co. Detroit 7, Mich. |

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*Ref. 6.19

## TABLE 6.7

(Concluded)

| Item | Description | Source |
|---|---|---|
| Coveralls | Vinyl plastic. One-piece, light weight disposable unit. Grey color | Mine Safety Appliance Co. |
| Caps | Dacron fabric. Baseball type, with removable sunshade for neck. | Worklon, Inc. |
|  | Dynel fabric | Chem-Wear<br>Mine Safety Appliance Co. |
| Hood | 8-mil vinyl methacrylate window, detachable head band, adjustable for size | Milburn Co.<br>Detroit 7, Mich. |
| Impermeable Jacket | Fiberthin Raynster, Neoprene coated Nylon, MRS-107 | U.S. Rubber Co.<br>Washington, Ind. |
| Impermeable Overalls | Fiberthin Raynster, MRO-107 | U.S. Rubber Co.<br>Washington, Ind. |
|  | OUTDOOR WINTER-WEIGHT PROTECTIVE CLOTHING |  |
| Shirts | 55-percent Dacron-45 percent wool Sport-type shirt, polystyrene buttons | Worklon, Inc.<br>New York, N.Y. |
| Trousers | 55-percent Dacron-45 percent wool No pockets, cuffs | Worklon, Inc.<br>New York, N.Y. |
| Cap | 100-percent Dacron pile lining, outer material | Borg Fabric Div.<br>G. W. Borg Co.<br>Delavan, Wisc. |
| Pants | 100-percent Dacron pile lining, outer material | Borg Fabric Div. |
| Boots | Neoprene, insulated boots. Similar to U.S. Army all-rubber, insulated combat boots | Hood Rubber Co.<br>Watertown, Mass. |
| Jacket | 100-percent Dacron pile lining, outer material | Borg Fabric Div. |

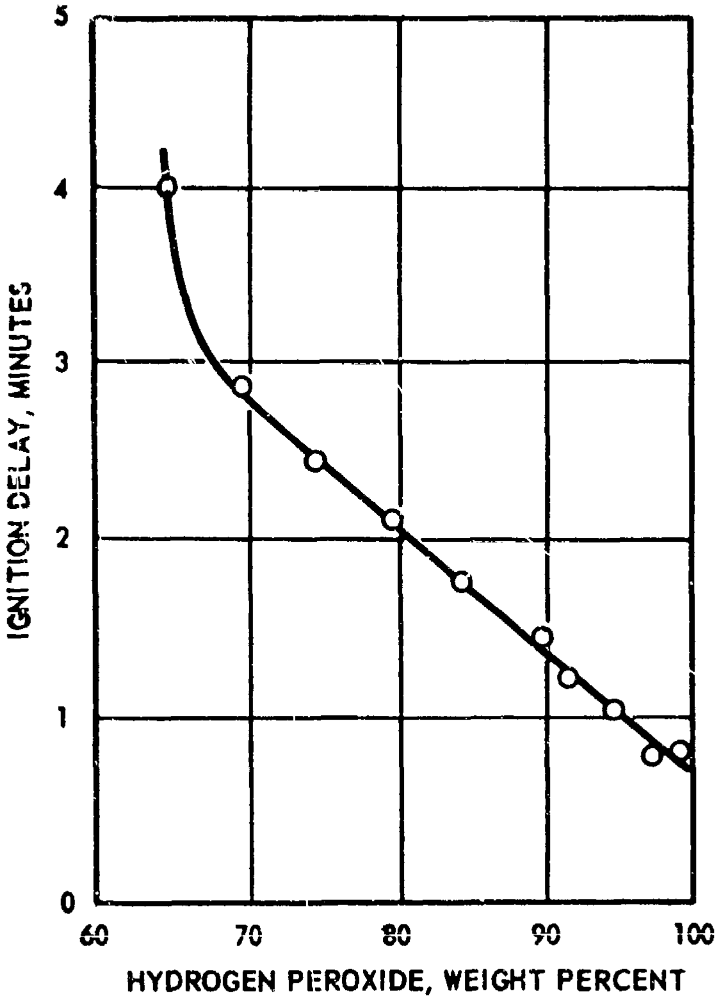

Figure 6.1. Ignition Delay of Hydrogen Peroxide With Felt (Ref. 6.7)

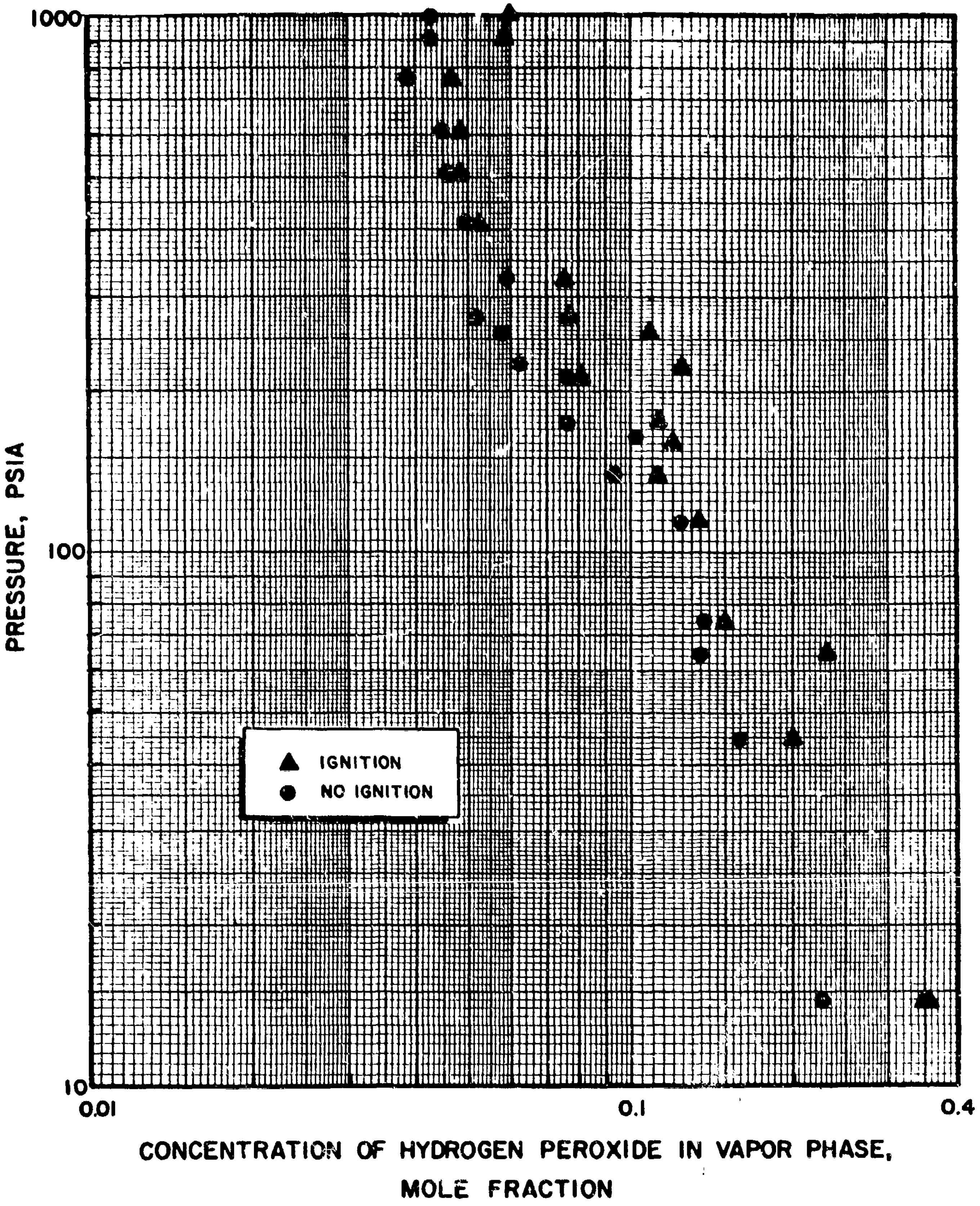

Figure 6.2. Ignition Limits of Hydrogen Peroxide Vapor (Ref. 6.8)

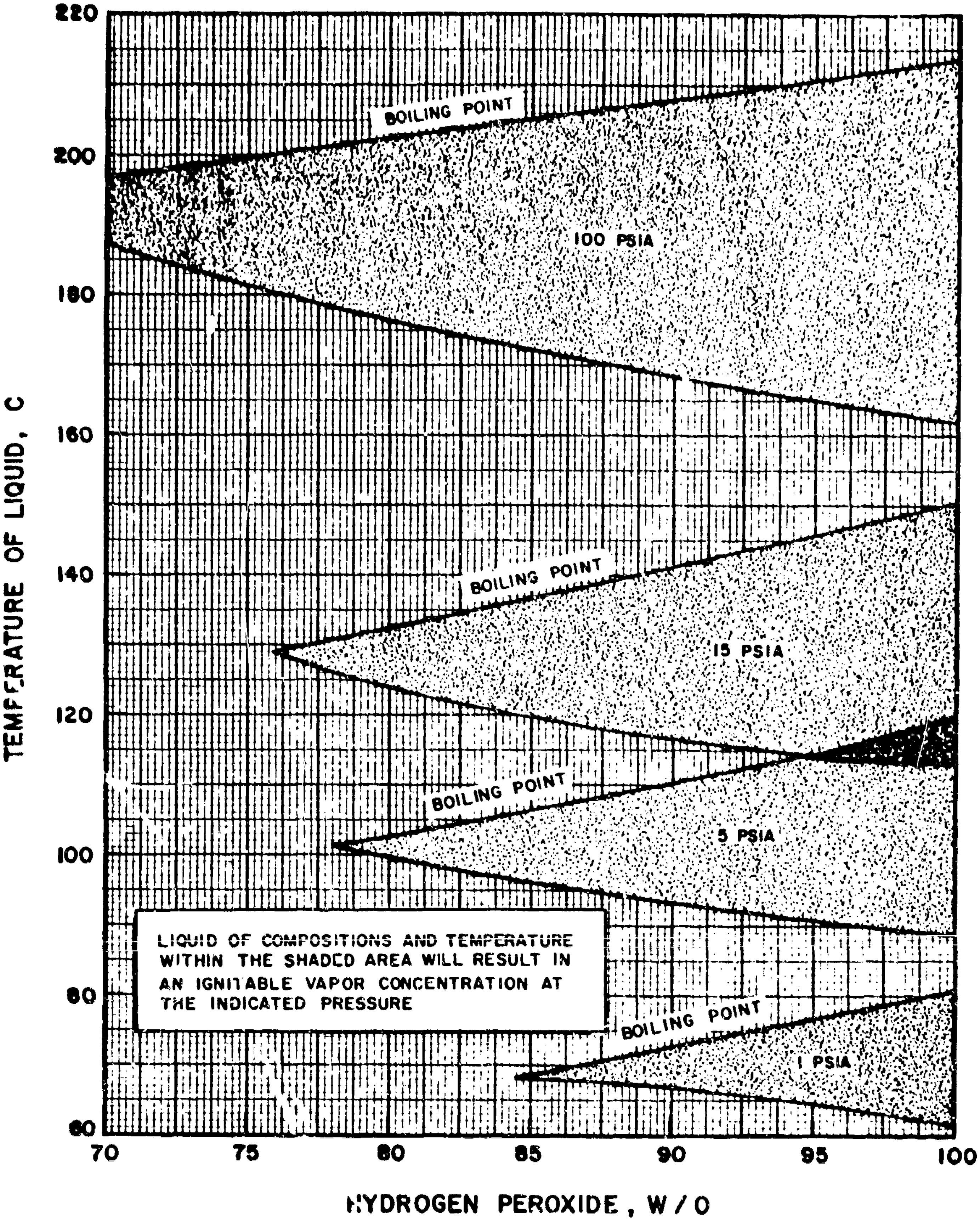

Figure 6.3 Liquid Compositions Which Result in Ignitable Vapor Concentrations (Ref. 6.10)

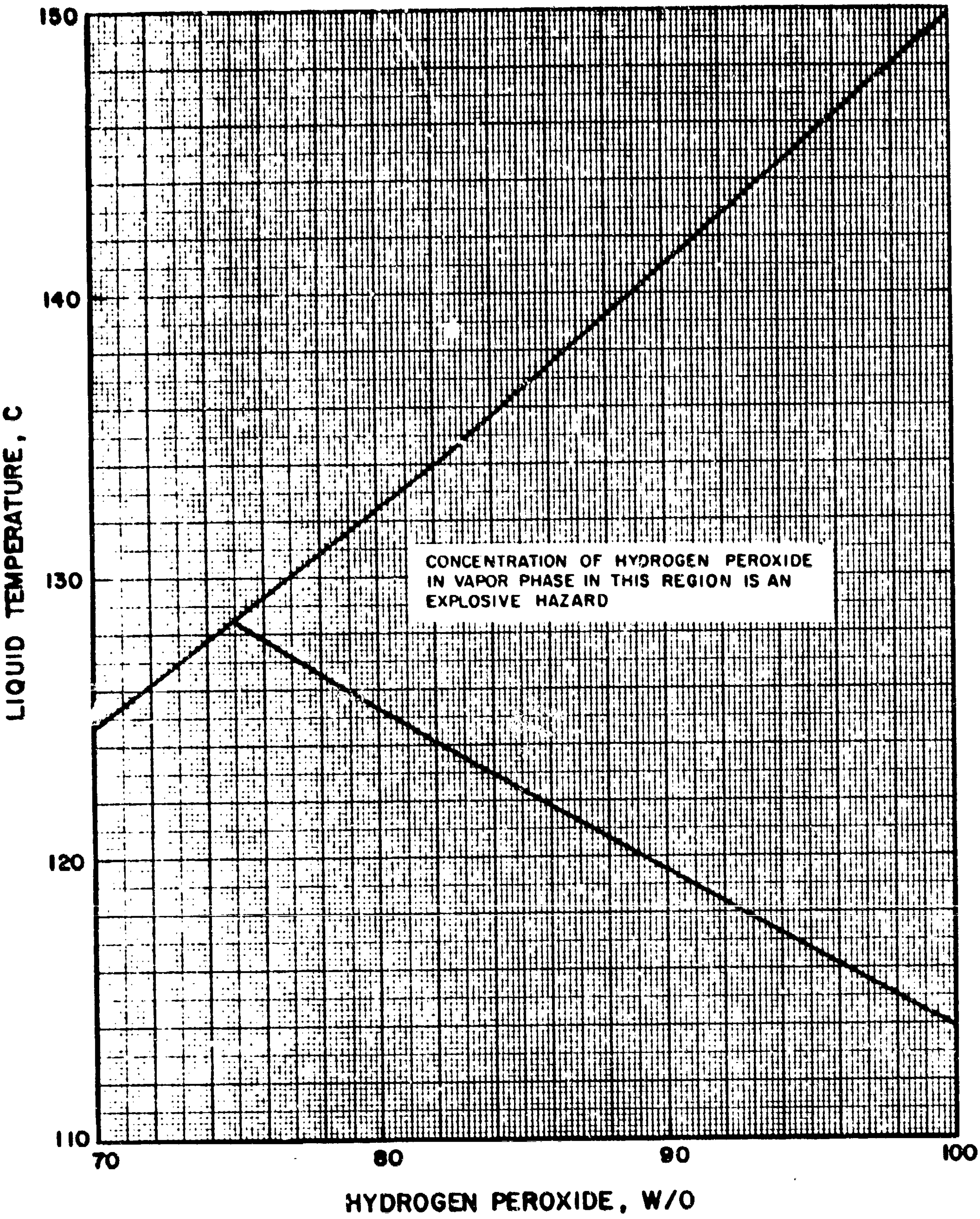

Figure 6.4. Hydrogen Peroxide Vapor Explosive Hazard Region (Ref. 6.11)

# SECTION 7: DECOMPOSITION

## 7.1 DECOMPOSITION MECHANISM

The decomposition of hydrogen peroxide may be represented by the equation:

$$H_2O_2 \longrightarrow H_2O + 1/2\ O_2$$

This decomposition process is irreversible. Kineticists studying this particular decomposition process can theoretically illustrate 10 to 20 intermediate reactions which may exist in hydrogen peroxide decomposition; however, the above equation is the effective result of these intermediate steps in the decomposition. Although the rate controlling reaction has not been identified, it is generally believed that it is one involving an electron transfer.

Since its discovery, when Thenard (Ref. 7.1) reported on the effect of over a hundred materials on the decomposition reaction, many decomposition studies have been conducted on hydrogen peroxide in attempts to characterize the decomposition process. Throughout these studies, it has been recognized that hydrogen peroxide decomposition is a result of both homogeneous and heterogeneous reactions. This decomposition, when both the liquid and vapor phases of hydrogen peroxide exist, has been considered as the sum of five types of reactions:(1) homogeneous reaction in the liquid phase between the hydrogen peroxide and dissolved catalytic or oxidizable components; (2) heterogeneous reaction of the liquid phase with surfaces of the container and/or suspended particles; (3) heterogeneous reaction of a film of condensed hydrogen peroxide on surfaces in contact with the vapor phase; (4) heterogeneous reaction of the vapor phase on dry surfaces; and (5) homogeneous decomposition of the vapor phase (Ref. 7.1).

In a recent investigation ( cf. 7.2) to define the contributions of these individual reactions to the ambient temperature decomposition of 90 w/o hydrogen peroxide, reaction types (4) and (5) were ignored. Reaction type (4) probably does not occur when the temperature of the surfaces is below the hydrogen peroxide boiling point and the effects of reaction type (5) were considered insignificant at the temperatures under consideration. In addition, it was indicated that reaction type (1) could probably be separated into further types of reactions; however, for the purpose of the particular study, the liquid phase homogeneous decomposition was considered as being essentially ionic catalysis. The differences between reaction types (2) and (3) were considered to be in the effective concentration of hydrogen peroxide on the surfaces, the concentration of contaminants which may build up in this condensed liquid film, and in the concentration of inhibitors which would be present in the condensed film (unless agitation of the vessel caused frequent wetting and washing of all surfaces with the hydrogen peroxide liquid phase).

Assuming these three types of reactions are the only contributing effects to hydrogen peroxide decomposition in the ambient temperature range, the rate of decomposition can be represented by the following expression:

$$\frac{d(HP)}{dt} = k_1 \quad (HP) + k_2 \quad (HP) \; (S/V)_{liq.} + k_3 (HP) \, (s/V)_{vapor}$$

where HP = concentration of hydrogen peroxide

$k_1$ = liquid phase homogeneous reaction rate

$k_2$ = liquid phase heterogeneous reaction rate

$k_3$ = vapor phase heterogeneous reaction rate

S/V surface to volume ratio of the liquid phase

s/V = surface to volume ratio of the vapor phase

t = time

Through the use of various purification techniques, relatively inert surfaces, and the absence of a vapor phase, the experimenters of Ref. 7.2 were able to isolate, for all practical purposes, the effective homogeneous reaction rates of the liquid from 20 to 100 C (68 to 212 F). Using these data, the effects of soluble additives (such as stabilizers) on the liquid phase were also determined. Although the data resulting from this work varied from test to test and as a function of stabilizer concentration and type, temperature, and manufacturing process, the homogeneous decomposition rate of the stabilized and unstabilized liquid was generally found to be less than ~ 0.03 w/o active oxygen loss (AOL) per year at 100 C (212 F). In addition, it was indicated that for future comparisons of results at different temperatures or the estimation of decomposition rates at various temperatures, the activation energy for the homogeneous decomposition of hydrogen peroxide can be assumed to be 18 kcal/mole.

As a result of this work, the experimenters indicated that the predicted homogeneous decomposition rate of hydrogen peroxide would correspond to the following expression:

$$D_1 = 10^{7.2} e^{-\frac{1800}{1.987T}}$$

where $D_1$ = homogeneous decomposition rate in weight fraction/year

and T = temperature in K.

Using an overall decomposition rate with a correction for the effect of the homogeneous rate, heterogeneous decomposition rates were also determined in this study. Values were calculated for $k_2$ using experimental decomposition rates obtained for hydrogen peroxide storage in 5-gallon storage tanks fabricated from different materials. In these tests it was assumed that the rate constants for both vapor phase and liquid phase heterogeneous decomposition were equivalent at the lower temperatures (on the basis that the rate of decomposition was sufficiently slow so that mass transfer of hydrogen peroxide to the vapor space surface was not the controlling rate); thus the heterogeneous decomposition rate for both phases was equivalent to $k_2$ (S/V) where (S/V) represented the total exposed surface area of the tank relative to the volume of the liquid hydrogen peroxide. Results of these tests indicated that $k_2$ for the different materials at 25 C (77 F) appeared to be as follows:

1260 aluminum = 0.0065 weight fraction AOL, cm/year
5052 aluminum = 0.0160 weight fraction AOL, cm/year
tin plate = 0.286 weight fraction AOL, cm/year
Kel-F = 0.0031 weight fraction AOL, cm/year

Additional studies in this and the homogeneous area are being conducted by the same investigators and have been reported thus far in Ref. 7.3 and 7.4.

A study of hydrogen peroxide homogeneous decomposition rates in the complete absence of catalytic surface effects (Ref. 7.5) was attempted through the use of solid hydrogen peroxide as the container wall. Unfortunately, during the period of the contracted work, the desired experimental conditions were not obtained, although definitive techniques were proposed for future study. However, during the study, total decomposition rates were measured on several purified and stabilized grades of 90 and 98 w/o hydrogen peroxide in both the frozen (-60 and -30 C) and the cooled liquid (0 C) state. The resulting decomposition rates from these tests, which were effectively due to homogeneous decomposition effects, were below 0.023 w/o AOL/year.

Throughout the various decomposition studies that have been conducted on hydrogen peroxide, it has been generally indicated that the homogeneous decomposition rates of liquid hydrogen peroxide were found to be dependent upon:

1. Hydrogen peroxide concentration

2. Type of additives or contaminants present
3. Concentration of additives or contaminants
4. pH
5. Particular combinations of foreign materials present
6. Temperature

Similarly, the heterogeneous reaction rates were found to be dependent upon:

1. Hydrogen peroxide concentration
2. Temperature
3. Passivation or cleaning technique
4. Surface area
5. Surface finish (area ratio)
6. Localized concentrations of impurities in the solid surface
7. Pressure (under certain conditions)

Numerous investigators have reported decomposition and stability data for hydrogen peroxide as a function of these variables and with hundreds of various materials. Because of the uncertainty involved in trying to separate any one of the contributing parameters in the decomposition process, illustrations of the individual parameters are not presented in this handbook. However, these decomposition data are summarized as total effects relative to engineering parameters such as storability (Section 4.1), materials compatibility (Section 4.2), passivation effectiveness (Section 4.3), etc., in other parts of this handbook.

For those users of this handbook who are interested in more details of various reaction rates and other aspects in the decomposition of hydrogen peroxide, the use of the previously referenced literature (Ref. 7.1, 7.2, 7.3, 7.4, and 7.5) as well as the use of references to literature on decomposition provided in the attendant bibliography (Section 8.9) will provide the basis for further investigation.

## 7.2 CONTROLLED DECOMPOSITION

The hydrogen peroxide decomposition process is used under controlled conditions to provide a high temperature gas as the working fluid for reaction control systems, auxiliary power units, turbopump drive, underwater propulsion, etc. Ordinarily, to achieve effective use of the decomposition process for these applications, the hydrogen peroxide must undergo a rapid and complete decomposition to $H_2O$ and $O_2$ within the confines of a combustion chamber; the decomposition must be immediately initiated upon entry to the chamber and must be completed upon exit. The process must occur smoothly without radical surges or oscillations in the working pressure. There have been two primary methods employed to initiate and maintain this type of a controlled decomposition of hydrogen peroxide in a combustion chamber: (1) catalytic decomposition and (2) thermal decomposition.

### 7.2.1 Catalytic Decomposition

Catalytic decomposition of hydrogen peroxide is, as implied, dependent on the use of a catalyst, either as a liquid in a fluid-type catalytic chamber or as a solid in a fixed bed chamber. In the use of a liquid catalyst, a suitable catalytic liquid is continuously injected into the combustion chamber with the hydrogen peroxide and ejected out of the combustion chamber with the decomposition gases. The liquid catalysts normally employed are aqueous solutions of calcium or potassium permanganate.

Solid catalyst beds normally consist of packed columns of porous materials or screens, which have been coated with the catalytic agent. The solid porous materials are usually referred to as catalytic stones and are activated by impregnation with the catalytic agent contained in a solvent with subsequent removal of the solvent (usually by drying). Materials that have been commonly used for this type of solid catalyst are aqueous solutions of calcium or potassium permanganate, or the metallic nitrates. Calcium permanganate is usually prefered to potassium permanganate, primarily due to its higher solubility in water. The most effective results from this type of catalyst are usually obtained with alumina or carborundum particles as the porous carrier medium.

Silver is probably the best known and the most active catalyst for the decomposition of hydrogen peroxide. This catalytic material is usually applied in a screen type of configuration. Since pure silver has proven somewhat undesirable from a physical integrity standpoint (especially at the temperatures obtained in this type of application) and because of its high cost, the silver catalyst is also used as a plating on brass, nickel, or stainless steel screens. To further reduce the cost imposed by the silver, stainless or nickel screens are intermingled with the silver or silver coated screens, without reducing catalyst effectiveness; of course a minimum number (which is dependent on the particular configuration) of catalyst screens, is required for satisfactory operation. The use of the silver plated screens usually offers better initial starting characteristics than the catalyst does and provides more structural integrity in the bed; however, such screens are more subject to catalyst stripping during operation. Because the initial activity of previously unused silver catalysts is normally low, they are usually "activated" by pretreatement with samarium nitrate (by immersion) and hot fired in a furnace prior to their use in the catalyst pack.

Although the silver and the permanganate catalysts have been the catalysts of choice for most of the controlled decomposition concepts, there are a number of other types of materials which have been investigated as hydrogen peroxide catalysts. Identification of these different materials and a more detailed discussion of the catalytic decomposition process are contained in Ref. 7.1, 7.6, 7.7, and 7.8. A complete bibliography of other data in this area has been compiled in Ref. 7.9.

7.2.1.1 Catalyst Pack Design and Descriptions. The permanganate liquid catalyst was initially used by the Germans during World War II for application in torpedo propulsion and in a gas generator to drive the turbopumps for the V-2 rocket. Although the liquid permanganate catalyst is still used for some underwater propulsion applications, the solid catalysts have proven to be more applicable to most of the present monopropellant hydrogen peroxide propulsion and gas generation concepts.

The first effective application of the solid catalyst concept was in the Redstone Missile gas generator system. This catalyst (Ref. 7.10) was used to decompose a 76 w/o hydrogen peroxide solution to provide working gases for a turbine which was used to drive the main propellant pumps of the missile system. The catalyst was a polysurfaced silicon carbide "stone" which had been impregnated with calcium permanganate. These "permanganate stones" (PMS) were screened to +16 mesh and packed into a catalyst bed of approximately 3 inches depth, where they were held in place by an inlet screen of 16 mesh and outlet screens of 16 and 80 mesh, supported by rigid perforated steel plates. A hydrogen peroxide flow rate of ~ 6.0 lbs/sec resulted in a bed loading rate of ~ 10 lb/sq in.-min and a 20- to 30-psi bed pressure drop. The catalyst was required to give suitable operation for 600 seconds; the start transient was ~70-150 ms from propellant entry into the chamber to 90% Pc.

Although the PMS catalyst provided a suitable catalyst for 76 w/o hydrogen peroxide, the use of concentrations in excess of 85 w/o $H_2O_2$ stripped the catalytic material from the porous carrier. In addition, the PMS catalyst had a tendency toward fracturing or "dusting" in handling with a resultant loss in catalytic efficiency. Thus the development of a more suitable catalyst for higher hydrogen peroxide concentrations was sought.

In the middle 1950's, silver catalyst screens were developed for use with 90 w/o $H_2O_2$. Since then, there have been a number of different types of silver catalysts developed for different applications. Each bed is unique to the application for which it is developed, thus each particular design may be slightly different. Because there are a number of different catalyst beds for decomposition of 90 w/o $H_2O_2$ in existence today, a listing of each in this handbook would be prohibitive. Therefore the description of a catalyst pack for 90 w/o $H_2O_2$ given in the succeeding paragraph represents a general description of the silver screen catalyst pack and does not represent any single design.

Silver catalyst screens may be (as mentioned previously) fabricated from pure silver or from silver plated-brass, -nickel, or -stainless steel screens. The screens are usually 16 to 20 mesh with a wire diameter of ~0.014 inches. Some specifications for catalyst screens call for a 66 to 71 percent light-transmission. After "activation" by samarium nitrate immersion and baking, the screens are packed into the combustion chamber (with a light force fit against the walls) at right angles to the combustion chamber. Usually the packing is such that a stainless steel or nickel screen (inactive screen) is placed between two catalyst screens. The number of catalyst screens is dependent on system requirements (operational life, bed size, throughput, pressure drop limitations, start transients, etc.) and may vary from 15 to as many as 100 catalyst screens.

Usually, the bed is terminated with several "inactive" screens. Perforated stainless steel supports are used as screen retainers, and also may be placed at different points in the bed to act as anti-channel baffles. The entire column is compressed to some specified compacting pressure to limit pressure oscillations and assure reproducible performance (pressure drop, flow rate, temperature gradient, etc.) from bed to bed in the same hardware. Most silver screen catalyst beds are operated at bed-loadings of ~ 20 lb/sq in-min; these bed loading rates may vary although it should be noted that higher catalyst bed loading rates will result in higher bed pressure drops and silver erosion rates. Bed pressure drops usually run from 75 to 125 psi.

The standard silver and silver-plated screen catalysts were found to be inadequate for sustained decomposition of 90 w/o $H_2O_2$ that is pre-heated to temperatures above 100 to 150 F, or for concentrations of hydrogen peroxide with adiabatic decomposition temperatures above 1400 to 1500 F. Because many present applications involve preheating of the hydrogen peroxide (as a result of its use as a regenerative coolant) and the use of 98 w/o $H_2O_2$ which decomposes at ~ 1800 F, the development of a catalyst which retains physical strength and chemical reactivity above this temperature has been pursued.

The initial development of a high temperature hydrogen peroxide catalyst was undertaken by Rocketdyne, first under company-sponsored funding and later under Contract NOas 56-1052J. Although this catalyst, which is described in Ref. 7.11, has been used successfully at Rocketdyne for several years in the decomposition of 98 w/o $H_2O_2$, the catalyst's physical and chemical stability at temperatures of 2000 F is questionable. Thus under Air Force Contract AF04(611)-11208, FMC initiated the development of new decomposition catalysts for 98 w/o $H_2O_2$. Their progress in these efforts have been reported in Ref. 7.12.

For those users of this handbook who are interested in the detailed design of catalyst beds for various concentrations of propellant-grade hydrogen peroxide, the use of data contained in Ref. 7.13, 7.14, 7.15, and 7.16, in addition to those already cited, are suggested.

7.2.1.3 Catalyst Poisoning. There are a number of impurities that may be contained in hydrogen peroxide, which will cause catalyst poisoning or catalyst pack malfunction. Although these impurities are normally associated with those additives used in stabilization, any non-volatile contaminant or additive in the hydrogen peroxide is a potential catalyst poison. Residual or nongaseous products from the decomposition process, such as tin or aluminum, may act as a catalyst poison by depositing on the catalyst to decrease the effective catalytic surface or by physically plugging the flow paths. Other materials such as the nitrates, chlorides, and phosphates may cause excessive erosion and loss of catalytic material, which reduces the effective activity of the catalyst. Additives which act as stabilizers during hydrogen peroxide storage by complexing and "tying up" the activity of heavy metal ions also tend to complex with the catalyst material in the combustion chamber.

Although the particular details of catalyst poisoning by various potential contaminants are not completely understood, most of the important hydrogen peroxide catalyst poisoners have been identified. Attempts at characterizing limitations for each of the individual species and the contributions and limitations of their interaction have met with little success. However, the limitations (which were determined under an extensive Navy "crash" program and further refined through extensive use) placed on inorganic contaminants in the hydrogen peroxide by the procurement specification MIL-P-16005D (see Section 3.3) for 90 w/o hydrogen peroxide have been effective in controlling poisoning of catalysts used for decomposition of propulsion grade hydrogen peroxide.

7.2.1.3.1 Effect of Organics. For some time there has been considerable controversy over possible differences between hydrogen peroxide produced by the various production techniques with respect to silver-screen catalyst performance and failure. Organic contaminants found in hydrogen peroxide produced by the organic process (namely the anthraquinone and propane-derivative oxidation processes) were suspected of being responsible for various catalyst pack failures that occurred periodically in various hydrogen peroxide decomposition systems (Ref. 7.15). Although there were a few catalyst pack failures (in contrast to the many successful operations) during operation of the packs with organically derived hydrogen peroxide, there was a lack of clear-cut analytical evidence indicating that the organic contaminants were contributing causes.

Because there was a belief that the higher carbon content of the organic materials either caused the reaction to exceed the melting point of the catalyst or caused a carbonate formation on the surface of the catalyst (to effectively poison it), a study was conducted by Rocketdyne (Ref. 7.11) to determine the potential effect of carbon content on catalyst performance. The performances of three types of organically derived hydrogen peroxide were compared with that from the electrolytic process in silver screen catalyst packs of the configuration used in the Rocketdyne Super Performance Aircraft Rocket Engine (Models AR-1, -2). The results from these tests indicated that the performance of one of the organically-derived hydrogen peroxides (with a carbon content of 150 to 200 mg/l) was equivalent or better than that of the electrolytically-produced reference hydrogen peroxide. The failure of the catalyst in the use of the other two organically-derived hydrogen peroxides (with similar carbon contents of 120 to 270 and 194 to 212 mg/l, respectively) was theorized to be a result of either (1) the specific nature of the carbon compounds present, (2) synergistic effects of organic and inorganic contaminants, or (3) synergistic effects of the purely inorganic impurities.

Later, after apparent improvements in the process for the manufacture of organically-derived hydrogen peroxide, production models of the Rocketdyne AR-2 engine system were qualified using 90 w/o hydrogen peroxide (which met the requirements of Mil-P-16005C)* from the three manufacturers of propellant-grade hydrogen peroxide. No catalyst failures were experienced during these tests that were attributable to any particular type of hydrogen peroxide, either organically-or electrolytically-derived.

Recently, studies were conducted by the Air Force Rocket Propulsion Laboratory (Ref. 7.17), in which 90 w/o hydrogen peroxide (procured under Mil-P-16005D from the various manufacturing processes) was catalytically decomposed in an LR-99 gas generator using a simulated flight feed system. No differences were observed in the operation or performance between the three types of propellant-grade hydrogen peroxide.

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*NOTE: Mil-P-16005C was superceded by MIL-P-16005D

It was concluded that "there was no evidence to indicate a desirability of a change in the current hydrogen peroxide specification".

As a result of these recent comparisons of hydrogen peroxide catalyst performance with both organically-derived and electrolytically-derived hydrogen peroxide, it is concluded that the propellant procured according to Mil-P-16005D requirements should not be detrimental to the performance of the present silver-screen catalysts. However, the roles of the individual contaminants of both types as well as their inter-relationship in catalyst poisoning are still not completely defined.

7.2.1.4 Operational Problems. Although reviews of the operational problems that frequently occur in the catalytic decomposition of hydrogen peroxide appear in many sources (including in particular, Ref. 7.1 and 7.15), a very adequate and concise discussion of the problems is given in Ref. 7.18 as follows:

> "It is now opportune to consider the various factors which lead to a loss of efficiency of a (catalyst-Ed.) pack.
>
> The first is that of increase in pressure drop across the pack during use. In this case, although the pack is still active, it may become impossible to maintain the desired rate of flow of H.T.P. (propellant-grade hydrogen peroxide-Ed.) due to the increase of resistance to flow through the pack. Such increased resistance may be caused by the deposition of large amounts of non-catalytic material such as tin stabilizer. The deposition of precipitated silver dissolved from the entry end of the pack can also cause an increase in pressure drop if the amount of free space provided downstream is small. Increased pressure drops have also been observed when large amounts of silver were provided on the downstream gauzes (screen-Ed.). This effect may result from the partial fusion of the silver, causing the gauzes to become 'welded' together and is likely to be accentuated when H.T.P. of high concentration is used.

A second factor leading to the loss of catalyst pack efficiency is the erosion of silver. This may occur in two principal ways: (1) When the adhesion of the silver plating to the base metal of the gauze is poor, mechanical stripping of silver may occur at high flow rates of H.T.P. through the interstices of the gauzes. The type of silver catalyst known as 'activated silver' which is a loose powdery deposit of silver made by dipping copper gauze in ammoniacal silver nitrate solution, is particularly prone to mechanical stripping. (2) Erosion occurs by solution of silver metal in the liquid H.T.P. near the entry end of the pack: most of the dissolved silver is redeposited downstream but a small fraction is blown out, and this leads to a gradual reduction in the total amount of silver available. However, more important than the gradual overall loss of silver is the fact that the gauzes at the entry end of the pack eventually become completely stripped of silver and then cease to contribute towards the decomposition of the H.T.P. This leads to a gradual shortening of the effective length of the pack, the liquid phase penetrating further towards the downstream end. Eventually the penetration reaches the downstream end and the efficiency of the pack falls rapidly.

The use of H.T.P. at low ambient temperatures, and the repeated stopping and restarting of the decomposer when cold, both accelerate the loss of efficiency of a pack, due to an increased rate of erosion of silver. Since the rate of decomposition of hydrogen peroxide at a silver surface decreases with decrease in temperature, the use of a decomposer at low temperatures involves a greater penetration of the pack by liquid H.T.P. and in consequence a higher overall rate of solution of silver. As mentioned above, the rapid starting of a decomposer involves a greater penetration of H.T.P. than occurs during steady 'running,' and there is in consequence a higher rate of solution of silver during the starting period. Repeated stopping of the decomposer and restarting when it has cooled down will therefore lead to an overall higher rate of loss of silver than occurs during a continuous 'run.' It is also a consequence of the greater penetration of liquid during a start that a decomposer which is losing efficiency, but is still usable, may not restart satisfactorily from cold if the 'run' is stopped at a late stage during its potential life under continuous 'running' conditions.

In connection with the erosion of silver it is necessary to consider the pheuomenon known as 'channeling,' which is the term given to the preferential erosion of silver over certain parts of the gauze area. As a result of 'channeling' the gauzes become completely stripped of silver over certain areas whilst the rest of the gauze still retains silver. This process in turn, leads to penetration by undecomposed H.T.P. along the channels. This condition brings about very inefficient usage of the available silver on the pack, since once a 'channel' has been produced the H.T.P. begins to flow more freely along it than through other parts of the gauze area.*

'Channeling' is caused by two principal factors, (1) irregular distribution of H.T.P. on the gauzes by the injector, and (2) the cooling effect at the periphery of the gauzes due to loss of heat to the surroundings. The presence of 'channeling' due to irregular distribution of H.T.P. is noticeable when an injector consisting of a number of holes in a plate is used, as each hole in the injector is matched by a channel on the gauze in the entry end of the pack. The cooling effect at the periphery of the gauze leads to a somewhat lower rate of decomposition in this region and a greater distance of penetration. This leads to more rapid erosion of silver at the periphery, and 'channeling' along the walls of the decomposer.

Finally, it is necessary to consider a third factor ~~which can lead to loss of decomposition efficiency,~~ namely loss of activity of the silver catalyst. This may occur in two major ways, (1) by the catalyst becoming covered with a layer of non-catalytic material, or (2) by direct chemical 'poisoning' of the catalytic surface. The first type of effect occurs whenever non catalytic material, such as alumina and tin oxide, is deposited on the gauzes downstream thereby reducing the efficiency of contact of H.T.P. with the catalyst surface. The second type of effect occurs when the H.T.P. contains contaminants which reduce the rate of decomposition at the catalyst surface."

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*Editor's Note: It is also believed that channeling can cause recirculation of the hot decomposition gases within the catalyst chamber. These gases can preheat the liquid stream entering the catalyst bed, which results in an increase in the normal decomposition temperatures in the bed. This increase in temperature is a probable major contributor to the failure of the present silver-screen catalyst packs.

## 7.2.2 Thermal Decomposition

The use of self-heating thermal chambers to maintain controlled decomposition of hydrogen peroxide has been limited to laboratory studies. In the thermal concept, the design of the decomposition chamber is similar to that employed in packed bed catalytic chambers, except that the chamber material is selected on the basis of thermal conductivity criteria rather than for catalytic activity. The thermal pack is heated with a "pilot light" either by diverting a small flow of hydrogen peroxide through a small catalyst chamber (and directing the decomposition gases into the thermal bed) or by hypergolic ignition slugs of fuel and oxidizer. When the thermal bed achieves a suitable temperature level, the main flow of hydrogen peroxide is initiated and the pilot flow is terminated. The assumed advantage of this operation is an elimination of most of the problems associated with the effects of temperature, poisoning, and erosion in the catalyst bed.

This concept was investigated with both 98 w/o (Ref. 7.19) and 90 w/o (Ref. 7.11) hydrogen peroxide and found to have limited usefulness. Although decomposition could be maintained with small bed loading rates, large propellant flows usually quenched the decomposition process within 3 to 5 seconds after "pilot light" termination. It was concluded that the slow rate of thermal decomposition of hydrogen peroxide cannot compete with the rates obtainable with catalytic decomposition.

## 7.3 REFERENCES

7.1 Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, *Hydrogen Peroxide*, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

7.2 Shell Development Company, Emeryville, California, *Final Report, Concentrated Storable Hydrogen Peroxide*, Report No. S-13974, August 1965, Contract DA-04-200-AMC-569(Z).

7.3 Shell Development Company, Emeryville, California, *Storable Concentrated Hydrogen Peroxide*, Report No. AFRPL-TR-66-207, Report period: March-May 1966, Contract AF04(611)-11416.

7.4 Shell Development Company, Emeryville, California, *Storable Concentrated Hydrogen Peroxide*, Report No. AFRPL-TR-66-262, Report period: June-August 1966, Contract AF04(611)-11416.

7.5 E. I. duPont de Nemours & Company, Inc., Final Report, *Research on the Stability of High Strength $H_2O_2$*, Report No. AFRPL-TR-66-13, 15 March 1966, Contract AF04(611)-10216.

7.6 Baumgartner, H. J., G. C. Hood, J. M. Monger, R. M. Roberts, and C. E. Sanborn, "Decomposition of Concentrated Hydrogen Peroxide on Silver. I. Low Temperature Reaction and Kinetics," *J. of Catalysis*, 2, 405-14 (1963); "II. High Temperature Decomposition," *J. of Catalysis*, 2, 415-20 (1963).

7.7 Hart, A. B. and R. A. Ross, *J. Catalysis*, 2, 251 (1953).

7.8 Rocket Propulsion Establishment, Westcott, Buckinghamshire, England, *Some Aspects of the Catalytic Decomposition of Hydrogen Peroxide by Silver. Part IV. The Rate of Decomposition*, R.P.E. Tech Note 197, December 1960.

7.9 F.M.C. Corporation, Princeton, New Jersey, *Heterogeneous Decomposition of Hydrogen Peroxide by Inorganic Catalysts*, Report No. AFRPL-TR-66-136, June 1966, Contract AF04(611)-11208.

7.10 Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, *Redstone Catalyst Improvement Program, Final Report for Period October 1958 to December 1960*, Report No. R-2985, 29 May 1961.

7.11 Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, *Summary Report, Research Program on Hydrogen Peroxide*, Report No. R-2094P, March 1960.

7.12 F.M.C. Corporation, Princeton, New Jersey, *Investigation of Decomposition Catalysts for 98% Hydrogen Peroxide*, Report No. AFRPL-TR-66-134, June 1966, Contract AF04(611)-11208, CONFIDENTIAL.

7.13 Aerojet-General Corporation, Sacramento, California, *Advanced Propellant Staged Combustion Feasibility Program*, Phase 1, Parts 1 and 2, Report No. AFRPL-TR-66-6, April 1966, Contract AF04(611)-10785, CONFIDENTIAL.

7.14 Aerojet-General Corporation, Sacramento, California, *Advanced Propellant Staged Combustion Feasibility Program*, Report No. 10785-Q-3, August 1966, Contract AF04(611)-10785, CONFIDENTIAL.

7.15 McCormick, J. C., F.M.C. Corporation, Buffalo, New York, *Hydrogen Peroxide Rocket Manual*, 1965.

7.16 Davis, N. S., Jr., and J. C. McCormick, "Design of Catalyst Pack for the Decomposition of Hydrogen Peroxide," A.R.S. Paper No. 1246-60, 1960.

7.17 Barclay, L. P., Air Force Rocket Propulsion Laboratory, Edwards, California, "Hydrogen Peroxide Evaluation," *8th Liquid Propulsion Symposium*, Cleveland, Ohio, November 1966, Vol. 2, CONFIDENTIAL.

7.18 Rocket Propulsion Establishment, Westcott, Buckinghamshire, England, *Some Aspects of the Catalytic Decomposition of Concentrated Hydrogen Peroxide (H.T.P.) by Silver: Part IX. Tests With Decomposers*, R.P.E. Report No. 42, June 1963.

7.19 Kazanjian, A. R., "Thermal Decomposition Rate Studies of 98% $H_2O_2$," Unpublished Data (RM 316-92), Rocketdyne, a Division of North American Aviation, Inc., 19 March 1958.

7.20 United States Naval Air Rocket Test Station, Lake Denmark, Dover, New Jersey, Mollier Charts for the Decomposition of Hydrogen Peroxide-Water Mixtures, NARTS Report 43, November 1954.

## SECTION 8: BIBLIOGRAPHY

In addition to the references actually used in compiling the data appearing in this handbook (these references are listed at the end of each section), many other articles and reports were reviewed. These additional references are listed below in the proper category for further information. In addition, several general, secondary references containing extensive physical property and/or handling data for $H_2O_2$ are included. Although these compilations are not repeated for each category, most are applicable to all sections.

## 8.1 GENERAL REFERENCES

Aerojet-General Corporation, Sacramento, California, *Final Report, Advanced Propellant Staged Combustion Feasibility Program*, Vol. I and Vol. II. Report No. AFRPL-TR-66-6, April 1966, Contract AF04(611)-10785, CONFIDENTIAL.

Aerojet-General Corporation, Sacramento, California, *Physical Properties of Liquid Propellants*, Report No. LRP 178, 13 July 1960.

Ardon, M., *Oxygen: Elementary Forms and Hydrogen Peroxide*, W. R. Benjamin, Inc., New York, New York, 1965.

The Battelle Memorial Institute, *Liquid Propellants Handbook*, "Hydrogen Peroxide," Vol. I, 1958, CONFIDENTIAL.

Bloom, R., Jr., and N. J. Brunsvold, "Anhydrous Hydrogen Peroxide as a Propellant," *Chem. Eng. Progr.*, *53*, 541 (1957).

De Castro-Ramas, R., "One Hundred Percent Hydrogen Peroxide," *Rev. cienc. aplicada*, *4*, 49-54 (1950).

Dierdorff, L. H., Jr., *Hydrogen Peroxide Physical Properties Data Book*, F. M. C. Corporation, New York, New York, 1955.

Laporte Chemicals Limited, Luton, England, *Hydrogen Peroxide Data Manual*, 1960.

Liquid Propulsion Information Agency, *Liquid Propellant Manual*, "Hydrogen Peroxide," 1958.

McCormick, J. C., F.M.C. Corporation, Buffalo, New York, *Hydrogen Peroxide Rocket Manual*, 1965.

*Military Specification, Propellant, Hydrogen Peroxide*, MIL-P-16005D, 18 March 1965.

*Military Specification, Hydrogen Peroxide, E-Stability 70% and 90% (for Torpedo Use)*, MIL-H-22868 (Wep), 21 March 1961.

Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, *Hydrogen Peroxide*, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

Shell Chemical Company, New York, New York, Concentrated Hydrogen Peroxide, $H_2O_2$, 2nd ed. Properties, Uses, Storage, Handling, Report No. SC: 62-23, 1962.

Wood, W. S., Hydrogen Peroxide, The Royal Institute of Chemistry Lectures, Monographs, and Reports, No. 2, 1954.

## 8.2 PHYSICAL PROPERTIES

### 8.2.1 Phase Properties

### 8.2.1.1 Melting (Freezing) Point

Cuthbertson, A. C., G. L. Matheson, and O. Maass, "The Freezing Point and Density of Pure Hydrogen Peroxide," J. Am. Chem. Soc., 50, 1120-1 (1928).

Foley, W. T. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. IV. Some Thermal Properties of Hydrogen Peroxide," Can. J. Chem., 29, 895-903 (1951).

### 8.2.1.2 Boiling Point

Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide-Physical and Chemical Properties," Ind. Eng. Chem., 39, 1536-43 (1947).

Simkin, D. J. and C. O. Hurd, "Vapor Pressure and Heat Contents of Saturated Liquid and Vapor Hydrogen Peroxide," Jet Propulsion, 27, 419-20 (1957).

Uchida, S., S. Ogawea, and M. Yamaguchi, Japan Sci. Rev., Eng. Sci., 1, No. 2, 41 (1950) (Eng.).

### 8.2.1.3 Density Solid

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," J. Am. Chem. Soc., 42, 2548-69 (1920).

### 8.2.1.4 Density, Liquid

Cuthbertson, A. C., G. L. Matheson, and O. Maass, "The Freezing Point and Density of Pure Hydrogen Peroxide," J. Am. Chem. Soc., 50, 1120-1 (1928).

Huckaba, C. E. and F. G. Keyes, "The Density of Aqueous Hydrogen Peroxide Solutions," J. Am. Chem. Soc., 70, 2578-81 (1948).

Huckaba, C. E. and F. G. Keyes, "Error in the Average Coefficients of Specific Volume Change From 0 to 20° in Aqueous Solutions of Hydrogen Peroxide," J. Am. Chem. Soc., 72, 5324-5325 (1950).

Kubaschewski, O. and W. Weber, "Freezing-Point Diagram, Heats of Mixing and Densities of the System Water-Hydrogen Peroxide," Zeit. fur Elektrochemie und angew. physik. Chem., 54, 300-4 (1950).

### 8.2.1.5 Coefficient of Thermal Expansion

Giguere, P. A. and P. Geoffrion, "Changes of Density of Hydrogen Peroxide Solutions on Cooling and Freezing," Can. J. Research, 28B, 599-607 (1950).

Huckaba, C. E. and F. G. Keyes, "The Density of Aqueous Hydrogen Peroxide Solutions," J. Am. Chem. Soc., 70, 2578-81 (1948).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide, I," J. Am. Chem. Soc., 42, 2548-69 (1920).

### 8.2.1.6 Parachor

Cuthbertson, A. C., G. L. Matheson, and O. Maass, "The Freezing Point and Density of Pure Hydrogen Peroxide," J. Am. Chem. Soc., 50, 1120-1 (1928).

Phibbs, M. K. and P. A. Giguere, "Hydrogen Peroxide and Its Analogs, III. Absorption Spectrum of Hydrogen and Deuterium Peroxides in the Near Ultraviolet," Can. J. Chem., 29, 173 (1951).

### 8.2.1.7 Surface Tension

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide, I," J. Am. Chem. Soc., 42, 2548-69 (1920).

### 8.2.2 Thermodynamic Properties

### 8.2.2.1 Heat of Formation

Coughlin, J. P., Contributions to the Data on Theoretical Metallurgy. XII. Heats and Free Energies of Formation of Inorganic Oxides, Bulletin 542, Bureau of Mines, U.S. Department of the Interior, U.S. Government Printing Office, Washington, D.C. (1954), p. 24.

Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, Hydrogen Peroxide, A.C.S. Monograph, 128, Reinhold Publishing Corporation, New York, New York, 1955.

### 8.2.2.2 Heat of Fusion

Giguere, P. A., I. D. Liu, J. S. Dugdale, and J. A. Morrison, "Hydrogen Peroxide: The Low-Temperature Heat Capacity of the Solid and Third Law Entropy," Can. J. Chem., 32, 117-28 (1954).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," J. Am. Chem. Soc., 42, 2548-69 (1920).

### 8.2.2.3 Heat of Vaporization

Egerton, A. C., W. Emte, and G. J. Minkoff, "Some Properties of Organic Peroxides," Discussions Faraday Society, 1951 (10), 278-82 (1951).

Foley, W. T. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. II. Phase Equilibrium in the System Hydrogen Peroxide-Water," Can. J. Chem., 29, 123-32 (1951).

Giguere, P. A., B. G. Morissette, A. W. Olmas, and O. Knop, "Hydrogen Peroxide and Its Analogues. VII," Can. J. Chem., 33, 804 (1955).

### 8.2.2.4 Heat of Sublimation

Foley, W. T. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. II. Phase Equilibrium in the System Hydrogen Peroxide-Water," Can. J. Chem., 29, 123-32 (1951).

### 8.2.2.5 Heat Capacity, Liquid

Foley, W. T. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. II. Phase Equilibrium in the System Hydrogen Peroxide-Water," Can. J. Chem., 29, 123-32 (1951).

Giguere, P. A. and I. D. Liu, "Recommended Values for the Thermodynamic Properties of Hydrogen and Deuterium Peroxides," J. Am. Chem. Soc., 77, 6477-9 (1955).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," J. Am. Chem. Soc., 42, 2548-69 (1920).

Papousek, D., "Intermolecular Interaction in Liquids. I. Adiabatic Compressibility and Structure in the System Hydrogen Peroxide-Water," Chemicke Listy, 51, 1781-6 (1957).

8.2.2.6 Entropy and Enthalpy

Mitchell, A. G. and W. F. K. Wynne-Jones, "Thermodynamic and Other Properties of Solutions Involving Hydrogen Bonding," Discussions Faraday Soc., 1953, No. 15, 161-8 (1953).

8.2.3 Transport Properties

8.2.3.1 Viscosity, Liquid

Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide-Physical and Chemical Properties," Ind. Eng. Chem., 39, 1536-43 (1947).

8.2.3.2 Viscosity, Vapor

Svehla, R. A., "Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures," NASA Tech Report R132, 140 pp. (1962).

8.2.4 Electromagnetic and Optical Properties

8.2.4.1 Index of Refraction

Cuthbertson, A. C. and O. Maass, "Hydrogen Peroxide. VIII. The Dielectric Constants, Refractive Indices and Ionizing Power of Hydrogen Peroxide and Its Aqueous Solutions," J. Am. Chem. Soc., 52, 489-99 (1930).

Egerton, A. C., W. Emte, and G. J. Minkoff, "Some Properties of Organic Peroxides," *Discussions Faraday Society*, *1951* (10), 278-82 (1951).

Ioffe, B. V., "Measurement of the Index of Refraction for a Mixture of Volatile Liquids on a Pulfrich Refractometer," *Zh. Fiz. Khim.*, *34*, 1133-35 (1960).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," *J. Am. Chem. Soc.*, *42*, 2548-69 (1920).

Phibbs, M. K. and P. A. Giguere, "Hydrogen Peroxide and Its Analogues. I. Density, Refractive Index, Viscosity, and Surface Tension of Deuterium Peroxide-Deuterium Oxide Solutions," *Can. J. Chem.*, *29*, 173-81 (1951).

### 8.2.4.2 Dipole Moment

Penny, W. G. and G. B. B. M. Sutherland, "Structure of Hydrogen Peroxide and Hydrazine With Particular Reference to Electric Moments and Free Rotation," *Trans. Faraday Soc.*, *30*, 898-902 (1934).

Randall, J. T., "Structure of Liquid Hydrogen Peroxide," *Proc. Roy. Soc.*, *A159*, 83-92 (1937).

Theilacker, W., "The Dipole Moment of Hydrogen Peroxide," *Z. physik. Chem.*, *B20*, 142-4 (1933).

### 8.2.4.3 Dielectric Constant

Cuthbertson, A. C. and O. Maass, "Hydrogen Peroxide. VIII. The Dielectric Constants, Refractive Indices and Ionizing Power of Hydrogen Peroxide and Its Aqueous Solutions," *J. Am. Chem. Soc.*, *52*, 489-99 (1930).

Gross, P. M., Jr., and R. C. Taylor, "The Dielectric Constants of Water Hydrogen Peroxide and Hydrogen Peroxide-Water Mixtures," *J. Am. Chem. Soc.*, *72*, 2075-80 (1950).

Linton, C. P. and O. Maass, "The Electric Moment of Hydrogen Peroxide," *Can. J. Research*, 7, 81-5 (1932).

Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide-Physical and Chemical Properties," *Ind. Eng. Chem.*, 39, 1536-43 (1947).

### 8.2.4.4 Electrical Conductivity

Gross, P. M., Jr., and R. C. Taylor, "The Dielectric Constants of Water Hydrogen Peroxide and Hydrogen Peroxide-Water Mixtures," *J. Am. Chem. Soc.*, 72, 2075-80 (1950).

Hatcher, W. H. and E. C. Powell, "Conductivity Data of Aqueous Mixtures of Hydrogen Peroxide and Organic Acids. II," *Can. J. Research*, 7, 270-82 (1932).

Hatcher, W. H. and M. G. Sturrock, "Conductivity Data of Aqueous Mixtures of Hydrogen Peroxide and Organic Acids," *Can. J. Research*, 4, 35-8 (1931).

### 8.2.4.5 Magnetic Susceptibility

Gray, F. W. and J. Farquharson, "Improvements in the Curie-Cheneveau Magnetic Balance," *J. Scientific Instruments*, 9, 1-5 (1932).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," *J. Am. Chem. Soc.*, 42, 2548-69 (1920).

Neiding, A. B. and I. A. Kazarnovskii, "Magnetic Susceptibility and Structure of Hydrogen Peroxide," *Doklady Akad. Nauk S.S.S.R.*, 74, 735-8 (1950).

Neiding, A. B. and I. A. Kazarnovskii, "Magnetic Susceptibility and Structure of Peroxides," *Zhur. Fiz. Khim.*, 26, 1167-72 (1952).

Savithri, K. and S. Ramachandra, "Magnetic Susceptibility of Some Peroxides," Proc. Indian Acad. Sci., 16A, 221-30 (1942).

## 8.3 STRUCTURE

Feher, F. and F. Klotzer, "The Crystal Structure of Hydrogen Peroxide," Z. Elektrochem., 41, 850-1 (1935).

Feher, F. and F. Klotzer, "Crystal Structure of Hydrogen Peroxide," Z. Electrochem., 43, 822-6 (1937).

Giguere, P. A., "Properties and Structure of Hydrogen Peroxide and of Deuterium Peroxide," Bull. Soc. Chim. France, 1954, 720-3 (1954).

Giguere, P. A., "The 0-0 Bond Energy in Hydrogen Peroxide," Can. J. Research, 28B, 17-20 (1950).

Glocker, G. and G. Matlock, "0-0 Bond Energy in Hydrogen Peroxide," J. Chem. Phys., 14, 50405 (1946).

Hunt, R. H., "The Determination of the Hindered Motion in Hydrogen Peroxide From Its Far Infrared Spectrum," University of Michigan, AD 420638 (1963).

Kazarnovskii, I. A., "Structure of Inorganic Peroxides," J. Phys. Chem. (U.S.S.R.), 14, 32-31 (1940).

Kazarnovskii, I. A., "The Structure of Inorganic Peroxides," Khim. Referat. Zhur., 4, No. 1, 30-1 (1941).

Natta, G. and R. Rigamonti, "Crystal Structure and Molecular Symmetry of Hydrogen Peroxide," Gazz. chim. ital., 66, 762-72 (1936).

Neiding, A. B. and I. A. Kazarnovskii, "Magnetic Susceptibility and Structure of Peroxides," Zhur. Fiz. Khim., 26, 1167-72 (1952).

Neiding, A. B. and I. A. Kazarnovskii, "Magnetic Susceptibility and Structure of Hydrogen Peroxide," Doklady Akad. Nauk S.S.S.R., 74, 735-8 (1950).

Parsons, A. E. and A. W. Searcy, "Prediction of the Shapes of Two Centered Covalent Molecules and Ions," *J. Chem. Phys.*, *30*, 1635-6 (1959).

Penney, W. G. and G. B. B. M. Sutherland, "A Note on the Structure of Hydrogen Peroxide and Hydrazine With Particular Reference to Electric Moments and Free Rotation," *Trans. Faraday Soc.*, *30*, 898-902 (1934).

Penney, W. G. and G. B. B. M. Sutherland, "The Theory of the Structure of Hydrogen Peroxide and Hydrazine," *J. Chem. Phys.*, *2*, 492-8 (1934).

Randall, J. T., "Structure of Liquid Hydrogen Peroxide," *Proc. Roy. Soc.*, *A159*, 83-92 (1937).

Sisler, H. and L. F. Audrieth, "Structural and Chemical Similarities of Hydrogen Peroxide, Hydroxylamine, and Hydrazine," *Trans. Illinois State Acad. Sci.*, *31*, 144-5 (1938).

## 8.4 SOLUBILITY

Akerlif, G. and H. E. Turck, *J. Am. Chem. Soc.*, *57*, 1746 (1935).

F.M.C. Corporation, New York, New York, *Safety Code for BECCO 90 Percent Hydrogen Peroxide* $(H_2O_2)$, May 1947.

Floyd, J. D. and P. M. Gross, Jr., "Solubilities of Some Strong Electrolytes in the Hydrogen Peroxide-Water System. I., Sodium Chloride, Fluoride and Nitrate, Potassium Chloride and Nitrate, and Lithium Nitrate," *J. Am. Chem. Soc.*, *77*, 1435-37 (1955).

Husain, S., *Z. anorg. allgem. Chem.*, *177*, 215 (1928).

Jones, H. C., J. Barnes, and C. P. Hyde, "Lowering of the Freezing Point of Aqueous Hydrogen Peroxide," *Am. Chem. J.*, *27*, 22 (1902).

Jones, H. C. and C. G. Carroll, "Lowering of the Freezing Point of Aqueous Hydrogen Peroxide, *Am. Chem. J.*, *28*, 284 (1902).

Kazanetzkii, P. V., "Behavior of Hydrogen Peroxide With Salts," *J. Russ. Phys. Chem. Soc.*, *46*, 1110 (1914).

Maass, O. and W. H. Hatcher, "The Properties of Pure Hydrogen Peroxide. I," *J. Am. Chem. Soc.*, *42*, 2548-69 (1920).

Matheson, G. L. and O. Maass, "Properties of Pure Hydrogen Peroxide. VI," *J. Am. Chem. Soc.*, *51*, 674-87 (1929).

Menzel, H. and C. Gabler, "Concerning Compounds of Alkaliphosphates with Hydrogen Peroxide," *Z. anorg. allgem. Chem.*, *177*, 187 (1928).

Minnesota Mining and Manufacturing Company, *Chemical Reactions as Related to Advanced Solid Propellants*, Report No. 1, MMM-0209-C, Report Period: 1 January - 31 March 1966, Contracts NOs65-0209-C and NOw-66-0466-C.

Price, T. S., "Depression of the Freezing Point of Aqueous Solutions of Hydrogen Peroxide by Potassium Persulphate and Other Compounds," *J. Chem. Soc.*, *91*, 531-36 (1907).

Schumb, W. C., C. N. Satterfield, and R. L. Wentworth, *Hydrogen Peroxide*, A.C.S. Monograph 128, Reinhold Publishing Corporation, New York, New York, 1955.

Shanley, E. S. and F. P. Greenspan, "Highly Concentrated Hydrogen Peroxide-Physical and Chemical Properties," *Ind. Eng. Chem.*, *39*, 1536-43 (1947).

## 8.5 HANDLING AND STORAGE

Aeronutronic, Newport Beach, California, *Explosive Hazards of Rocket Launchings*, Technical Report No. U108:98, 30 November 1960.

The Battelle Memorial Institute, Columbus, Ohio, *Liquid Propellants Handbook*, "Hydrogen Peroxide," Vol. I, 1958, CONFIDENTIAL.

Bethlehem Steel Company, Shipbuilding Division, Bethlehem, Pennsylvainia, *Design of Prototype System for Shipboard Storage and Handling of Liquid Propellants for Guided Missiles: Concentrated Hydrogen Peroxide*, Contract NOas 45349, Task Order V., CONFIDENTIAL.

Davis, N. S., Jr., and R. Bloom, Jr., *New Techniques for Transferring $H_2O_2$ at High Pressures*, 9th Annual Meeting, American Rocket Society, December 1954.

E. I. duPont deNemours & Co., Inc. Wilmington, Delaware, *Research on the Stability of High Strength $H_2O_2$*, Contract AF04(611)-10216
Final Report AFRPL TR-66-13, 15 March 1966

| | |
|---|---|
| QPR December 1964 | AD610853 |
| QPR March 1965 | AD615036 |
| QPR June 1965 | AD619179 |

General Electric Co., Rocket Engine Section, Cincinnati, Ohio, *Handbook of Operation and Maintenance Instructions, X-405H Rocket Engine VEGA Second Stage Propulsion*, 1 June 1960, CONFIDENTIAL.

Keefe, J. H. and C. W. Raleigh, "Field Transportation of Concentrated Hydrogen Peroxide," *Jet Propulsion*, *27*, 663 (1957).

Laporte Chemicals, Ltd., Luton, England, *Hydrogen Peroxide Data Manual*, 1960.

Liquid Propulsion Information Agency, *Liquid Propellant Manual*, "Hydrogen Peroxide," 1958.

Manufacturing Chemists Association, Washington, D.C., *Hydrogen Peroxide Properties and Recommended Practice for Packaging, Handling, Transportation, Storage and Use*, Supplement B, Chemical Data Sheet SD-53.

McCormick, J. C., F.M.C. Corporation, Buffalo, New York, *Hydrogen Peroxide Rocket Manual*, 1965.

McCormick, J., A. Livewski, and G. Carmine, *Storage of 90 & 98% by Weight Hydrogen Peroxide in Sealed Containers for Extended Periods*, U.S. Dept. Comm. Office of Tech. Services, AD268,379 (1961).

Mecker, G. W., Jr., *Hydrogen Peroxide: Problems and Operating Procedures at the Air Force Flight Test Center*, New York (1952).

Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, "Handling of Hydrogen Peroxide," *Engineering Procedures Manual*, April 1963.

Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, *Passivation of Stainless Steel Parts for Hydrogen Peroxide*, Process Specification PR 601-3, Amendment 1, January 1960.

Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, *Passivation of Materials Used in Contact With Hydrogen Peroxide*, Process Specification PR 1-17, September 1951; PR 1-37, October 1958.

Satterfield, C. N., "C & EN Commodity Series; Hydrogen Peroxide," *Chem. Eng. News*, *32*, 2726-30 (1954).

Shell Chemical Company, New York, New York, *Concentrated Hydrogen Peroxide, 2nd Ed. Properties, Uses, Storage, Handling*, Report No. SC:62-23, 1962 (revision of SC:58-16).

Shell Chemical Company, New York, New York, *Concentrated Hydrogen Peroxide, Summary of Research Data on Safety Limitations*, Report No. SC:59-44R, 1959.

Shell Chemical Company, New York, New York, *Study of Temperature Measuring Systems for High Strength Hydrogen Peroxide Storage*, Report No. IC:63-7, 1963.

Shell Development Company, Emeryville, California, *Concentrated Storable Hydrogen Peroxide*, Contract DA-04-200-AMC-569Z

Final Report, S-13974, August 1965

QPR 1, May-July 1964, S-13928

APR 2, August-October 1964, S-13938

QPR 3, November 1966 - January 1965, S-13950

QPR 4, February-June 1965. S-13961

Shell Development Company, Emeryville, California, Hydrogen Peroxide by Oxidation of Isopropyl Alcohol. Part XVI. Vapor Explosives and Miscellaneous Explosion Test Data, Tech. Report No. 7-60, January 1960.

Shell Development Company, Emeryville, California, Thermal Stability of 90% Hydrogen Peroxide, Final Report S-13801, Report Period: July 1958-31 December 1959, CONFIDENTIAL.

Southwest Research Institute, San Antonio, Texas, Missile/Space Vehicle Launch Site Fire Protection Study, WADC Technical Report, No. 59-464, June 1959.

Technidyne, Inc., West Chester, Pennsylvania, Feasibility of Modifying Certain Physical Chemical Parameters of Liquid Propellants, Report No. RR-65-26, April 1965, Contract DA-36-04-AMCO-153Z, CONFIDENTIAL.

Thiokol Chemical Corporation, Denville, New Jersey, "Water, Specification for General Purpose Rinse and Dilution," Reaction Motors Division Specification 4085.

Thiokol Chemical Corporation, Denville, New Jersey, "Rinse and Dilution Water for $H_2O_2$ Systems," Reaction Motors Division Specification 7253.

Thiokol Chemical Corporation, Denville, New Jersey, "Passivating, Conditioning, and Stability Testing - Hydrogen Peroxide System Components," Reaction Motors, Incorporated, Specification 7000.

Thiokol Chemical Corporation (Reaction Motors, Incorporated), Denville, New Jersey, Field Handling and Storage of 90 Percent Hydrogen Peroxide.

"Threshold Limit Values for 1960," Adopted at the 22nd Annual Meeting of the American Conference of Governmental Industrial Hygienists, Rochester, New York, April 1960.

Tschinkel, J. G. and A. E. Graves, "Development of an Apparatus for Warming Hydrogen Peroxide by Its Own Controlled Decomposition," Jet Propulsion, 27, 796-8 (1957).

Air Force Flight Test Center, Edwards Air Force Base, California, *Safety Procedures for Rocket Propellants,* Report No. FTR-TM-58-1, November 1958.

General Services Administration, National Archives and Records Service, Federal Register Division, Washington, D.C., *Code of Federal Regulations*, Title 49, Chapter I - Interstate Commerce Commission, Parts 71 to 90, revised 1956.

United States Department of the Air Force, *General Safety Precautions - Missile Liquid Propellants,* Report No. AFTO 11C-1-6C, August 1962.

United States Department of the Navy, *Ammunition Ashores, Vol. I, Handling, Storage, and Shipping*, Report No. OP-5, revised 9 August 1957.

United States Naval Underwater Ordnance Station, Newport, Rhode Island, *Hydrogen Peroxide and Its Application to Ordnance*, NAVORD Report No. 5215, 8 July 1957.

United States Naval Underwater Ordnance Station, Newport, Rhode Island, "High Performance Thermal Propulsion Systems for the Future," *Torpedo Propulsion Conference, Vol. II*, July 1963, CONFIDENTIAL.

Vedenkin, S. G. and V. S. Sinyavskii, "Aluminum Alloys for Railroad-Car Construction," *Tr. Uses. Nauchn. - Issled. Inst. Zheleznodor. Transp.*, *1959*, No. 171, 5-66 (1959).

Victor, M., "Rockets," *Rev. aluminum*, *24*, 69-74 (1947).

## 8.6 MATERIALS COMPATIBILITY

The Battelle Memorial Institute, Columbus, Ohio, *Compatibility of Rocket Propellants With Materials of Construction*, Defense Metal Information Center Memo 65, September 1960.

Connecticut Hard Rubber Company, New Haven, Connecticut, Development of Rubberlike Materials for Applications Involving Contact With Liquid Rocket Propellants, Report No. WADC-TR-651, Part III, 1960.

Davis, N. S. and J. H. Keefe, Jr., "Equipment for Use With High-Strength Hydrogen Peroxide," J. Am. Rocket Soc., 22 (2), 63-9 (1952).

Explosives Research and Development Establishment, Waltham Abbey, England, The Sensitiveness of Fluorocarbon Lubricant/HTP Mixtures, E.R.D.E. Tech Memo 16/M/52.

General Electric Company, Cincinnati, Ohio, Handbook of Operation and Maintenance Instructions. X-405H Rocket Engine. VEGA, Second-Stage Propulsion, 1960, CONFIDENTIAL.

Kopituk, R. C., "Materials Compatibility with 90% Hydrogen Peroxide," Presented at the 42nd National Meeting A.I.Ch.E., Atlanta, Geogia, February 1960, A.I.Ch.E. Preprint 1.

LTV Astronautics Division, Dallas, Texas, "Influence of Oven Baking of 321 Stainless Steel Tubing Upon Its Compatibility With Concentrated Hydrogen Peroxide," Report No. LR-000-TR-005, 1965.

McFarland, R., Jr., "Rigid Polyvinyl Chloride as a Construction Material for Valves," Corrosion, 11, 103t-4t (1955).

Monsanto Research Corporation, Dayton, Ohio, Evaluation of Elastomers as O-Ring Seals for Liquid Rocket Fuel and Oxidizer Systems, Part II, Report No. ASD-TDR-63-496, August 1964, Contract AF33(616)-8483.

Reichert, J. S. and R. H. Pete, "Materials of Construction Versus Hydrogen Peroxide," Chem. Eng., 58, 263 (1951).

Rocket Propulsion Establishment, Westcott, England, The Compatibility of Silicone Rubbers With Concentrated Hydrogen Peroxide (H.T.P.), R.P.E. Tech Note 233, August 1964, CONFIDENTIAL.

Rocket Propulsion Establishment, Westcott, England, The Nature of the Oxide Film Formed on Stainless Steel Immersed in Hydrogen Peroxide, R.P.E. Tech Note 187, January 1960, CONFIDENTIAL.

Rocket Propulsion Department, Royal Aircraft Establishment, England, The Compatibility and Engineering Applications of Various Materials With Concentrated Hydrogen Peroxide, February 1955.

Rosen, A., "Evaluation of Lubricants for 90% $H_2O_2$ Service," Unpublished Data (RM 245-93), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California.

Royal Aircraft Establishment, Rocket Propulsion Department, Westcott, England, The Compatibility and Engineering Applications of Various Materials With Concentrated Hydrogen Peroxide (H.T.P.), Report No. R.P.D. 24, February 1955, CONFIDENTIAL.

Schuler, F. T., "Evaluation of AR O-Rings in 90% $H_2O_2$ at 160 and 180 F," Unpublished Data (RM 249-93), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, November 1957.

Schuler, F. T. and A. Blitstein, "A Study of the 17-7 PH Stainless Steel and 42B Aluminum Alloy for Service in Ninety Percent Hydrogen Peroxide," Unpublished Data (RR 57-27), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 20 June 1957.

Southwest Research Institute, San Antonio, Texas, Survey of Lubricant Compatibility Test Methods for Missile Systems, Technical Documentary Report No. ASD-TDR-62-190, January 1962.

Pitman-Dunn Laboratories Group, Frankford Arsenal, Philadelphia, Pennsylvania, Lubricants for Missile Systems, Report No. R-1522, December 1959.

Rocket Propulsion Laboratory, Air Force Systems Command, Edwards, California, A Compatibility Evaluation of Plastic Membrane Filters With Liquid Propellants and Solvents, Report No. RPL-TDR-64-38, February 1964.

U.S. Army Rocket and Guided Missile Agency, Redstone Arsenal, Huntsville, Alabama, Minutes of the First Symposium on Materials Compatibility With Liquid Propellants, 27 October 1961.

## 8.7 TRANSPORTATION

Laporte Chemicals Limited, Luton, England, *Hydrogen Peroxide Data Manual*, 1960.

## 8.8 SAFETY

Aeronutronic, Newport Beach, California, *Explosive Hazards of Rocket Launchings*, Technical Report No. U-108:98, 30 November 1960.

Aeronutronic, Newport Beach, California, *Toxic Hazards of Rocket Propellants*, Technical Report No. U-108:9, 30 November 1960.

Ahlert, R. C., "Explosive Limits for Vapor Phase Hydrogen Peroxide," Unpublished Data (RR 56-77), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 1956.

The Battelle Memorial Institute, Columbus, Ohio, *Liquid Propellants Handbook*, "Hydrogen Peroxide," Vol. I, 1958, CONFIDENTIAL.

Bethlehem Steel Company, Shipbuilding Division, *Design of Prototype System for Shipboard Storage and Handling of Liquid Propellants for Guided Missiles: Concentrated Hydrogen Peroxide*, NOas 45349, Task Order V, CONFIDENTIAL.

Edwards, J. O., editor, *Peroxide Reaction Mechanisms*, Conference, Providence, Rhode Island, 1960, Interscience Publishers (Published 1962).

Explosives Research and Development Establishment, Waltham Abbey, England, *The Sensitiveness and Detonability of Certain Fuel/Oxidant Mixtures and Emulsions*, E.R.D.E. Tech Memo 23/R/58.

Jacobson, E. H., U.S. Army Chemical Research and Development Laboratories, Army Chemical Center, Maryland, "Propellant Toxicity," Presented at the 3rd JANAF Meeting, CONFIDENTIAL.

Levine, D. and C. Boyars, "Measurement of Impact Sensitivity of Liquid Explosives and Monopropellants," *Advanced Propellant Chemistry*, Advances in Chemistry, Series No. 54, pp. 201-78, American Chemical Society, 1965.

Manufacturing Chemists' Association, Washington, D.C., "Properties and Essential Information for Safe Handling and Use of Hydrogen Peroxide," Chemical Safety Data Sheet, Manual Sheet SD-53, 15 pp. (1953).

Manufacturing Chemists' Association, Washingtor, D.C. "Hydrogen Peroxide. Properties and Recommended Practice for Packaging, Handling, Transportation, Storage and Use; Supplement B," Chemical Data Sheet SD-53.

Meckert, G. W., Jr., Edwards Air Force Base, California, "Hydrogen Peroxide; Problems and Operating Procedures at the Air Force Flight Test Center," New York, 1952.

Monger, J. M., H. J. Baumgartner, G. C. Hood, and C. E. Sanborn, "Explosive Limits of Hydrogen Peroxide Vapor," J. Chem. Eng. Data, 9, 119-124 (1964).

Poeschl, H. and H. Seidel, "New Testing Procedures for Determination of Friction, Impact and Heat Sensitivity," Chem. Tech. (Berlin), 18 (9), 565-7 (1966) (Ger.).

Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, "Handling of Hydrogen Peroxide," Engineering Procedures Manual, April 1963.

Rocket Propulsion Establishment, Ministry of Aviation, London, England, The Effect of Some Halogenated Methanes on the Limits of Inflammability of Oxygen-Enriched Ethane-Air Flames, R.P.E. Tech. Note No. 183, October 1959.

Satterfield, C. N., E. Kehat, and M. A. T. Mendes, "Ignition of and Flames Above Hydrogen Peroxide Solutions," Combustion and Flame, 4, 99 (1960).

Satterfield, C. N. and T. W. Stein, "Decomposition of Hydrogen Peroxide Vapor," Ind. Eng. Chem., 49, 1173 (1957); J. Phys. Chem., 61, 537 (1957).

Shanley, E. S. and J. R. Perrin, "Prediction of the Explosive Behavior of Mixtures Containing Hydrogen Peroxide," Jet Propulsion, 28, 382-5 (1958).

Shell Development Company, Emeryville, California, Concentrated Storable Hydrogen Peroxide, Contract DA-04-200-AMC-569(Z):

Final Report, May 1964-August 1965, S-13974

QPR-1, May-July 1964, S-13928

QPR-2, August-October 1964, S-13938

QPR-3, November 1964-January 1965, S-13950

QPR-4, February-June 1965, S-13961

Shell Development Company, Emeryville, California, Storable Concentrated Hydrogen Peroxide, Report No. AFRPL-TR-66-262, Report period: June-August 1966, Contract AF04(611)-11416.

Shell Development Company, Emeryville, California, Final Report, Thermal Stability of 90% Hydrogen Peroxide, Report No. S-13801, Report period: 1 July 1958-31 December 1959, CONFIDENTIAL.

Southwest Research Institute, San Antonio, Texas, Missile/Space Vehicle Launch Site Fire Protection Study, WADC Technical Report No. 59-464, June 1959.

Thiokol Chemical Corporation (Reaction Motors, Inc.), Denville, New Jersey, Field Handling and Storage of 90 Percent Hydrogen Peroxide, "Threshold Limit Values for 1960," Adopted at the 22nd Annual Meeting of the American Conference of Governmental Industrial Hygienists, Rochester, New York, April 1960.

Ulich, H., "Another Lecture Experiment in Combustion Chemistry," Angew. Chem., 49, 619-20 (1936).

United States Bureau of Mines, Pittsburgh, Pennsylvania, Review of Fire and Explosion Hazards of Flight Vehicle Combustibles, Progress Reports No. 1 and 2, 1960.

United States Bureau of Mines, Pittsburgh, Pennsylvania, Review of Fire and Explosion Hazards of Flight Vehicle Combustibles, Report No. ASD-TR-61-278, April 1961.

United States Bureau of Mines, Pittsburgh, Pennsylvania, Review of Fire and Explosion Hazards of Flight Vehicle Combustibles, Information Circular No. 8137, 80 pp. (1963).

Air Force Flight Test Center, Edwards Air Force Base, California, Safety Procedures for Rocket Propellants, Report No. FTR-TM-58-1, November 1958.

General Services Administration, National Archives and Records Service, Federal Register Division, Code of Federal Regulations, Title 49, Chapter I - Interstate Commerce Commission, Parts 71 to 90, revised 1956.

United States Department of the Air Force, General Safety Precautions - Missile Liquid Propellants, Report No. AFTO 11C-1-6C, August 1962.

United States Department of the Army, Ordnance Safety Manual, Report No. ORDM 7-244.

United States Army Chemical Center, Medical Division, Maryland, Health Hazards of Military Chemicals, Report No. 4, 1 February 1950.

United States Department of the Navy, Bureau of Aeronautics, Handbook for Field Handling of Concentrated Hydrogen Peroxide (over 52 w/o $H_2O_2$), NavAer Report 06-25-501, January 1957.

United States Department of the Navy, Ammunition Ashore, Vol. I, Handling, Stowing and Shipping, Report No. OP-5, revised 9 August 1957.

United States Naval Underwater Ordnance Station, Newport, Rhode Island, Hydrogen Peroxide and Its Application to Ordnance, 8 July 1957.

United States Naval Underwater Ordnance Station, Newport, Rhode Island, Safety of 90% Aqueous Hydrogen Peroxide Based on Its Physical and Chemical Properties, December 1957.

The Safety Equipment Manual, NAVEXOS P-422, November 1960.

Victor, M., "Rockets," Rev. aluminum, 24, 69-74 (1947).

## 8.9 DECOMPOSITION

Abel, E., "Instability and Stabilization of Hydrogen Peroxide," Z. anorg. allgem. Chem., 263, 229-32 (1950).

Aerojet-General Corporation, Sacramento, California, Advanced Propellant Staged Combustion Feasibility Program, Report No. 10785-Q-1, September 1965, Contract AF04(611)-10785, CONFIDENTIAL.

Aerojet-General Corporation, Azusa, California, Final Report, Development of Self-Generating Propellant Pressurization Systems, Report No. 1890, AFFTC-TR-6-68, Part I, October 1960, CONFIDENTIAL.

Aerojet-General Corporation, Sacramento, California, Performance and Properties of $N_2O_4$/Aerozine 50 Selected Metalized Storables, Report No. LRP 302, March 1963, CONFIDENTIAL.

Ahlert, R. C., "Comments on Catalytic Stone Production," Unpublished Data (RM 73-92), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 5 September 1956, CONFIDENTIAL.

Ahlert, R. C., "Identification of Materials That 'Poison' PMS Catalyst Stones," Unpublished Data (RM 100-92), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 15 October 1956, CONFIDENTIAL.

Ahlert, R. C., "Low Pressure Evaluation of Hydrogen Peroxide," Unpublished Data (RM 56-11), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, March 1956.

Ahlert, R. C., "Test Tube Evaluation of 90% $H_2O_2$ and Ag Screen Decomposition Catalyst," Unpublished Data (RR 56-12), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, January 1956, CONFIDENTIAL.

Ahlert, R. C. and S. E. Stephanou, "Research Support of AR-1 Engine Development," Unpublished Data (RR 56-40), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, August 1956, CONFIDENTIAL.

Ahlert, R. C. and C. A. Younts, "An Investigation of Ag Screen Catalyst for the NAA 75-110 Gas Generator," Unpublished Data (RR 59-36), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, October 1959, CONFIDENTIAL.

Ahlert, R. C. and C. A. Younts, "Low Temperature Starting Characteristics of PMS Catalyst Stones," Unpublished Data (RM 218-92), Rocketdyne, a Division of North American Aviation, Inc, Canoga Park, California, September 1957,CONFIDENTIAL.

Anonymous, "Temperature Dependence of the Degree of Dissociation of Water and Hydrogen Peroxide," Theor. i Eksperim. Khim., Akad. Nauk. U.K.R. S.S.S.R., 1 (6), 833-6 (1965).

Barclay, L. P., Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California, "Hydrogen Peroxide Evaluation," Presented at the 8th Liquid Propulsion Symposium, Cleveland, Ohio, 7-9 November 1966.

Bender, R. W., "Chemical Arc - Jet Rocket Feasibility Study," Proc. Astronautical Aeron., 9, 95-120 (1963).

Bianchi, G., F. Mazza, and T. Mussini, "Catalytic Decomposition of Acid Hydrogen Peroxide Solutions on Platinum, Iridium, Palladium and Gold Surfaces," Report No. AFOSR-4236, reprint from Electrochimica Acta, 7, 457-73 (1962).

Broughton, D. B., D. M. Mauke, M. E. Laing, and R. L. Wentworth, "Activity of Metal Hydroxides as Catalysts for the Decomposition of $H_2O_2$," Unpublished Data, Massachusetts Institute of Technology, Cambridge, Massachusetts, 28 February 1946.

Broughton, D. B., R. L. Wentworth, and M. L. Farnsworth, "Mechanism of Decomposition of Hydrogen Peroxide With Cobalt Compounds," J. Am. Chem. Soc., 71, 2346 (1949); Anal. Chem., 19, 72 (1947).

Broughton, D. B., R. L. Wentworth, M. E. Laing, and D. M. Mauke, "Mechanism of Catalytic Decomposition of $H_2O_2$ Solutions With Manganese Dioxide," *J. Am. Chem. Soc.*, *69*, 741 (1947).

Broughton, D. B., R. L. Wentworth, M. E. Laing, and D. M. Mauke, "Mechanism of Catalytic Decomposition of $H_2O_2$ Solutions With Manganese Dioxide," *J. Am. Chem. Soc.*, *69*, 744 (1947).

Chykalo, A. L. and A. G. Tabachnikov, "Calculation of the Thermodynamic Properties of Hydrogen Peroxide, Allowing for Dissociation, From 273 to 2000°K and 0 to 5000 Bars," *Teplofiz. Vys. Temp.*, *4* (no. 6) (1966).

Dedman, A. J., Explosives Research and Development Establishment, Waltham Abbey, England, *Automatic Methods of Recording Decomposition Rates of Hydrogen Peroxide at Ambient Temperatures*, E.R.D.E. Tech Memo 8/M/61, 13 March 1961, CONFIDENTIAL.

Dedman, A. J., P. Flood, T. J. Lewis, D. H. Richards, and D. A. Salter, "Acid-Base Properties of Hydrogen Peroxide - Water Mixtures," *J. Chem. Soc.*, *1965*, 3505-12 (1965).

Dedman, A. J., T. J. Lewis, and D. H. Richards, "Peroxy-Complexes of Inorganic Ions in Hydrogen Peroxide-Water Mixtures. Part IV. Decomposition by Tungstate Ions," *J. Chem. Soc.*, *1963*, 5020-24 (1963).

E. I. duPont de Nemours and Co., Inc., Wilmington, Delaware, *Stability of High Strength $H_2O_2$, Quarterly Report No. 2, March 1965, Contract AF04(611)-10216.*

E. I. duPont de Nemours and Co., Inc., Wilmington, Delaware, *Stability of High Strength $H_2O_2$, Quarterly Report No. 3, June 1965, Contract AF04(611)-10216.*

Edwards, J. O., Editor, *Peroxide Reaction Mechanisms*, Conference, Providence, Rhode Island, 1960 (Publ. 1962, Interscience Publishers).

Fiesel, H., "Experimental Investigation of the Kindling Temperature and the Reaction Velocity of the Hydrogen-Oxygen Mixture," *Z. Physik. Chem.*, *97*, 158-78 (1921).

Flood, P., T. J. Lewis, and D. H. Richards, "Peroxy-Complexes of Inorganic Ions in Hydrogen Peroxide-Water Mixtures. Part II. Decomposition by Chromate Ions," *J. Chem. Soc.*, *1963*, 2446-53 (1963) (Explosives Research and Development Establishment Tech Memo 5/R/62).

Flood, P., T. J. Lewis, and D. H. Richards, "Peroxy-Complexes of Inorganic Ions in Hydrogen Peroxide-Water Mixtures. Part V. Decomposition by Vanadate Ions," *J. Chem. Soc.*, *1963*, 5024-29 (1963) (Explosives Research and Development Establishment Tech Memo 14/R/62).

F.M.C. Corporation, Princeton, New Jersey, *Heterogeneous Decomposition of Hydrogen Peroxide by Inorganic Catalysts. A Literature Survey*, Report No. AFRPL-TR-66-136, June 1966, Contract AF04(611)-11208.

F.M.C. Corporation, Princeton, New Jersey, *Investigation of Decomposition Catalysts for 98% Hydrogen Peroxide*, Report No. AFRPL-TR-66-66, March 1966, Contract AF04(611)-11208, CONFIDENTIAL.

F.M.C. Corporation, New York, New York, *Isothermal Reaction of 90% Hydrogen Peroxide With Silver at 20°C*, Report No. TR 213-2, September 1958, Contract NOas-56-921-d, CONFIDENTIAL.

F.M.C. Corporation, Buffalo, New York, *Storage of 90% and 98% by Weight Hydrogen Peroxide in Sealed Containers for Extended Periods*, Report No. SSD-TR-61-29 (Propulsion Dept. Report No. 3504-7), November 1961.

Foner, S. N. and R. L. Hudson, "Ionization and Dissociation of Hydrogen Peroxide by Electron Impact," *J. Chem. Phys.*, *36*, 2676-80 (1962).

Fontana, B. J., "The Heat of Reaction of the Cerous-Ceric Couple in 0.5 Molal Perchloric Acid at 25°C," in *The Chemistry and Metallurgy of Miscellaneous Materials. Thermodynamics*, NNES, Division 4, Vol. 19B, 1st edition (L. L. Quill, editor), McGraw-Hill Book Co., Inc., New York (1950).

Giguere, P. A., Chemical Reactions in the Electrical Discharge, U.S. Dept. of Commerce, Office of Technical Services, PB Report 144 905, 6 pp. (1959).

Gray, P. D., "Effects of the Space Environment on Liquid Rocket Systems," Chem. Engr. Progr. Symp. Series, 60(52), 180-4 (1964).

Greiner, N. R., "Flash Photolysis of $H_2O_2$ Vapor in the Presence of $D_2$, Ar, and $H_2O$," J. Chem. Phys., 45 (1), 99 (1966).

Hart, A. B., "Thermal Decomposition of Hydrogen Peroxide in the Vapor Phase," Nature, 163, 876-77 (1949).

Islein, H. S., G. C. Williams, and C. N. Satterfield, "Theoretical Analyses of the Decomposition of High Strength Hydrogen Peroxide Solutions," J. Am. Rocket Soc., March-April 1952, p. 70.

Kataen, G. A. and L. N. Rozanova, "Kinetics of the Reaction Between Hydrogen Peroxide and Germanium," Khim. Perekisnykh Soedin., Akad. Nauk S.S.S.R., Inst. Obshch. i Neorgan. Khim., 1963, 63-7 (1963).

Kazanjian, A. R., "Thermal Decomposition Rate Studies of 98% $H_2O_2$" Unpublished Data (RM 316-92), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 19 March 1958.

Kehat, E., A. Wechsler, L. Israel, R. S. C. Young, and C. N. Satterfield, Quarterly Periodic Status Report of the Hydrogen Peroxide Laboratories, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Lewis, T. J., Explosives Research and Development Establishment, Waltham Abbey, England, The Corrosion of Aluminum in Concentrated Hydrogen Peroxide, Report No. 20/R/60, CONFIDENTIAL; J. Appl. Chem., 11, 405 (1961).

Lewis, T. J. and D. H. Richards, "The Behavior of Stannic Acid Sols in Concentrated Hydrogen Peroxide, III. The Ageing of Stannic Acid Sols in Water and Hydrogen Peroxide," J. Appl. Chem., 11, 443-49 (1961).

Lewis, T. J., D. H. Richards, and D. A. Salter, "Peroxy-Complexes of Inorganic Ions in Hydrogen Peroxide-Water Mixtures. Part I. Decomposition by Ferric Ions," J. Chem. Soc., 1963, 2434-46 (1963).

Lewis, T. J. and T. M. Walters, "The Behavior of Stannic Acid Sols in Concentrated Hydrogen Peroxide," Chem. and Ind., pp. 701-2 (1959) (Explosives Research and Development Establishment Tech Memo 21/R/59, Parts I and II).

Lewis, T. J. and T. M. Walters, "The Behavior of Stannic Acid Sols in Concentrated Hydrogen Peroxide. I. Factors Affecting the Stability of Stannic Acid Sols in Concentrated Hydrogen Peroxide," J. Appl. Chem., 10, 396-403 (1960) (Explosives Research and Development Establishment Tech Memo 21/R/59, Part I).

Lewis, T. J. and T. M. Walters, "The Behavior of Stannic Acid Sols in Concentrated Hydrogen Peroxide. II. The Mechanism of Stabilization of Concentrated Hydrogen Peroxide by Sodium Stannate," J. Appl. Chem., 10, 403-7 (1960) (Explosives Research and Development Establishment Tech Memo 21/R/59, Part II).

Lisievici-Draganescu, A., "Relation Between the Stabilization and the Modification of the Surface Tension of Hydrogen Peroxide Solutions," Bul. soc. chim. Romania, 6, 42-5 (1924).

Arthur D. Little, Inc., Cambridge, Massachusetts, Liquid Propellant Losses During Space Flight, Report No. 63270-00-03 (Combined 3rd and 4th Quarterly Reports), November 1961.

Maass, O. and P. G. Hiebert, "The Properties of Pure Hydrogen Peroxide. IV," J. Am. Chem. Soc., 46, 290-308 (1924).

Malone, H. E. and J. T. Nakamura, 6593O Test Group (Development), Edwards Air Force Base, California, "Propellant Contamination," Presented at the 3rd JANAF Meeting, 7-9 November 1961, pp. 441-459, CONFIDENTIAL.

Matt, R. J., "The Problems of Sealing Hydrogen Peroxide in a 3000°F Environment," J. Eng. Power, 84, 341-4 (1962).

McCormick. J. C., A. Lijewski and G. Cornine, Storage of 90% and 98% by Weight Hydrogen Peroxide in Sealed Containers for Extended Periods, U.S. Dept. Commerce, Office of Technical Services, Report No. AD 268 379, 1961

New York University, New York, New York, Liquid Propellant Review, First Quarterly Report, June 1961, CONFIDENTIAL.

Rocketdyne, a Division of North American Aviation, Inc., "Decomposition Temperatures of Hydrogen Peroxide," Unpublished Data (APR 55-168), 3 November 1955.

Roth, E. M. and E. S. Shanley, "Stability of Pure Hydrogen Peroxide," Ind. Eng. Chem., 45, 2343-9 (1953).

Rudel, H. W. and M. M. Haring, "Effect of Copper and Lead Ions Upon the Rate of Decomposition of Hydrogen Peroxide at Various Acidities," Ind. Eng. Chem., 22, 1234-7 (1930).

Sanborn, C. E., H. J. Baumgartner, G. C. Hood, and J. M. Monger, "Decomposition Heat Transfer to Liquid 90% Hydrogen Peroxide," Presented at the 6th National Heat Transfer Conference, A.I.Ch.E.-A.S.M.E., Boston, Massachusetts, August 1963, A.I.Ch.E. Preprint No. 20.

Satterfield, C. N., Massachusetts Institute of Technology, Cambridge, Massachusetts, Quarterly Periodic Status Report, Report No. DSR 5-7476, December 1959.

Satterfield, C. N. and P. K. Sarda, Massachusetts Institute of Technology, Cambridge, Massachusetts, Rates of Catalytic Decomposition of Liquid Hydrogen Peroxide on Metal Surfaces, Report No. 58.

Satterfield, C. N. and T. W. Stein, "Decomposition of Hydrogen Peroxide Vapor," Ind. Eng. Chem., 49, 1173 (1957); J. Phys. Chem., 61, 537 (1957).

Shell Development Company, Emeryville, California, Concentrated Storable Hydrogen Peroxide, Quarterly Progress Reports 1-4, Report No. S-13928, S-13938, S-13950, and S-13961, Contract DA-04-200-AMC-569(Z), CONFIDENTIAL.

Shell Development Company, Emeryville, California, Hydrogen Peroxide by Oxidation of Isopropyl Alcohol. XVI. Vapor Explosions and Miscellaneous Explosion Test Data, Technical Report 7-60, January 1960.

Shell Development Company, Emeryville, California, Hydrogen Peroxide I. Mechanism of Decomposition on Silver, Technical Report 290-63, March 1963.

Shell Development Company, Emeryville, California, Thermal Stability of 90% Hydrogen Peroxide, Final Report No. S-13731, Report period: 1 July 1956-30 June 1957, CONFIDENTIAL.

Shell Development Company, Emeryville, California, Thermal Stability of 98% Hydrogen Peroxide, Final Report No. S-13801, Report period: 1 July 1958-31 December 1959, CONFIDENTIAL.

Stephanou, S. E. and A. R. Kazanjian, "Preliminary Testing of 98% $H_2O_2$," Unpublished Data (RM 169-92), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 7 June 1957.

Texaco Experiment, Inc., Richmond, Virginia, Nonequilibrium Combustion, Report No. TM-1420, March 1963, CONFIDENTIAL.

Tschinkel, J. G. and A. E. Graves, "Development of an Apparatus for Warming Hydrogen Peroxide by Its Own Controlled Decomposition," Jet Propulsion, 27, 796-8 (1957).

National Aeronautics and Space Administration, The Effect of Catalyst-Bed Arrangement on Thrust Buildup and Decay Time for a 90% $H_2O_2$ Control Rocket, Report No. TN-D-516, September 1960.

National Aeronautics and Space Administration, Investigation of Catalyst Beds for 98-Percent Concentration Hydrogen Peroxide, Report No. TN-D-1808, June 1963.

U.S. Naval Air Rocket Test Station, Lake Denmark, Dover, New Jersey, Organically Produced 98% $H_2O_2$ Evaluation Program, NARTS Technical Note 0125, CONFIDENTIAL.

U.S. Naval Research Laboratory, Washington, D.C., *The Role of Inorganic Contaminants in the Catalytic Decomposition of Hydrogen Peroxide*, NRL Report 5117, April 1958, CONFIDENTIAL.

Yeung, R. S. C., Massachusetts Institute of Technology, Cambridge, Massachusetts, *Quarterly Periodic Status Report of the $H_2O_2$ Laboratories*, 31 December 1960.

Younts, C. A., "Development of NAA 75-110 Gas Generator Catalyst," Unpublished Data (RM 390-92), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 6 August 1958, CONFIDENTIAL.

Younts, C. A., "Improved Catalyst for the NAA 75-110 Gas Generator," Unpublished Data (RR 58-38), Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, 7 October 1958, CONFIDENTIAL.

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13 ABSTRACT

This handbook is a compilation of the engineering properties and handling characteristics of propellant-grade hydrogen peroxide. The handbook includes data and information on hydrogen peroxide physicochemical properties, production, storability, materials compatibility, materials treatment and passivation, facilities and equipment, disposal, transportation, safety, and decomposition.

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