



400 Commonwealth Drive, Warrendale, PA 15096-0001

AEROSPACE INFORMATION REPORT

SAE AIR839

REV.
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Issued 1965-01
Revised 1969-04
Cancelled 2000-07

Superseding AIR839B

Recommended Materials and Practices for Use With Cryogenic Propellants

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FOREWORD

This report presents the second revision to "Recommended Materials and Practices for Use with Cryogenic Propellants" which was originally issued as SAE AIR 839 on 1/10/65 and revised on 4/15/67. The first revision has been completely updated, and one additional fluid - helium - has been incorporated in this latest edition.

The information presented in this document is meant to provide a basis for summary evaluation of selected cryogenic propellants. An attempt has been made to furnish a coverage which is broad in scope, yet comparatively brief in content, considering the amount of material involved. The information has been compiled from sources in the unclassified literature wherever possible; in this regard, extensive use has been made of material presented in The Handling and Storage of Liquid Propellants manual prepared for the Office of the Director of Defense Research and Engineering by a work group of the Advisory Panel on Fuels and Lubricants, the Liquid Propellant Manual prepared by the Liquid Propellant Information Agency at the Johns Hopkins University, Silver Spring, Maryland, and the Manual for Handling Missile Propellants (AFMTC TR 58-7) prepared for the Air Force Missile Test Center, Patrick AFB, Florida, by Pan American World Airways, Inc.

Inclusion of a comprehensive annotated bibliography and a tabular summary of the physical properties of each propellant - providing a ready source to the original references - allows the user to perform his own evaluation of the data if he so desires. The bibliography offers a more complete coverage of subject material than anything heretofore available in the literature; annotations should increase the value of this section. Physical property values presented in this work are "interim values" taken from selected references by the Cryogenic Data Center of the National Bureau of Standards Cryogenic Engineering Laboratory. An evaluation program is under way to determine the "most-probable" or "best" values.

Prepared by SAE Committee AGE-1, Military and Space Support Equipment (Fluid Systems Subcommittee). Particular acknowledgment is given to committee member Alan F. Schmidt for the selection, compilation, and organization of the information.

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I. RECOMMENDED MATERIALS AND PRACTICES FOR USE WITH CRYOGENIC PROPELLANTS

- A Compilation from the Literature with Annotated Bibliography -

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1. INTRODUCTION:

1.1 General:

Liquid propellant fuels and oxidizers are, in general, highly reactive chemicals. Consequently, the propellants and their reaction products possess certain hazardous properties which must be fully understood by all who are required to handle them. This manual is intended as a guide to help establish rules as needed to fit actual cases. The fitting of details into this framework must be left to personnel assigned to specific operations. Accordingly, information on the properties of these materials is given so that hazards will be recognized and understood.

1.2 Personnel Training and Supervision:

All operating personnel shall be taught the nature of propellants and the general principles of safe conduct in handling, storage, and use of such materials. Propellants described here can be handled safely when certain simple basic principles are known and followed faithfully. On the other hand, ignorance or carelessness can result in permanent injury or death. Each person engaged in this work should be taught procedures of self-aid and first-aid, which if applied promptly afford a substantial measure of protection against injury in the event of accident.

2. HAZARDS:

The three hazards to be dealt with in operations involving cryogenic propellants are health, fire, and explosion. Spills pose serious problems in inhabited areas since the low-temperature fluids and vapors may lead to physiological hazards such as frostbite and asphyxiation, and in some cases, to fires and explosions.

2.1 Health:

Considering the response of the human body to its environment, appropriate engineering design and operating procedures must be exercised to minimize spills and leaks and to insure adequate ventilation. Local exhaust ventilation is usually preferable to general ventilation because it controls contamination of air at the source. The choice between the two types of ventilation will normally be dictated by the nature of the specific operation.

Adequate water supplies must be available for instant use in an appropriate form, such as showers and eye-wash fountains. Water is the best single agent for minimizing burns by propellants.

As a general guide to the control of toxic vapors, gases, and mists, hygienic standards such as Threshold Limit Values (often referred to as MAC's or Maximum Allowable Concentrations) are useful. There are other gases, such as hydrogen, nitrogen, and helium, which though not toxic in the usual sense, can cause asphyxiation by exclusion of oxygen from the immediate environment.

2.2 Fire:

Each working area must be kept free of combustible materials. Ventilation is essential for keeping vapor and dust concentrations at a safe level. Fuels and oxidizers must be kept separated; fire-fighting equipment and extinguishing agents must be suited to the type of fire which may occur with a particular fuel or oxidizer. Where flammable vapors may be present, electrical equipment must be of the approved explosion-proof type and equipment and containers grounded. Nonstatic general wearing apparel should be provided and used where necessary. Approved lightning protection systems should be installed where required.

2.3 Explosion:

Principles guiding the elimination and control of fire hazards are generally applicable to explosion hazards as well. In addition, earth, sand, concrete, or metal barricades of sufficient mass should be provided in appropriate places to lessen the effects of an explosion. Shock-sensitive materials must be protected from vibration and impact.

3. SAFETY MEASURES:

Properly engineered systems are paramount to safe usage of propellants. In the construction of such systems, only materials compatible with the particular propellants for which the system is designed can be used. In order to eliminate the possibility of an accident, the entire system must be cleaned properly to eliminate any foreign matter.

Successful control of hazards requires thorough training of personnel in the following subjects:

1. The chemical and physical characteristics of the fuels and oxidizers.
2. The hazards peculiar to each fuel and oxidizer and the proper personal protective measures required.
3. The most efficient technique required for control of fires involving a specific fuel or oxidizer.

4. TRANSFER AND STORAGE:

Fire and explosion hazards have an important influence on the design of main storage units and on their location with respect to each other and to populated buildings and areas. Fuels and oxidizers must be separated by distance or barriers, and ready storage quantities should consist only of the minimum amount necessary for the operation. Storage tanks should be diked, and ventilation should take advantage of prevailing winds and natural terrain.

Ample water for fire-fighting and decontamination must be provided. Cleanliness must be observed throughout the area, and rules regarding safe practices must be rigidly enforced.

All operations with cryogenic fluids should be planned carefully, and a set of preparatory, operating, and emergency procedures should be prepared for the operating personnel; these procedures should cover special cleaning and fire-fighting instructions, required clothing, safety devices, etc.

GENERAL BIBLIOGRAPHY

A general listing by title and mode of publication is presented below, followed by technical literature abstracts of each item:

Books

- Cryogenic Engineering
- Cryogenic Technology
- Applied Cryogenic Engineering
- Cryogenic Systems
- Cryogenics
- Safety with Cryogenic Fluids
- Rocket Propellant and Pressurization Systems
- Ground Support Systems for Missiles and Space Vehicles

Conference Proceedings

Advances in Cryogenic Engineering - Proceedings of the National Cryogenic Engineering Conferences
Cryogenic Safety - A Summary Report of the Cryogenic Safety Conference
Proceedings of the Propellant Thermodynamics and Handling Conference
Proceedings of the Conference on Long-Term Cryo-Propellant Storage in Space

Manuals

The Handling and Storage of Liquid Propellants
Liquid Propellant Manual
Manual for Handling Missile Propellants
General Safety Precautions for Missile Liquid Propellants
Liquid Propellants Safety Handbook
Handling Hazardous Materials

Compendiums, Handbooks, Monographs, Surveys

A Compendium of the Properties of Materials at Low Temperatures (Phase I)
A Compendium of the Properties of Materials at Low Temperatures (Phase II)
Cryogenic Materials Data Handbook
Mechanical Properties of Structural Materials at Low Temperatures
Properties of Materials at Low Temperatures
Specific Heats and Enthalpies of Technical Solids at Low Temperatures
Thermal Expansion of Technical Solids at Low Temperatures
Infrared Reflectances of Metals at Cryogenic Temperatures
Tensile and Impact Properties of Selected Materials from 20 to 300°K
Cryogenic Data Book
Properties of Selected Rocket Propellants
Compatibility of Materials with Rocket Propellants and Oxidizers
Compatibility of Plastics with Liquid Propellants, Fuels and Oxidizers
Properties of Plastics and Related Materials at Cryogenic Temperatures
Metals and Alloys for Cryogenic Application - A Review
Effects of Low Temperature on Structural Materials
Low Temperature and Cryogenic Steels
Aerospace Fluid Component Designers Handbook
Advanced Valve Technology
Cryogenic Valves . . . a Survey
Cryogenic Control Valves for Industrial Processes
A Broad Survey of Cryogenic Pumping
Handbook of Compressed Gases
Handbook of Thermal Design Data for Multilayer Insulation Systems
Thermal Insulation Systems
Boiling Heat Transfer for O₂, N₂, H₂, and He
Boiling Heat Transfer for Cryogenics
Review of Static Seals for Cryogenic Systems
Bearings and Seals for Cryogenic Fluids

Miscellaneous Publications, Papers, Reports

- Introduction to Cryogenics
- Introduction to Cryogenic Engineering
- The Storage and Handling of Cryogenic Liquids
- Safe Handling of Cryogenic Fluids
- Air-Condensing Cryogenic Fluids
- Air-Solidifying Cryogenic Fluids
- Cryogenic Safety
- Fire-Hazard Properties of Flammable Liquids, Gases and Volatile Solids
- Review of Fire and Explosion Hazards of Flight Vehicle Combustibles
- Explosion and Fire Hazards Associated with the Use of Low-Temperature Industrial Fluids
- Sparking Characteristics and Safety Hazards of Metallic Materials
- Problems in Cryogenics
- Thermal Problems Peculiar to Cryogens in Space
- Cryogenic Instrumentation
- Cryogenic Thermocouple Thermometry
- Mass Flowmeters in Cryogenic Service
- Cryogenic Flow Measurement - Flow Meters
- Flow Measurement of Cryogenic Fluids
- Large Size Cryogenic Turbine Type Flowmeter Technology
- Cooldown of Large-Diameter Liquid Hydrogen and Liquid Oxygen Lines
- Cooldown of Cryogenic Transfer Systems
- Flexibility Considerations for the Design of Cryogenic Transfer Lines
- Cryogenic Piping System Design Considerations
- Fundamentals of Low Temperature Piping Design
- Cryogenic Storage Vessels
- How to Specify Low Temperature Storage Vessels
- Design of Cryogenic Storage Tanks for Industrial Applications
- Large Cryogenic Storage Vessels
- Construction of High Pressure Storage Vessels
- The Past, Present and Future of Metals for Liquid Rockets
- Low Temperature and Cryogenic Steels: How to Choose, Use, and Weld Them

Bibliographies

- Rocket Propellants, DDC (AD 233 500)
- Rocket Propellants, DDC (AD 315 500)
- Rocket Propellants, DDC (AD 263 000)
- Rocket Propellants, DDC (AD 325 000)
- Cryogenics and Low Temperature Research, DDC (AD 271 000)

Journals

- Cryogenics - An International Journal of Low Temperature Engineering and Research
- Cryogenic Engineering News
- Cryogenic Information Report
- Cryogenic Technology - Journal of the Cryogenic Society of America

CRYOGENIC ENGINEERING - Scott, R. B. - D. Van Nostrand Company, Inc., Princeton, New Jersey (1959) 368 pp.

Throughout the preparation of this book an objective always considered was to present the necessary information in such a manner that an investigator with a new idea involving cryogenic techniques can assess the feasibility of his project and gain some idea about the difficulties that he should expect. Because this book is intended primarily for the reader who is unfamiliar with low temperatures, the treatment is deliberately elementary, but it is not trivial. It is believed that considerations of practical importance can be presented in language that is easily understood. There is little or no attempt to deal with either the esoteric concepts of modern cryogenic physics or the refinements that engineering practice has established in some disciplines used by cryogenists such as heat exchange, distillation, or adsorption. References to authoritative information on such subjects are given. The emphasis here is upon both basic and applied information most important in engineering research and development at low temperatures.

Since this treatise emphasizes the practical aspects of low-temperature technology, it is hoped that the information will be most useful to the design engineer who has the responsibility of making "practical" equipment work.

CRYOGENIC TECHNOLOGY - Vance, R. W. - John Wiley & Sons, Inc., New York (1963) 585 pp.

The goal of this treatise is to provide a source of reference for those engaged either in applications of, or basic, theoretical studies. The text material contains an analysis of thermodynamic principles and cycles describing in detail how low temperatures are achieved, followed by discussions of the properties of liquids and solids, applications of phase equilibria relationships to industrial processes, heat transfer, thermometry, insulation techniques, and the fundamental theories involved in superconductivity. To augment this theoretical background are discussions of some of the principle applications of cryogenic engineering such as the cryotron and other superconductive devices, the solid-state maser, space simulation and cryopumping, nuclear propulsion, the safety aspects and explosive potentials of cryogenic propellants, and deep-space probes, including the cryogenic storage problems in extraterrestrial environments. An analysis of cryobiology technology provides an unusual climax.

APPLIED CRYOGENIC ENGINEERING - Vance, R. W. and Duke, W. M. - John Wiley & Sons, Inc., New York (1962) 510 pp.

This compilation of lectures is designed to enhance the knowledge of scientists and engineers engaged in research and development as well as operating personnel, in the field of cryogenics. It is particularly applicable to missile and space vehicle systems, but the basic theory explained is appropriate to all fields of endeavor requiring technical skills in the application of low temperatures to industrial processes.

The book has been divided into two parts: Part I - Basic Theory; Part II - Applications of Cryogenic Engineering.

Part I discusses basic theory, beginning with the properties of cryogenic fluids and covering mechanical properties of materials in cryogenic environments, low temperature thermometry, fluid flow and heat transfer, insulation techniques and some non-missile applications of cryogenic equipment. It consists of eight chapters in which the theories applicable to the use of cryogenic materials in ballistic missiles and space vehicles are condensed into engineering form augmented by organized experimental data.

Part II describes many of the applications of cryogenic theories to space vehicles and systems. Also, predictions have been made as to what the future propulsion systems might be for space vehicles.

CRYOGENIC SYSTEMS - Barron, R. - McGraw Hill Company, Inc., New York (1966) 678 pp.

The objective of this book is to present an introduction to the engineering aspects and challenges of cryogenics. Emphasis is placed on the design and analysis of systems used to produce, maintain, and utilize low temperatures. The text is an outgrowth of class notes and lecture material associated with a course in cryogenic systems taught at Ohio State University and is slanted primarily toward senior mechanical engineering students, although the text is arranged so that it may be used by an engineer unfamiliar with cryogenic techniques when he is called upon to assist in the design of a system for low temperatures.

CRYOGENICS - McClintock, M. - Reinhold Publishing Corp., New York (1964) 270 pp.

The purpose of this book is to give to the engineer or scientist with another specialty, or to the educated non-scientist, a qualitative understanding of the basic aspects and some of the representative applications of cryogenics.

SAFETY WITH CRYOGENIC FLUIDS - Zabetakis, M. G. - Plenum Press, New York (1967) 156 pp.

This monograph provides a concise, complete exposition of the principles of safety in the handling of cryogenic liquids. It covers safety rules, design data, first aid precautions, and hazard control procedures while stressing the basic principles of handling low-temperature materials and the properties of cryogenic fluids. Thus it permits the reader to design his own unique operation with assurance and security even when the physical situation is not specifically covered by standard safety engineering rules.

ROCKET PROPELLANT AND PRESSURIZATION SYSTEMS - Ring, Elliot (Editor) - Prentice-Hall, Inc., Englewood Cliffs, N.J. (1964) 310 pp.

Presented here are those subjects which make up the entire propulsion field, engine, propellant, feed systems, and pressurization systems, and the specific problems in each. Included are sections on cryogenic loading problems, geysering, stratification, special zero gravity fluid problems, propellant hardware, instrumentation, etc. The book is designed to deal in depth with such problems.

GROUND SUPPORT SYSTEMS FOR MISSILES AND SPACE VEHICLES - Brown, K. and Weiser, P.
- McGraw-Hill Company, Inc., New York (1961) 490 pp.

The aim of this book is to present a complete picture of the systems required to support either a missile or a space vehicle. Liquid propellant handling considerations are covered in Part IV (book is divided into five parts) and include a detailed discussion on cryogenics, hazards and safety, and the design and development of fast-fill propellant loading systems.

ADVANCES IN CRYOGENIC ENGINEERING - Timmerhaus, K. D. (Editor) - Advances in Cryogenic Engineering Vols. 1-13, Plenum Press, New York (1960-68)

A series of volumes dealing with low temperature phenomena and their applications; each volume constitutes the Proceedings of one Cryogenic Engineering Conference, beginning with Volume I - Proceedings of the First National Cryogenic Engineering Conference held at the National Bureau of Standards, Boulder, Colorado (September 1954) and covering all subsequent conferences to date.

CRYOGENIC SAFETY - A SUMMARY REPORT OF THE CRYOGENIC SAFETY CONFERENCE - Air Products, Inc., Allentown, Pa., (July 1959) 145 pp 77 fig 12 tab 61 ref.

This report covers material presented in five sessions and eleven seminars at the 1959 Cryogenic Safety Conference. The session topics included (1) Hazards of Cryogenic Systems, (2) Technical Character of Cryogenic Hazards, (3) Design and Construction for Safety, (4) Operations for Safety, and (5) Liquid Hydrogen Safety.

PROCEEDINGS OF THE PROPELLANT THERMODYNAMICS AND HANDLING CONFERENCE - Bollinger, L. E. and Lemmons, A. W. (Editors) Proc. of Propellant Thermodynamics and Handling Conference, Ohio State Univ. (July 20-21, 1959) O.S.U. Eng. Experiment Station Report. No. 12.

The "Propellant Thermodynamics and Handling Conference" was one of the first "specialist" conferences held by the American Rocket Society. Coverage of two technical areas was planned originally for the conference: propellant thermodynamics and propellant handling. The propellant handling area had papers covering such aspects as materials problems, handling techniques, safety, and toxicity of high-energy and cryogenic liquid propellants and their combustion products.

Included in this collection are the following titles:

The Large Scale Production, Handling, and Storage of Liquid Hydrogen.
Safety Aspects in the Handling and Storage of Liquid Hydrogen.
Experience with Handling Liquid Hydrogen in Engine Testing.
Transportation, Transfer and Storage of Liquid Fluorine.
Materials of Construction for Handling Fluorine.
Some Problems in Using Fluorine in Rocket Systems.
Safety and Handling of Ozone-Oxygen Mixtures.

PROCEEDINGS OF THE CONFERENCE ON LONG-TERM CRYOPROPELLANT STORAGE IN SPACE - NASA - Marshall Space Flight Center, Huntsville, Ala. (Oct. 12-13, 1966) 264 pp.

This conference was planned to promote long-term storage of cryogenic propellants in space. The papers represent a cross section of significant topics on design, testing and instrumentation. Included in this collection are the following titles:

Thermal Mass Penalties Associated with Cryogenic Propellant Storage on Manned Mars and Venus Missions.
Lunar Storage of Cryogenic Reactants.
Development of Materials and Materials Application Concepts for Joint Use as Cryogenic Insulation and Micrometeoroid Bumpers.
Thermal Problems Associated with the Development of a Flight Configured Cryogenic Insulation System.
Shadow Shield Experimental Studies.
Performance of a LH₂ Shrouded Supercritical Helium System.
Study of Vapor/Liquid Separators for Venting Cryogenic Propellant Tanks in Space.
Characteristics of Two-Phase Flow in a Choked Nozzle.
Thermodynamic Model for Orbital Cryogenic Propellant Tanks with P-T Correlations for Saturn S-IV Stage and Centaur Flights.
Topics Requiring Further Study on the Effect of Gravity upon Heat Transfer.
The Growth of Hydrogen Bubbles in Low Gravity.
Finite Difference Solution of Stratification and Pressure Rise in Containers.
Flow Visualization and Thermal Stratification of Water in a Horizontal Cylinder and a Sphere.
Vapor Pull-Through at a Tank Drain with and without Dielectrophoretic Baffling.
Gradient Stabilization of Electrohydrodynamically Oriented Liquids.
Heat Transfer to Rotating Cryogenic Fuel Tanks in Orbit.
Low Gravity Fluid Behavior and Heat Transfer Results from the S-IV B-203 Flight.
Liquid-Solid Hydrogen Mixtures as Vehicle Propellants.
Slush Hydrogen Characteristics.
Cryogenic Transparent Tank Development.

THE HANDLING AND STORAGE OF LIQUID PROPELLANTS - Chemical Propulsion Information Agency, Defense Research and Engineering, Wash., D.C. (Jan. 1963) 338 pp.

This manual is published as a source of information; it is intended for use as a basis for the preparation of regulations governing the handling and storage of liquid propellants.

Included in the contents are four chapters on cryogenic propellants (fluorine, oxygen, nitrogen, hydrogen), fifteen chapters on non-cryogenic propellants, and appendices covering fire fighting techniques, fire protection and extinguishment, cleaning procedures and hazard characteristics.

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LIQUID PROPELLANT MANUAL - Liquid Propellant Info. Agency, Johns Hopkins Univ., Silver Springs, Md., Manual (March 1961) Contr. No. NOrd 7386.

The liquid propellant manual is a compendium of the properties of liquid propellants, and is intended to provide a survey of the physico-chemical properties of selected propellants and promising propellant candidates in order to assess their performance or feasibility in rocket applications. Additional information and revisions will be issued at frequencies depending upon the receipt of new data. Units for specific elements, compounds, and mixtures used as liquid propellants will contain information on the physical, chemical, thermodynamic, transport, and electromagnetic properties for these materials. In addition, information on safety, handling, compatibility of materials, and logistics will be included.

MANUAL FOR HANDLING MISSILE PROPELLANTS - Pan Am. World Airways, Patrick AFB, Fla., AFMTC Rept. No. TR 58-7 (1958) DDC AD 134 277.

This manual presents in a single authority the miscellaneous information available from diverse sources. It combines such data with practical experience and offers a standard of operation as current as possible. It deals with the hazards involved in the storage, handling, and the use of propellants employed in rocketry. The procedures and cautions recommended herein should be adhered to for the safety of personnel and property. It is intended as a guide and an outline of the most important precautions to be taken in operations involving certain hazardous fuels, oxidizers, and other chemicals. This publication is not to be considered as an engineering manual or as a design handbook; neither should it restrict development of new methods and procedures. It can be called a list of "things to do" and "not to do" for maintaining a reasonable degree of safety relating to the materials discussed. These procedures, in combination with the general principles of industrial safety, intelligently utilized should result in accident-free operations.

LIQUID PROPELLANTS SAFETY HANDBOOK - NASA-Kennedy Space Center (Safety Office), Cocoa Beach, Fla. - NASA Rept. SP-4-44-S (April 1, 1965).

This handbook contains the latest information concerning liquid propellants utilized by the NASA at the Kennedy Space Center at Merritt Island Launch Area as of the date of this publication. Changes will be issued periodically to keep the handbook current and accurate.

HANDLING HAZARDOUS MATERIALS - NASA - Technology Utilization Division - NASA Rept. SP-5032 (Sept. 1965), 93 pp.

This publication deals with highly reactive materials that have been studied in the search for fuels and oxidizers for space work: Liquid hydrogen, fluorine, ozone (and several non-cryogenics). It describes both the hazards that have restricted the use of these materials and the procedures by which they have been handled and stored safely. References are given to work done by NASA and other investigators.

GENERAL SAFETY PRECAUTIONS FOR MISSILE LIQUID PROPELLANTS - Air Force Tech. Order 11C-1-6 (Oct. 18, 1961).

The purpose of this technical order is to provide safety measures, safety standards, procedures, instructions, and precautions for preventing fires, explosions, personal injuries, poisonous and injurious conditions, and property damage pertaining to:

- a. Servicing operations at test facilities and launch complexes involving missile liquid propellants.
- b. The construction, operation, or alteration of test facilities and launch complexes designed for the testing, servicing, or launching of liquid propulsion systems or missiles.
- c. The arrangement or safeguarding of equipment, machinery, plumbing, tanks, containers, and accessories for operating buildings and technical facilities.

This publication is not to be considered as a design manual or engineering handbook on missile liquid propellants, nor is it intended to restrict development in this field. Its primary purpose is to present the things "to do" and "not to do" to obtain reasonable and adequate safety in the operational handling and use of highly reactive chemicals.

A COMPENDIUM OF THE PROPERTIES OF MATERIALS AT LOW TEMPERATURES - PHASE I: Part I. Properties of Fluids (July 1960); Part II. Properties of Solids (Oct. 1960); Part III. Bibliography of References (Oct. 1960). Johnson, V. J. (General Ed.) Natl. Bur. Standards Cryogenic Eng. Lab., WADD Tech. Rept. 60-56, Contr. No. AF 33(616)58-4.

Phase I of the Compendium is divided into three parts: Part I, ten properties of ten fluids, Part II, three properties of solids; Part III, an extensive bibliography of references. Density, expansivity, thermal conductivity, specific heat and enthalpy, transition heats, phase equilibria, dielectric constants, adsorption, surface tension and viscosity for the solid, liquid and gas phases of helium, hydrogen, neon, nitrogen, oxygen, air, carbon monoxide, fluorine, argon and methane are given wherever adequate data could be collected. Thermal expansion, thermal conductivity and specific heat and enthalpy are given for a number of solids of interest in cryogenic engineering. Data sheets, primarily in graphic form, are presented from "best values" of data collected. The source of the material used, other references and tables of selected values with appropriate comments are furnished with each data sheet to document the data presented. Conversion tables and other helpful information are also included.

A COMPENDIUM OF THE PROPERTIES OF MATERIALS AT LOW TEMPERATURE - PHASE II, Part IV. Stewart, R. B. and Johnson, V. J. (General Ed.) Natl. Bur. Standards Cryogenic Eng. Lab. WADD Tech. Rept. 60-56 (1961) Contr. No. AF 33(616)59-6, 501 pp.

Phase II of the Compendium includes data sheets on compressibility factor, velocity of sound and entropy of fluids, vapor-liquid equilibrium concentration of binary mixtures of fluids, and electrical resistivity and thermal conductivity integrals of metallic solids. Data sheets are included for each of these properties for the following materials: Compressibility Factor (Helium, Hydrogen, Neon, Nitrogen, Air, Methane); Entropy (a T-S diagram for Neon); Velocity of Sound (in liquids: Helium, Hydrogen, Nitrogen, Oxygen, Argon, Methane; in gases: Helium, Hydrogen, Neon, Nitrogen, Oxygen, Air, Carbon Monoxide, Methane; Nitrogen in Oxygen, Carbon Monoxide, Argon, Methane); Electrical

Resistivity (53 of the pure metallic elements); and Thermal Conductivity Integrals (44 pure metallic substances, 36 non-ferrous alloys, 9 ferrous alloys and 4 glasses and plastics). In general the data sheets present the data primarily in graphical form, and in addition include tables of selected values, references to the sources of the data and other references. Appropriate comments of interest to the user are also given.

CRYOGENIC MATERIALS DATA HANDBOOK - Durham, T. F., McClintock, R. M. and Reed, R. P. - Natl. Bur. Standards Cryogenic Eng. Lab., Contr. No. AF 04(647)-59-3, 556 pp 1107 ref.

This handbook of data on solid materials at low temperatures contains certain mechanical and physical properties of selected metals and non-metals over the temperature range minus 454°F to plus 500°F. The materials are mostly ones in current use for missile applications at cryogenic temperatures, but a few have been included because of their potential for such uses. The properties are those which are most generally useful to the designer. The compilation is believed to include all reliable data which have appeared in the literature from 1940 thru 1959 and recent data from test laboratories. In some cases the data reported have not yet been published. Information from a few papers published prior to 1940 has also been included.

MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS AT LOW TEMPERATURES; A COMPILATION FROM THE LITERATURE - McClintock, R. M. and Gibbons, H. P. Natl. Bur. Standards Monograph 13 (June 1960) 180 pp 104 ref.

The tensile strength, yield strength, tensile elongation, and impact energy of about two hundred materials, metallic and non-metallic, are given graphically as functions of temperature between 4° and 300° Kelvin.

PROPERTIES OF MATERIALS AT LOW TEMPERATURES - Corruccini, R. J. - Chem. Eng. Progress 53, 262-67, 342-46, 397-402 (A three-part article) (1957).

This review summarizes the knowledge acquired from work at the (NBS) Boulder Laboratory on low-temperature data, organized and interpreted in the light of theory, and shows how useful estimation procedures may sometimes be derived from theory to fill gaps in the available data.

SPECIFIC HEATS AND ENTHALPIES OF TECHNICAL SOLIDS AT LOW TEMPERATURES; A COMPILATION FROM THE LITERATURE - Corruccini, R. J. and Gniewek, J. J. - Natl. Bur. Standards Monograph 21 (Oct. 1960) 20 pp 4 tab 165 ref.

Tables are given of the specific heat, cp, and the enthalpy of 28 metals, 3 alloys, 8 other inorganic substances, and 8 organic substances in the temperature range, 1° to 300°K.

THERMAL EXPANSION OF TECHNICAL SOLIDS AT LOW TEMPERATURES; A COMPILATION FROM THE LITERATURE - Corruccini, R. J. and Gniewek, J. J. - Natl. Bur. Standards Monograph No. 29 (May 1961) 22 pp 4 tab 246 ref.

Tables are given of the linear contraction relative to 293°K, $(L_{293} - L_T)/L_{293}$, and the linear expansion coefficient, $dL/L_{293}dT$, of thirty elements, forty-five alloys, twenty-two other inorganic substances and twenty plastics and elastomers in the temperature range, 0 to 300°K.

INFRARED REFLECTANCES OF METALS AT CRYOGENIC TEMPERATURES - A COMPILATION FROM THE LITERATURE - Dickson, P. F. and Jones, M. C. - Natl. Bur. Standards Tech. Note 348 (Oct. 1966) 66 pp. 11 fig. 20 tab. 33 ref.

Spectral and total reflectances for metals at cryogenic temperatures in the infrared wavelength region are compiled from the literature. Information concerning sample preparation and purity, radiation source, and methods of reflectance measurement are also presented. Observations regarding the effects on reflectance of temperature, oxide layer, wavelength, and sample preparation are given.

TENSILE AND IMPACT PROPERTIES OF SELECTED MATERIALS FROM 20 TO 300°K - Warren, K. A. and Reed, R. P. - Natl. Bur. Standards Monograph 63 (June 1963) - 51 pp 30 fig 7 tab 3 ref.

The tensile and impact properties of structural materials were experimentally determined at temperatures from 20 to 300°K. Tensile properties of a few materials were also determined at 4°K. The materials included forty-two commercial alloys of iron, aluminum, titanium, copper, nickel, and cobalt, and two metal-bonded carbides. The properties experimentally determined were the yield strength, tensile strength, elongation, and reduction of area, the stress versus strain curve, and the impact energy. The test equipment and procedures are described. The individual data are presented in tables, and the average results are displayed in graphs.

CRYOGENIC DATA BOOK (CGS UNITS) - Chelton, D. B. and Mann, D. B. (NBS-CEL, Boulder, Colo.) Calif. Univ., Radiation Lab., Berkeley, Rept. No. UCRL-3421 (May 1956) 116 pp.

Increased activities in Cryogenic Engineering have brought about the need for a compilation of available data. The purpose of the Cryogenic Data Book is to provide a condensed source of reliable data and reference information for those working in the cryogenic field. Specifically the data were compiled with a view toward the design of liquid hydrogen bubble chambers.

The compilation does not constitute a critical survey of the literature.

PROPERTIES OF SELECTED ROCKET PROPELLANTS - Vol. I (1963) Vol. II (1964) - The Boeing Company, Seattle, Washington - Document D2-11677 DDC AD 444 642.

The purpose of this document is to provide information on chemical, physical and thermodynamic properties, handling and safety characteristics, methods of production, and availability and cost of selected rocket propellants. (Cryogenic propellants hydrogen, fluorine, and oxygen are included in this work.)

COMPATIBILITY OF MATERIALS WITH ROCKET PROPELLANTS AND OXIDIZERS - Boyd, W. K., Berry, W. E., and White, E. L. - Battelle Mem. Inst., Defense Metals Inform. Center, Columbus, Ohio DMIC Memo. No. 201 (Jan. 1965) 41 pp 36 tab 302 ref.

This report summarizes the available information on the compatibility of liquid rocket propellants with prominent materials of construction. Fuels and oxidizers of current interest are discussed. The corrosion data which are presented will apply to storing, handling and control equipment outside of missiles and to missile components excluding combustion chamber. The compatibility of materials with reaction products in combustion chambers, nozzles, etc., has not been considered.

The report is subdivided into sections according to the propellant. Each material of construction is rated for a given medium as belonging to one of four classes, based primarily upon corrosion resistance. Consideration also is given to such factors as catalytic decomposition and sensitivity to impact.

COMPATIBILITY OF PLASTICS WITH LIQUID PROPELLANTS, FUELS AND OXIDIZERS - Beach, Norman E., Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, PLASTEC REPORT 25 (Jan. 1966) 119 pp. 43 ref. - DDC AD 632 287.

Much has been published on the subject of the compatibility of plastics with liquid propellants, fuels and oxidizers, but invariably from the standpoint of the propellant or fuel. This report is a rearrangement of the published compatibility data from the standpoint of the plastic material. It is in the form of a tabulation, with primary arrangement by plastic (or elastomeric) material; and thereunder, by fuel. All arrangements are alphabetical, in the form given in the original reference; that is, either by generic or trade designation. The compatibility evaluation is in terms of the original document, briefly culled to show behavior of the material at a given temperature and for a given time. Elastomers are included (although they are not a stated concern of PLASTEC); but oils, lubricants and greases are omitted, even though based on polymers. The information has been drawn from 43 references, which are annotated so that the information extracted from them shall have additional significance.

PROPERTIES OF PLASTICS AND RELATED MATERIALS AT CRYOGENIC TEMPERATURES - Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, PLASTEC Rept. 20 (July 1965) 253 pp 46 fig 34 tab 319 ref.

This report reviews the effects of cryogenic temperatures on plastics and such related materials as elastomers and adhesives. It presents an annotated bibliography of 319 references from open literature, government project and contract reports, and conference papers. A detailed subject index and a number of supplemental indexes are included. Topics covered are: Molded Polymeric Materials (Plastics); Cryogenic Insulation; Structural Plastic Laminates; Elastomers, Seals and Sealants; Adhesives; Plastic Films, Film Laminations and Vapor Barriers; Fibers; Electrical Applications; Wear and Friction; Liquid Oxygen (LOX) Compatibility; Radiation and Combined Effects; and Miscellaneous Applications. Test Methods are not treated in a separate section in the discussion, but the subject index refers to many references with information on test procedures and apparatus.

METALS AND ALLOYS FOR CRYOGENIC APPLICATION - A REVIEW - Kendall, E. G. - Aerospace Corp., El Segundo, Calif., SSD-63-371 Rept. No. TDR-269 (4240-10)-6 (Jan. 1964) Contr. No. AF 04(695)-269, 61 pp 19 fig 11 tab 64 ref.

An up-to-date review of metals and alloys suitable for cryogenic aerospace structural applications has been made. The mechanical properties of austenitic stainless steels, other steels, aluminum alloys, titanium alloys, nickel alloys and cobalt alloys from +78 to -423°F are presented, including tensile and yield strengths, elongation and notch/tensile ratios. Mechanical properties of weldments are also presented. The question of notch toughness and the notch acuity factor, K_t , is discussed with respect to low temperature tensile testing. Compatibility with the liquid gases is discussed and alloys most suitable for containing liquid oxygen and hydrogen in aerospace vehicles are recommended.

EFFECTS OF LOW TEMPERATURES ON STRUCTURAL MATERIALS - NASA Tech. Utiliz. Rept. NASA SP-5012 (Dec. 1964) 55 pp 45 fig 37 tab 2 ref.

There are many problems, associated with the storage and handling of cryogenic fluids, which must be considered in the design and fabrication of tankage and other components of cryogenic rocket systems. Thus, a continuing program is being conducted by the Propulsion and Vehicle Engineering Laboratory of the Marshall Space Flight Center to evaluate the applicability of various metallic materials at cryogenic temperatures.

LOW TEMPERATURE AND CRYOGENIC STEELS MATERIALS MANUAL - United States Steel, Pittsburgh, Pa. - 191 pp 81 fig 30 tab 218 ref.

This manual is designed to provide knowledge of steels produced for use in low-temperature and cryogenic service. It embodies a synopsis of material properties and fabrication techniques, as well as an economic evaluation of containers and other criteria required when designing cryogenic process equipment.

AEROSPACE FLUID COMPONENT DESIGNERS' HANDBOOK - TRW Systems Group, Redondo Beach, Calif., - AFRPL TDR 64-25 (March 1967) - Contr. Nos. AF04(611) - 8385, AF04(611) - 11316, Two volumes: DDC AD 809 182, DDC AD 809 183.

The Aerospace Fluid Component Designers' Handbook is a compilation of basic information on the design, analysis, selection, and specification of valves and associated fluid components used in aerospace fluid systems. The handbook is intended to be used as a basic reference for engineers and other technical personnel who are involved in any phase of aerospace fluid component technology. It contains sections dealing with heat transfer, fluid mechanics, fluid systems, fluid components, modules, analysis, computers, specifications, contamination and cleaning, reliability, materials and environments. The handbook will continue to be revised periodically for the purposes of maintaining the currency of the data and adding applicable new material.

ADVANCED VALVE TECHNOLOGY - Burmeister, L. C., Loser, J. B. and Sneegas, E. C. - Midwest Research Inst. - NASA SP-5019 (1967) - 183 pp 118 fig 30 tab 159 ref.

The exploration of space has necessitated a multitude of innovations and improvements in valves, the controlling elements of both simple and complex fluid-handling systems. In view of the benefits that can be derived from what has been learned about the design, performance, and manufacture of these devices, this survey was undertaken.

CRYOGENIC VALVES . . . A SURVEY - Beard, C. S. - Cryogenic Eng. News 2, 62-64; 66, 68, 69 (Nov. 1967).

The differences between cryogenic and ordinary valves are both visible and invisible. The author reviews requirements for valve bodies, materials, seats, and lubricants for compatibility with cryogens and ultra-low temperatures.

CRYOGENIC CONTROL VALVES FOR INDUSTRIAL PROCESSES - Ives, R. P. - Cryogenic Eng. News 3, 38-41 (Aug. 1968) 7 fig.

There is nothing mystic about cryogenic control valves. Their design, application and installation is simply an extension of basic control valve engineering and technology. A process or instrument engineer must review the service conditions, review the available equipment, select the unit best suited for the specific job, and apply the control valve as outlined. This does not differ from the technique used to apply a control valve to any process.

A BROAD SURVEY OF CRYOGENIC PUMPING - Hoelscher, F. W. - Cryogenic Eng. News 2, 78-80, 82, 84, 85 (Aug. 1967).

A wide-ranging outline of cryogenic pumping equipment is presented, including designs, uses, requirements, problems and limitations.

HANDBOOK OF COMPRESSED GASES - Compressed Gas Association - Reinhold Publishing Corporation, New York (1966) 416 pp.

Prepared by the staff of the Compressed Gas Association, the foremost research leader on safety and technical standards in this field, the book covers the essential core of knowledge and practice in all safe and efficient handling, storage and transportation of gases. Some of the many compressed gases included in the handbook are: acetylene, ammonia, carbon dioxide, chlorine, ethylene, fluorine, fluorocarbons, hydrogen chloride, hydrogen sulfide, krypton, LP-gases, medical gases, methane, nitrogen, nitrous oxide, oxygen, vinyl methyl ether, and xenon. An extremely important section of the book describes vital materials available nowhere else in book form-the most widely applicable safety standards for compressed gas handling and for container construction, developed by the compressed gas industry itself. These standards are the result of many years of research conducted by the Compressed Gas Association. Special attention has been given to recent advances, as in the book's coverage of cryogenic liquid gases used so spectacularly in the aerospace industries. The appendices contain valuable material summarizing the regulations pertaining to compressed gas shipment and storage that have been adopted by states throughout the United States.

HANDBOOK OF THERMAL DESIGN DATA FOR MULTI-LAYER INSULATION SYSTEMS - Coston, R. M. - Lockheed Missiles and Space Company - Prepared for NASA-Marshall Space Flight Center, Contr. No. NAS 8-20353, NASA CR-87485 (June 1967) 207 pp 71 fig 5 tab 115 ref.

The prime intent in assembling the data presented in this volume is to provide a sourcebook of consistent data on thermal and physical properties of multilayer insulations so that the data can be applied in mathematical thermal models of cryogenic propellant tankage.

The second intent of this report is to provide readily available design data for general usage by designers and thermal analysts of cryogenic space vehicles who will not necessarily employ the mathematical models. A variety of design data is presented, including thermal conductivity, specific heat, density, linear thermal expansion, weight per unit area, and maximum material operating temperatures.

Data presented here are divided into four major categories: (1) Gases; (2) Metals; (3) Fiberglass Laminates; (4) Multilayer Insulations; (4.1) Substrates; (4.2) Multilayer-Insulation-System Materials; (4.3) Multilayer Composites; (4.4) Attachment Methods; (4.5) Test Methods.

THERMAL INSULATION SYSTEMS - NASA Tech. Utiliz. Rept., NASA SP-5027 (1967) - 148 pp 77 fig 10 tab 101 ref.

The purpose of this survey is to summarize, and thus make more accessible to industry, data on the performance of thermal insulations and systems combining such insulations, particularly for cryogenic applications, and to indicate opportunities for improvements. Included in this work are chapters on: Applications of Thermal Insulations; Principles of Thermal Insulation Systems; Cryogenic Insulation Systems; Structural and Non-insulating Cryogenic System Components; High-Temperature Thermal Protection Systems.

BOILING HEAT TRANSFER FOR OXYGEN, NITROGEN, HYDROGEN, AND HELIUM - Brentari, E. G., Giarratano, P. J. and Smith, R. V. - Natl. Bur. Standards Tech. Note 317 (Sept. 1965) 119 pp 83 fig 7 tab 110 ref.

This study has been conducted to provide an orderly examination of the information relative to boiling heat transfer for four cryogenic fluids. The general approach has been to examine experimental data with respect to the predictive correlations which would appear to have probable success and which would be likely to be used by design engineers. These correlations were graphically and statistically compared. The results are discussed, and when it appears a best or acceptable recommendation can be made, computation aids for designers are included. These aids are in the form of graphical presentations for preliminary studies and equations for computer studies. The authors have also indicated the apparent limits for the use of these correlations, when possible. The effect of many variables which would often be significant are not included in the predictive correlations. The influence of these variables is discussed in a separate section on boiling variables.

BOILING HEAT TRANSFER FOR CRYOGENICS - Seader, J. D., Miller, W. S. and Kalvinskas - Rocketdyne - NASA CR-243 (June 1965) NASA Contr. No. NAS 8-5337 117 pp 47 fig 9 tab 154 ref.

An extensive survey of available information from the literature on heat transfer to boiling hydrogen, nitrogen, and oxygen is presented. Included are a bibliography of available experimental data, a summary of boiling theory, graphical comparisons of the experimental data, and compilations of pertinent physical properties for each of the three cryogenic fluids. Based upon the results of the survey, recommendations are made for a test program to provide critical information where data are lacking.

REVIEW OF STATIC SEALS FOR CRYOGENIC SYSTEMS - Robbins, R. F. and Ludtke, P. R. - J. Spacecraft Rockets 1, No. 3, 253-59 (May-June 1964) 6 fig 1 tab 55 ref.

Although cryogenic techniques have advanced rapidly, little effort has been devoted to standardization of seals for cryogenic systems. This paper surveys and evaluates various demountable, low-temperature static seals. Rectangular-sectioned gaskets of Teflon or Kel-F, or of soft metal, or with plastic sealing surfaces can be used, but gaskets require heavy flanges. O-rings of rubber, Viton, and neoprene have been used successfully down to 20°K with high-initial-loading designs. Hollow, metallic

O-rings can be used, but they are hard and require good surface finishes, ≥ 16 rms. Solid O-rings of soft metals (e.g., indium, lead, copper, and aluminum) can seal to 10^{-5} arm-cc/sec/linear-in. Pressure-actuated seals of C, U, V, or W configuration are said to be superior to all others for cryogenic space systems (a table of available types is given); they use lightweight flanges and will follow flange deflections; they are expensive, and small leak paths can develop, but they have proved reliable in the field. Temperature-actuated seals (favorable thermal contraction relationships) also show promise but have not been used extensively.

BEARINGS AND SEALS FOR CRYOGENIC FLUIDS - Scibbe, H. W. - NASA-Lewis Research Center, Cleveland, Ohio - NASA TM X-52415 (March 1968) - [Technical paper presented at SAE Fuels and Lubricants Meeting, Cleveland, Ohio, Nov. 13 1967].

Bearings and seals in rocket engine turbopumps operate directly in the cryogenic propellant. Special design and lubricating techniques are required since ordinary oils and greases become glasslike solids at these extremely cold temperatures. The bearing load carrying surfaces are lubricated by thin transfer films. The lubricant is provided by the bearing cage which is usually fabricated from a self-lubricating Teflon compound. Material compatibility and wear are the important factors for face contact seals in these cryogenic fluids. Carbon, normally used in seal nosepieces, has violent reactions when run in liquid fluorine, an extremely chemically active fluid. Wear at the rubbing contact is minimized when the seal is designed for positive face separation with acceptable leakage.

INTRODUCTION TO CRYOGENICS - Vance, R. W. - Machine Design 36, 169-192 (Oct. 8, 1964).

The principal engineering problems associated with cryogenics, including the fundamental relations, theories, equations and concepts, have been described in detail by many authorities. This article highlights some of these considerations and points the way toward practical solutions to selected design problems.

INTRODUCTION TO CRYOGENIC ENGINEERING - Reiff, D. D. - ASME Paper No. 64-WA/PID-8 (Nov. 1964) 12 pp 7 fig 11 ref.

The purpose of this report is to introduce a few of the essential disciplines in cryogenic engineering. The basic principles of liquefaction of gases and low-temperature heat transfer and insulation are briefly treated. The discussion of storage, transfer, and handling of cryogenic fluids has been slanted to hydrogen; however, the basic principles of cryogenic technology are embraced. In addition, mobile ground-service equipment is discussed briefly.

THE STORAGE AND HANDLING OF CRYOGENIC LIQUIDS - Zenner, G. H. - Progress in Cryogenics 2, 3-39, Academic Press Inc., New York (1960) 24 fig 6 tab 51 ref.

Included in the contents of this article are sections on the properties of liquids O_2 , N_2 , A, CH_4 , F_2 , H_2 , H_e , storage and transport containers (stationary, truck, tank car), converters, meters, pumps (rotary and reciprocating), transfer methods and piping design.

SAFE HANDLING OF CRYOGENIC FLUIDS - Neary, R. M. - Chemical Section, National Safety Congress, Chicago, Ill., (Oct. 16, 1961) paper 20 pp 8 ref.

Cryogenic fluids have been handled safely by a few companies since the early part of the century. Their use, and the number of people handling them, have increased tremendously in recent years. To ensure safety, old and new users alike require a thorough understanding of the properties of these fluids and a willingness to make use of reasonable safeguards in handling them. Since handling small quantities presents some safety considerations different from handling larger volumes, these subjects will be covered in separate sections of this paper.

AIR-CONDENSING CRYOGENIC FLUIDS - Neary, R. M. - Union Carbide Corp., Linde Division - Paper presented at National Safety Congress (Oct. 31, 1963).

With the recent advances in the missile and electronics industries and of numerous research applications, such as Telstar and space chambers, liquefied hydrogen and helium are fast becoming important cryogenic fluids. Unlike the more common cryogenic fluids, namely oxygen and nitrogen, the properties of liquefied hydrogen and helium are unusual and, as a result, special equipment and handling techniques are required. This paper briefly summarizes the properties, design of equipment, and practical procedures for the safe and efficient handling of these fluids.

AIR-SOLIDIFYING CRYOGENIC FLUIDS - Neary, R. M. ASME Paper No. 64-WA/SAF-1 (Sept. 1964) 8 pp 8 fig 1 tab 8 ref.

With the recent advances in the missile and electronics industries and of numerous research applications, liquefied hydrogen and helium are fast becoming important cryogenic fluids. Unlike the more common cryogenic fluids, namely liquid oxygen and nitrogen, liquefied hydrogen and helium are capable of solidifying air. This and other properties make it necessary to handle these products with different equipment and procedures. Personal protective equipment is reviewed. The design of small, medium and large tankage is reviewed briefly. Special emphasis is placed on design and safety devices for small liquefied helium containers commonly used in laboratories because several serious accidents have resulted from solid air plugging of the vents.

CRYOGENIC SAFETY - Spencer, E. W. - J. Chem. Education 41 (Sept. 1964) 4 pp 5 fig 1 tab 14 ref.

A general discussion on the hazards, storage, and general precautions pertinent to the handling of cryogenic fluids. This article is a portion of the paper which appeared previously in the Journal of American Society of Safety Engineers.

FIRE-HAZARD PROPERTIES OF FLAMMABLE LIQUIDS, GASES AND VOLATILE SOLIDS - National Fire Protection Association, Rept. No. 325 (May 1960).

This tabulation of available data on the properties of flammable liquids and other materials listed is sponsored by the NFPA Committee on Flammable Liquids. The table summarizes available data on the fire-hazard properties of more than 1000 substances, listed alphabetically by their chemical name. The values selected are representative figures deemed suitable for general use.

REVIEW OF FIRE AND EXPLOSION HAZARDS OF FLIGHT VEHICLE COMBUSTIBLES - Van Dolah, W., Zabetakis, M. G., Burgess, D. S. and Scott, G. S. - ASD TR 61-278 (April 1961) (See also subsequent annual supplements).

The prevention of fires and explosions involving the combustibles and oxidants likely to be found in flight vehicles requires a knowledge of the flammability and related characteristics of these materials. This is a compilation of the available characteristics data for a series of combustibles and oxidants of current interest (including fluorine, oxygen and hydrogen).

EXPLOSION AND FIRE HAZARDS ASSOCIATED WITH THE USE OF LOW-TEMPERATURE INDUSTRIAL FLUIDS - Burgoyne, J. H. - Trans. Inst. Chem. Engrs. (London) 185, CE 7-10 (Jan. - Feb. 1965).

Hazards of low-temperature fluids are considered under the headings of pressure bursts, gas explosion, fire, and explosion of liquid mixtures (e.g., of fuel and oxygen). The literature on these subjects is reviewed and an attempt is made to distinguish areas where gaps in knowledge exist and further systematic research should be rewarding. It is concluded that gas explosion properties at low temperatures and the explosibility of low-temperature liquid mixtures merit considerable attention.

SPARKING CHARACTERISTICS AND SAFETY HAZARDS OF METALLIC MATERIALS - Bernstein, H. and Young, G. C. - NAVORD Rept. 5205, Tech. Rept. NGF-T-57 (April 1957).

This report is a survey of the sparking characteristics and safety hazards of metallic materials. The fundamentals of sparking theory and methods of spark testing are presented. The ignition hazards associated with sparks are discussed. Attention is called to an alternate and possibly more significant source of ignition - impacts. The data indicate that sparks and impacts can result from the use of "non-sparking" materials. The authors conclude that no benefit is gained by employing non-sparking hand tools in place of steel to prevent explosions.

RECENT ADVANCES IN CRYOGENIC ENGINEERING - Jacobs, R. B. - ARS Jour., 245-51 (Apr. 1959) 56 ref.

The point to be emphasized is that cryogenic engineering is a synthesis of the older branches of engineering (mechanical, chemical, electrical), and therefore does not involve new basic principles. The discussion presented here has avoided those areas where usual engineering experience is directly applicable. An attempt has been made to discuss situations where the unwary may go astray and where the cryogenic engineer has evolved new techniques. In addition, an attempt has been made to indicate the location of data and information applicable to new materials and situations, as well as that applicable to the familiar materials and situations in the low temperature regions.

PROBLEMS IN CRYOGENICS - Nesbitt, L. B. - General Electric Co., Schenectady, N.Y. - ASME Paper No. 63-WA-288 (Nov. 1963) 4 pp 1 fig.

A major impediment in the growth of cryogenic engineering as a productive segment of the engineering sciences has been the many real and imaginary problems whose solutions are now available. The author points out the pitfalls in the study of cryogenics and indicates a sound approach to cryogenic experimentation and development.

THERMAL PROBLEMS PECULIAR TO CRYOGENICS IN SPACE - Adelberg, M. and Schwartz, S. H. - SAE Paper No. 670588 (June 1967) 10 pp 9 fig 3 tab 24 ref. - [Published in Proc. of the SAE Aerospace Systems Conference, Los Angeles, Calif.]

Thermal problems peculiar to cryogenics stored in a reduced gravity environment are discussed along with some techniques considered for their solution. Included are gravitational effects upon transient and steady state nucleate boiling, heat transfer and temperature fluctuation and meniscus displacement and distortion. To place these problems in proper perspective, a brief survey of the various heat transfer modes is presented. One device, which appears to warrant a serious consideration, is the thermodynamic separator and its operation is briefly described.

To illustrate the importance of certain problems peculiar to reduced gravity, a number of numerical examples are presented.

HANDLING LIQUID PROPELLANTS - Dachs, L. L. - Space/Aeronautics 46, 77-84 (Oct. 1966).

Beyond obvious fluid management problems, liquid propellants spawn sneaky, second order effects like cavitation, oscillation and zero-g "migration". Equipment configuration is the key to knocking down bubble population; baffles and the like arrest sloshing; expulsion devices help the orbital restart.

CRYOGENIC INSTRUMENTATION - Angerhofer, A. W. - Air Reduction Co., Inc. - Control Engineering 12, 67-73, 77-84 (1965) (A two-part article).

Because of their low temperatures and high volatility, some unique measurement problems arise in the use of cryogenic fluids. Conventional sensors can solve most of these problems, but satisfactory operation requires care in application and a knowledge of the complications that can occur. The first article discusses special cryogenic problems in temperature and level sensing; the second article covers fluid flow and analysis instruments.

CRYOGENIC THERMOCOUPLE THERMOMETRY - Sparks, L. L. and Powell, R. L. - Measurements and Data 1, 82-90 (March - April 1967)

Commercially available low-temperature thermocouple wire from all major U.S. manufacturers has been exhaustively tested to determine the inhomogeneity and interchangeability characteristics of the wire. Spot calibrations between liquid-helium and liquid-nitrogen temperatures, and between liquid-nitrogen and ice temperatures, show that the NBS interim low-temperature tables are sufficient for most engineering and scientific requirements. Preliminary work on several gold-iron alloys indicates that these alloys will allow more accurate thermoelectric temperature measurement in the liquid-helium/liquid-hydrogen temperature range. Research, now well underway, will lead to establishment of standard thermocouple tables for temperatures from liquid helium up to 0°C for all of the cryogenically useful commercial thermocouple alloys.

MASS FLOWMETERS IN CRYOGENIC SERVICE - Alspach, W. J., Miller, C. E. and Flynn, T. M. - Paper presented at 1966 ASME Flow Measurement Conf., Pittsburgh, Pa. - (Published in Flow Measurement Symposium) 23 pp 27 fig 29 ref.

This paper concerns cryogenic fluid mass flow measurement by a variety of techniques, including those that are available and those that are being developed. Attention is given to the principle of operation, performance results, and operational and design characteristics.

The problem of cryogenic fluid flowmeter calibration is examined and discussed with reference to available facilities, techniques, limitations, and accuracy. The problem of calibration for special cryogenic applications, such as slush hydrogen and cold gases, where no calibration facilities are available is also examined. Inferred calibration from a substitute fluid calibration or design practices is also reviewed.

To improve the mass flow measurement of cryogenic fluids, discussions are directed towards measurement technique selection, density measurements for inferential mass systems, improvements in volumetric flow measurements, improvements in direct measuring mass flowmeters, and improvements in calibration.

CRYOGENIC FLOW MEASUREMENT - FLOW METERS - Bucknell, R. - Cryogenic Eng. News 1, 28-30, 43 (April 1966).

The author presents a discussion of flow meters and their characteristics in cryogenic service.

FLOW MEASUREMENT OF CRYOGENIC FLUIDS - Close, D. L. - Instruments and Control Systems 41, 109-114 (Feb. 1968) 7 fig 4 tab 15 ref.

The fundamentals of flow measurement of ambient temperature fluids can be applied to cryogenic liquids, which are typically colder than -150°C . There are three special concerns in cryogenic flow measurement regardless of meter type: (1) the condition of the liquid to be metered; (2) the materials and construction of the primary element; (3) the safe installation of that element.

LARGE SIZE CRYOGENIC TURBINE TYPE FLOWMETER TECHNOLOGY - Deppe, G. R. - Aerojet-General Corp. Rept. No. 8800-60, - NASA CR 54810 (June 1966) 45 pp 14 fig 3 tab 11 ref.

The procurement, calibration, facility installation, and use of turbine flowmeters for the very large liquid oxygen/liquid hydrogen components of the M-1 Rocket Engine are described. Also, construction details of one turbine flowmeter and limited calibration data for several turbine flowmeters are given. The relative capabilities of the nation's major testing organizations are presented along with facility recommendations.

COOLDOWN OF LARGE-DIAMETER LIQUID HYDROGEN AND LIQUID OXYGEN LINES -
Commander, J. C. and Schwartz, M. H. - Aerojet-General Corp. - Rept. No. 8800-54, NASA CR 54809
(April 1966) 56 pp 22 fig 6 tab 8 ref.

This report concerns the analytical study and operational experience associated with the large cryogenic propellant systems used in Test Zone E of the M-1 test complex. The techniques applicable to initial chilldown of large diameter cryogenic piping systems are discussed; major consideration is given to liquid hydrogen and liquid oxygen propellant systems that utilize the cryogenic boil-off gases at a predetermined rate to effect system chilldown. The use of this technique reduces or eliminates the problem of thermal stress concentrations in the system materials during chilldown.

The principal areas of discussion include:

- A. Various methods considered for chilldown of cryogenic piping systems.
- B. Analysis of thermal stress at selected points in liquid hydrogen and liquid oxygen piping systems where cross-section transitions produce maximum thermal gradients.
- C. Analysis of system chilldown characteristics when cold gaseous cryogens are utilized to effect the initial reduction in system temperatures, including predictions of time in relationship to equilibrium temperature for systems exposed to various combinations of gas flow rate and initial temperature.
- D. Analysis of the effects caused by cold shocking on critical cross-section transitions of the 18 inch liquid hydrogen discharge line which have stabilized at equilibrium temperatures of 260 R, 160 R, and 60 R.

COOLDOWN OF CRYOGENIC TRANSFER SYSTEMS - Liebenberg, D. H., Novak, J. K. and Edeskuty, F. J. - AIAA Paper No. 67-475 (July 1967) 9 pp 8 fig 3 tab 16 ref.

Operation of a cryogenic system is frequently complicated by the transient process of cooling it to its equilibrium operating temperature. A knowledge of the time and amount of cryogen necessary to cool the line is valuable since sufficient cryogen storage must be provided to complete the cooling of a large line. It is also necessary to cool the line in a manner which will not result in damage to the line or to associated components. Improper cooldown procedures can produce bowing (a distortion of the pipe caused by uneven cooling around the pipes circumference), unacceptable pressure and flow surges if the flow is improperly initiated or limited, unacceptable stresses in components if temperature gradients are too large, or can, through uneven cooling, cause binding in moving parts, such as pumps, mechanical interference of components, etc. Specific rules for eliminating these problems cannot be given, but general suggestions for avoiding the problems are presented.

FLEXIBILITY CONSIDERATIONS FOR THE DESIGN OF CRYOGENIC TRANSFER LINES - Flieder, W. G., Smith, W. J. and Wetmore, K. R. - Advances in Cryogenic Engineering 5, 111-19 (Proc. of 1959 Cryogenic Eng. Conf.) Plenum Press, Inc., New York (1960) Paper B-5, 9 fig. 5 ref.

In conventional piping systems, sufficient uniform thermal cooldown flexibility is obtainable by the use of expansion loops. Uniform thermal cooldown occurs when the pipe is full of liquid and the entire pipeline has cooled to liquid temperature. In the case of missile systems employing cryogenic transfer lines, space and cooldown weight limitations may preclude the use of expansion loops for achieving flexibility. In addition, the uninsulated thin-walled transfer piping is subject to temperature gradients of

a scale not usually encountered in process piping systems, and as a consequence of these temperature gradients the phenomenon of pipeline bowing occurs. Bowing is the tendency of the centerline of the pipe to be deformed into an arc.

A brief analytical study is presented to show how flexibility for cryogenic lines may be obtained by the use of expansion loops and expansion joints that satisfy both the requirements for uniform thermal cooldown and bowing considerations. Finally, the liquid oxygen transfer piping developed for the Atlas missile launching complex is presented and special features of this system are explained.

CRYOGENIC PIPING SYSTEM DESIGN CONSIDERATIONS - Jacobs, R. B. - Heating, Piping Air Conditioning 32, 130-40, 142-56 (1960) (A two-part article).

Piping systems for transporting liquefied gases are not basically different from those for the more familiar fluids. But, some differences must be considered by the designer because of the temperature range encountered - room temperature down to almost absolute zero or -459.6°F . The topics presented (in the first article) include properties of materials and insulation techniques. How low temperatures affect the fluid-mechanical design, selection of pumping equipment, heat exchanger design, piping system instrumentation, and the fabrication and installation of the piping system are presented in the second article.

FUNDAMENTALS OF LOW TEMPERATURE PIPING DESIGN - Surdi, V. L. and Romaine, D - The M. W. Kellogg Co. - Hydro. Proc. and Petr. Ref. 43, 116-24 (June 1964).

While the design of piping for low temperature is, for the most part, the same as for above ambient temperature, there are two basic conditions that must be given special consideration.

First, the cost of refrigeration increases as the temperature is reduced. From this it is clear that low temperature insulation and insulation techniques merit special design consideration, and, as is shown in this paper, such consideration leads to a number of concepts that differ from conventional warm piping.

Second, carbon steel and gasket materials become brittle at lower temperatures. For operation below -50°F , it is necessary to choose either nickel steels, stainless steel, copper, or aluminum as the material of construction. While each of these materials serves very well in certain situations, each nevertheless has certain limitations that require special design consideration. Gasket materials become brittle and are generally less effective at low temperatures. Designing flanges and joints to avoid leaks takes on a new significance in low temperature plants where vessels, piping, and valves frequently are made of dissimilar metals with attendant differences in coefficients of thermal expansion.

CRYOGENIC STORAGE VESSELS - Chicago Bridge and Iron Co. - Publication G-50-64 - 15 pp 18 fig 4 tab.

The information contained in this bulletin deals primarily with storage vessels. Included are sections on insulation systems, vessel geometry and design requirements, materials of construction, fittings, and foundations.

HOW TO SPECIFY LOW TEMPERATURE STORAGE VESSELS - Zick, L. P. and Clapp, M. B. - Chicago Bridge and Iron Co. - Hydro. Proc. and Petr. Ref. 43, 125-32 (June 1964).

Greater exposure to brittle fracture at full stress is the most significant difference between vessels used for storage at refrigerated temperatures and storage at atmospheric temperature. Therefore, the selection of notch tough material is extremely important for refrigerated storage vessels. Notches should be eliminated in the design details and construction of parts carrying high stress, insofar as possible. Unavoidable stress concentrations are better tolerated by notch tough materials.

This article is based upon the current state-of-the-art, but the reader should remember that a precise evaluation of the ductile versus brittle behavior of materials used in storage vessels operated at refrigerated temperatures is not clearly defined. Nevertheless, certain levels of toughness which may be determined by tests will result in safe structures.

DESIGN OF CRYOGENIC STORAGE TANKS FOR INDUSTRIAL APPLICATIONS - Marsh, H. W. - Am. Soc. Testing Materials, Spec. Tech. Publ. No. 302 (March 1962) pp 172-83, 4 fig 1 tab 4 ref.

This is a discussion of the facets of cryogenic storage tank design directed toward those who have only limited experience in the field. Design considerations as to cost, suitability of materials for the temperatures and pressures involved, configuration of inner vessels and jackets, support systems, and types of insulation, evacuated and nonevacuated, for both shop-built and field-erected vessels are discussed in brief. The potential requirements for cryogenic storage for industrial applications are listed. Military applications for both ground and air-borne use are excluded as these involve unusual design conditions foreign to the usual industrial installation.

LARGE CRYOGENIC STORAGE VESSELS - Adams, L. - Pittsburgh-Des Moines Steel Co. - ASHRAE Jour. _____, 48-9 (July 1964).

This article summarizes data on the size, shape, and design of large capacity, field-erected vessels for the storage of cryogenic fluids, and includes information on metals, thermal insulation, heat leak, and some pertinent physical properties of the products stored.

CONSTRUCTION OF HIGH PRESSURE CRYOGENIC VESSELS - Sangdahl, G. S. and Wilson, L. C. - Chicago Bridge and Iron Co. - ASME Paper No. 64-PET-17 (Sept. 1964) 12 pp 8 fig 4 tab 11 ref.

The large increase in the use of oxygen, nitrogen, hydrogen, methane and other gases for industrial purposes has greatly increased the need for storage of these gases. This can most efficiently and safely be done as a liquefied gas at a temperature below the boiling point of the gas and at atmospheric pressure. Special applications may require high pressure storage. This article describes the many factors which must be considered in the construction of high pressure cryogenic vessels - such as: design, material selection, forming, welding, heat treatment, inspection, and cleaning.

THE PAST, PRESENT, AND FUTURE OF METALS FOR LIQUID ROCKETS - Lucas, W. R. - Metals Engineering Quarterly 6, 58-62 (Feb. 1966).

The utilization of metals in liquid-propelled rocket systems is discussed in terms of the unique environments in which performance is required. Weldability, toughness at cryogenic temperature, stress-corrosion resistance, and chemical compatibility with propellants are identified as important criteria in the selection of metals for these applications. Aluminum has been the predominant metal in liquid rocket structures, and its use has paralleled aluminum alloy development in this country. Recent achievements in the development of new wrought aluminum alloys, a new aluminum casting alloy, and other light-weight materials are discussed. Composite materials are projected as the materials of the future because they afford the possibility of increasing the strength-to-density ratio by the reduction of density rather than by the increase of strength and the possibility of utilizing simultaneously the most favorable properties of two or more materials.

LOW TEMPERATURE AND CRYOGENIC STEELS: HOW TO CHOOSE, USE, AND WELD THEM - Anonymous - Special Report - Welding Design and Fabrication _____, 51-73 (April 1964).

In this report information is provided on which steels are proving to be best for each low temperature level; what welding electrodes and methods are recommended; which ASME pressure vessel codes apply; and what ASTM designations are used for each steel grade.

ROCKET PROPELLANTS - Armed Services Tech. Inform. Agency, Arlington, Va., Bibliography Rept. AD 233 500 (March 1960) 56 pp.

The bibliography is a compilation of approximately 292 abstracts of unclassified reports on liquid and solid propellants which were added to the ASTIA collection from 1953 to 15 Feb. 1960. The first part of the bibliography includes separate sections dealing with general information on solid rocket propellants and on liquid rocket propellants. The second part of the bibliography includes sections for each of the following compositions used in rocket propellants: (1) acetylenes, (2) amines, (3) ammonia, (4) ammonium perchlorate, (5) boron hydrides, (6) ethylene oxide, (7) fluorine, (8) hydrazines, (9) hydrocarbons, (10) hydrogen, (11) hydrogen peroxide, (12) lithium compounds, (13) methanol; (14) nitric acid, (15) nitrogen, (16) nitrogen-fluorine compounds, (17) nitrogen oxides, (18) nitro-paraffins, (19) oxygen, (20) ozone, (21) perchloryl fluoride, and (22) thiophosphites. Abstract entries in each subdivision of the first and second parts are arranged alphabetically by corporate author, numerically by contract number and by date. Only final or summary reports were included in the bibliography, except when the final report was not received or when a progress report contained significant information which was not included in the final report. A bibliography of confidential entries on solid and liquid propellants (AD 315 500) was compiled separately.

ROCKET PROPELLANTS - Armed Services Tech. Inform. Agency, Arlington, Va., Bibliography Rept. AD 263 000 (Aug. 1961) 75 pp.

A list of references was prepared as a sequel to previous ASTIA bibliographies on rocket propellants identified as AD 233 500 (unclassified) and AD 315 500 (confidential). Citations are limited to unclassified documents cataloged by ASTIA from February 1960 to August 1961. A classified edition of the bibliography was also published as AD 325 000. Entries are arranged in two broad categories of references: liquid, hybrid, solid or non-conventional propellant systems, and specific chemical components of propellants.

CRYOGENICS AND LOW TEMPERATURE RESEARCH. AN ASTIA REPORT BIBLIOGRAPHY - Armed Services Technical Information Agency, Arlington, Va., ASTIA AD 271 000 (Feb 62) 865 refs.

This bibliography was presented by ASTIA in response to numerous inquiries concerning cryogenics and low temperature research. Citations are included for documents cataloged by ASTIA from 1953 through 1 February 1962, and are restricted to unclassified, unlimited references. The classified section of the bibliography appears separately as a secret document, identified as AD-327 650. References are arranged alphabetically by subject areas pertaining to low temperature research, instrumentation, and materials. These subject areas are further subdivided into more specific topics which include references on superconductivity, thermochemistry, temperature measurement and control, adhesives, elastomers, liquefied gases, lubricants, metals, and propellant research.

CRYOGENICS - AN INTERNATIONAL JOURNAL OF LOW TEMPERATURE ENGINEERING AND RESEARCH - Mendelssohn, K., Scott, R. B., and Weil, L. (Editors) Heywood and Company, Ltd., London (Distributed in U.S. and Canada by Plenum Press, Inc., New York)

The purpose of CRYOGENICS is to publish original papers on all aspects of low temperature research, engineering, and development. Each issue also features an invited survey article, written by an authority on the subject, as well as shorter technical notes, letters and book reviews. The complete texts of all papers appear in English, with abstracts printed in English, French, German, and Russian.

The many different trends of low temperature research and development today are not only intensified, they are also divergent. However, all share the same cryogenic methods and techniques and all must rely on the same basic research and engineering data. Concentration of relevant information on these subjects in one journal should be invaluable to all those working in the field. It is the aim of CRYOGENICS to save time and labor of researchers and engineers in the field by providing them with significant and current information in one convenient publication.

CRYOGENIC ENGINEERING NEWS - (A controlled circulation publication printed monthly by Business Communications, Inc., Cleveland, Ohio).

A publication concerning the production and use of ultra-low temperatures.

CRYOGENIC INFORMATION REPORT - (Published by Technical Economics Associates, Estes Park, Colo.).

A monthly survey, bringing together information on the developments and activities in the various areas of the cryogenic field.

CRYOGENIC TECHNOLOGY - JOURNAL OF THE CRYOGENIC SOCIETY OF AMERICA - (Published bi-monthly by Cryogenic Technology Publications, Inc., Bel Air, Los Angeles, Calif.).

CRYOGENIC TECHNOLOGY is an official publication of the Cryogenic Society of America, devoted to the various technical and practical aspects of the several branches of cryogenics.

CRYOGENIC DATA CENTER

Since the purpose of this report is to provide summary information concerning fluid and solid material properties and practices relating to selected cryogenic propellants, it may be considered useful to indicate something about the primary world source for such information - the National Bureau of Standards Cryogenic Data Center. The Center is a Section in the Cryogenics Division of the National Bureau of Standards (Boulder, Colorado Laboratories) and is divided into two principal groups, the Data Compilation Unit and the Documentation Unit.

The Data Compilation Unit is engaged in the critical evaluation and compilation of thermodynamic and transport properties of cryogenic fluids and fluid mixtures and cryogenic properties of solids. Tables and charts of property data, based on selected values from the scientific literature, are compiled for wide ranges of temperature and pressure. As a participant in the National Standard Reference Data System program, the Data Compilation Unit is recognized as a national authority for data on the properties of materials at cryogenic temperatures, and thus many of the tasks undertaken by this unit are organized to produce data tables suitable for entry into the NSRDS.

The Documentation Unit's functions complement the activities of the Data Compilation Unit. These functions are: 1) to maintain an awareness of current publications and reprints of cryogenic interest, 2) to acquire and catalog such literature as needed by the Data Compilation Unit, other laboratory staff, and for completing the Data Center's files, 3) to code the pertinent literature in depth for storage and retrieval, and 4) to develop an operative mechanized bibliographic and indexing service for the comprehensive retrieval of information and data in specific subject areas as needed. This unit also handles the distribution of all the Cryogenic Division's publications and announces availability of new materials periodically.

Of possible interest to the readers of this document are the various services available to the public from the Cryogenic Data Center:

Literature Searches. Nearly 60,000 accessions of cryogenic literature have been entered into the Data Center's system. Approximately two-thirds of these (on the properties of materials, cryogenic equipment and processes) have been processed for machine searching. Custom bibliographies are prepared for specific subjects or for broad subject areas; indexing follows from the nature of search queries and can be quite detailed. Simple searches can be made for as little as \$25.00 with more

extensive searches at a proportionately higher cost. The feasibility and estimated cost of a search can be obtained from the Data Center.

Current Awareness Service. An awareness of publications and reports of cryogenic interest is maintained by the regular review of nearly two hundred periodicals cover to cover, by a weekly review of the "Current Contents" service, by reviewing some fifteen abstract journals, and by noting references in cryogenic documents. Weekly lists of new literature of cryogenic interest are prepared and distributed to subscribers at a subscription price of \$15.00 per year for 52 issues. A subscription may be obtained simply by ordering from the Cryogenic Data Center.

Announcements of Cryogenics Division Publications and Reports. Announcements and abstract cards of new literature evolving from the Cryogenic Division's research programs are sent to more than 4000 persons and institutions periodically. Nearly five hundred separate items of literature are now available. Request can be made for inclusion on the mailing list by writing to the Cryogenic Data Center. Distribution of the available literature is now being handled by the government Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151. Ordering information is included with the announcements.

Anyone desiring information concerning the various services described above may write to the

Cryogenic Data Center
National Bureau of Standards
Boulder, Colorado 80302

or telephone

(303) 447-1000, ext. 3834

II. RECOMMENDED MATERIALS AND PRACTICES FOR USE WITH LIQUID OXYGEN

- A Compilation from the Literature with Annotated Bibliography -

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1. HAZARDS:

1.1 Health:

The health hazards of liquid oxygen arise from its very low temperature. If liquid, or cold gaseous, oxygen contacts the skin, damage resembling burns can result. The extent of such damage can range from relatively minor burns to complete embrittlement and destruction of exposed tissue. The immediate effects of freezing by liquid oxygen can be minimized by soaking affected parts in tepid water. Extensive burns require prompt medical attention.

Oxygen gas will not cause toxic effects in propellant operations, except that inhalation of the very cold gas may cause some upper respiratory irritation.

1.2 Fire:

Liquid oxygen will not burn but vigorously supports combustion. Its low temperature causes cooling and freezing of liquid fuels if both liquids are brought together. Such mixtures are shock sensitive and are capable of reaction with the violence of a detonation.

Liquid oxygen is capable of saturating normal clothing and rendering it flammable. Workers must not smoke or strike fires in oxygen storage or handling areas or while wearing clothing saturated with oxygen, since the clothing may retain a high concentration of oxygen for a considerable period of time.

Two types of combustion reactions may occur depending on conditions of mixing and ignition. Intensity of combustion reaction is dependent on the type of fuel involved. Although the mixing of fuel and liquid oxygen may be accomplished without fire, a detonation occurs upon ignition or mechanical shock excitation. Where combustion is initiated prior to or concurrently with fuel-oxygen contact, flare type combustion occurs, accompanied by repeated explosions.

Putting out fires involving liquid oxygen requires procedures varying with the type of fire conditions. Where the fire results from a leak or flow of liquid oxygen onto wood, paper, waste, or similar combustible material, first stop the flow if possible. For small spills, or after the leak or flow of liquid oxygen has been stopped, use enough water to put the fire out quickly. Where the fire involves liquid oxygen and liquid fuels, control it as follows:

- (a) When liquid oxygen leaks or flows into large quantities of fuel, shut off the flow of liquid oxygen, and put the remaining fuel-fire out with Class B fire fighting agents.
- (b) When fuel leaks or flows into large quantities of liquid oxygen, shut off the fuel flow.
- (c) When fuel and liquid oxygen have been mixed, or are mixing, but not yet burning, isolate the area from ignition sources and get out quickly, allowing the oxygen to evaporate. Where large pools of water-soluble fuel are present, use water to dilute the fuel and to reduce the intensity of the fire. This method cannot be used with fuel which do not mix with water. Do not use on fires in deep pools of liquid oxygen as this causes more rapid release of gaseous oxygen. Appropriate extinguishing agents may be used to put out fuel fires after the oxygen has evaporated.

NOTE: Mixtures of liquid oxygen and fuels present an extreme detonation hazard. Such materials as wood pulp, cotton, lampblack, hydrocarbons, metal powders, sulfur and coal dust are often used in combination with liquid oxygen as a relatively cheap explosive; the latter combination produces an effect dissimilar to 40% nitroglycerine dynamite. It seems likely that almost any combustible material might detonate when in contact with liquid oxygen. Several incidents may illustrate this: A leak developed in a pipe joint in a liquid oxygen line and the liquid flowed onto an asphalt-paved surface. When a workman attempting to repair the leak struck the joint, the impact was transmitted from the joint to the pavement below and the pavement detonated. A similar incident has been reported where gravelled asphalt detonated when a man walked across an area where liquid oxygen had previously been spilled.

1.3 Explosion:

All materials that will burn, especially rocket fuels, present an explosion hazard when mixed with liquid oxygen. Such mixtures can usually be exploded by static electricity, mechanical shock, electrical spark, and similar energy sources. Under most conditions, the ordinary burning of rocket fuels or other combustible materials, when mixed with liquid oxygen, may progress to a detonation.

Liquid oxygen forms high concentrations of oxygen gas from spills or leaks. During transfer operations large volumes of gas are formed due to "boil-off." In confined areas, gaseous oxygen can form mixtures with fuel vapors that can be exploded by static electricity, electrical spark, or flame.

Pressure rupture can occur when the liquid is held in a closed system with no refrigeration. Oxygen cannot be maintained as a liquid if its temperature rises above the critical temperature (-181°F) regardless of confining pressure. Liquid oxygen trapped between valves can cause violent rupture of the pipe or tube, while loss of refrigeration can cause a storage tank to rupture if the pressure is not relieved by suitable devices. Loss of vacuum in vacuum-jacketed tanks can cause increased evaporation and overload the normal venting system, resulting in high pressures.

All sources of ignition or heat must be kept away from oxygen transferring and servicing operations and from areas where spills have occurred. All tanks and equipment must be provided with proper grounding to remove static electricity. It is absolutely essential to keep combustible or other reactive materials to a minimum in liquid oxygen storage and handling areas. Porous combustible materials such as clothing may retain hazardous quantities of gaseous oxygen, creating a dangerous fire hazard.

Pressure rupture of equipment can be avoided by checking all parts of the oxygen system to see that refrigeration and/or vacuum jacketing is maintained. Closed systems and "dead ends" must be avoided unless properly protected with pressure relief valves and blow-out discs. Such devices protect the system in the event of refrigeration or vacuum failure. Blow-out discs, or their equivalent, are also required on vacuum-insulated equipment jackets.

2. SAFETY MEASURES:

2.1 General:

All hazardous operations or experiments involving the handling of liquid oxygen shall be performed by two or more persons working in a group. Trained supervision of all potentially hazardous activities involving liquid oxygen is essential.

2.2 Personnel Education:

The following subjects shall be explained to all persons concerned with liquid oxygen handling, transfer, and storage:

- (a) Nature and properties of oxygen in both the liquid and the gaseous phases.
- (b) Approved materials which are compatible with liquid oxygen.
- (c) Proper equipment and its operation.
- (d) Use and care of protective equipment and clothing.
- (e) Safety, self-aid and first-aid instructions.

2.3 Personal Protection:

The principal hazards associated with the handling of liquid oxygen are fire and the extremely low temperature of the liquid.

For hand protection, gauntlet type gloves which can be easily and rapidly removed are satisfactory. These gloves may be either of asbestos or degreased chrome leather with an inner liner of impermeable material. For protection of the feet, leather shoes which can be readily removed should be used. These can be high top or low top; the choice depends entirely on the area in which the individual will be working. If high top boots are used, pants legs will be outside the boot tops. Where soles of shoes have been exposed to the liquid, the footwear should be removed immediately to prevent delayed frostbite.

Head and face protection requires the use of acid-type goggles (preferably) or a face shield to stop splashes. Flame resistant and static-free clothing should be worn by personnel conducting hazardous operations or experiments with liquid oxygen because of the fire hazard. In addition, an apron of approved material shall be worn if the liquid is being handled in an open system.

3. TRANSFER AND STORAGE:

3.1 General:

Liquid oxygen must be stored in containers (either fixed or mobile) of approved design, materials, and construction.

Storage, transfer, and test areas must be kept neat, and free from combustibles. These areas must be inspected frequently.

An adequate water supply or fire extinguishers must be available for combating fires. Approved deluge-type personnel showers should be properly located for immediate use in an emergency.