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FINAL REPORT

MARCH 1963

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ADVANCED VALVE TECHNOLOGY FOR SPACECRAFT ENGINES

Contract No. NAS7-107

Report No. 8651-6016-RU-000

Prepared for
CHIEF, LIQUID-PROPULSION SYSTEMS, CODE RPL
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

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SPACE TECHNOLOGY LABORATORIES, INC.
a subsidiary of Thompson Ramo Wooldridge Inc.
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

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FOREWORD

This report was prepared by the Mechanics Division of Space Technology Laboratories, Inc., Redondo Beach, California, under NASA Contract NAS7-107 entitled "Advanced Valve Technology for Spacecraft Engines." This contract was initiated under Dr. Henry Burlage, Chief, Liquid Propulsion Systems, Headquarters, Washington, D. C. The Headquarters Project Manager was Mr. Frank Compitello, and the program was under the technical direction of Mr. Louis Toth of Jet Propulsion Laboratory. The work was accomplished between 25 February 1962 and 25 January 1963.

The Propulsion Development Laboratory in the STL Mechanics Division was responsible for the technical efforts on this program. Grateful acknowledgment is made of the assistance provided by the following personnel and departments at STL:

Dr. A. Grenall	Product Engineering Department
Mr. A. Ambruso	" " "
Dr. J. M. Denney	Materials Department
Mr. R. L. Hammel	" "
Dr. A. Rosen	Space Physics Department
Mr. J. L. Vogl	" " "
Mr. K. A. Bloom	Mechanics Division
Mr. J. R. Smirra	" "

Acknowledgment is also made to the many members of the Aerospace Industry whose cooperation in furnishing needed information contributed to the success of the program.

ABSTRACT

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This final report describes the work that was done to determine the state-of-the-art of valves required for space exploration vehicles and the steps that were taken to advance the technology.

Interviews were held with personnel of major prime manufacturers to determine current problems and current and future requirements. Manufacturers were surveyed by mail to determine what equipment is presently being produced. An extensive search of patent office files was made to determine if any novel valve concepts not already applied to aerospace valves might exist. A literature search was conducted to provide the necessary technical information that was required for the program.

Several extensive studies were made to determine the effects on materials resulting from use in space applications, and an investigation of the basic phenomena of valve seat wear was initiated. With the information developed in the surveys and studies, the significant problems associated with valves were identified and are described under "Discussion of Problems."

A novel valve concept was developed and a prototype valve was built and successfully tested. A seal compound of Teflon and stainless steel was developed which possesses superior cold flow characteristics while retaining the desirable properties of the basic Teflon material.

SUMMARY

The Advanced Valve Technology program was conducted to determine the state-of-the-art of valves used for liquid propulsion systems of space exploration vehicles, and to define the steps required to advance the state-of-the-art.

The foundation for the program was evolved from a series of surveys that were conducted to provide the necessary information and background for the program plan. The surveys consisted of the following:

a) Literature Survey

An extensive literature survey was conducted, in which general information on valves and materials was sought. Specific information on several classes or types of valves of particular concern to the program was also searched. A large portion of the effort was devoted to material on the various space environments, with particular emphasis being placed on subjects dealing with the effects of the environments on engineering materials.

b) Patent Search

A patent search was conducted to determine if any novel, useful ideas not already applied to space valves might be found. The search included five general classes of valves, (flow metering, vent, shutoff, disconnect and regulators) and also included the more general areas of closures and structures.

c) Prime Manufacturers' Survey

Interviews were arranged with design and system engineers at most of the prime manufacturers' plants. The purpose of the interviews was to determine the present and future problems associated with valves, and also to determine projected valve performance parameters. From the data obtained a profile of known requirements was established.

d) Vendor Survey

Approximately 500 letters were sent to manufacturers of valve equipment to determine the depth of industrial effort in this field. From the replies received, an excellent roster of aerospace manufacturers was compiled which permits identification of the manufacturers with respect to the type of equipment they produce.

FUNCTIONAL PARAMETERS AND SPACE ENVIRONMENTS

With the information obtained in the surveys the functional and environmental parameters which may influence valve performance were defined in detail. The parameters considered include:

- Flow Media
- Sterilization Temperature
- Operating Temperature, Pressure and Life
- Weight
- Power Requirements
- Leakage
- Contamination
- Response, Vibration, Shock
- Space Maintenance
- Space Vacuum
- Radiation in Space
- Zero Gravity
- Time
- Temperature in Space
- Meteoroids
- Products of Combustion
- Planetary Environments

ADDITIONAL DESIGN STUDIES

Additional studies were conducted to determine the extent and probable technical considerations associated with the use of available engineering materials used in valves. These studies include the following:

1. Materials compatibility with propellants.
2. The effects of vacuum on organic materials.
3. The effects of space radiation on valve materials.
4. The influence of the planetary atmospheres on materials.
5. Machining in a space environment.
6. Wear particle study.
7. Temperature and structural-mechanical effects.

With the information obtained in the studies described above, an analysis was made of the number and severity of the problems that might be expected in the use of valves for aerospace applications. From this analysis, the steps required to advance the state-of-the-art were determined.

NEW DESIGN CONCEPTS

Conduct of the program indicated that an unfulfilled need for a zero leak, contamination insensitive multi-cycle valve existed. While there are many valves available in which the leakage levels are quite low, certain applications for long missions (two years or more) demand that the leakage during this period be limited to that which might be attributed to diffusion. Such leakage may be regarded as being essentially zero. Similarly, valves are available in which the leakage is essentially zero, but these consist of burst type or squib operated valves, which are single actuation devices. Therefore, a prototype valve involving a new concept was produced and subjected to limited testing, and the results indicated that construction of a valve meeting the requirements stated above is feasible.

In brief, the closure of the valve depends upon the fusion of the mating parts of the valve together by the application of heat. Various solders, having a wide range of melting points, may be used in effecting the seal. The limits of the valve with respect to compatibility of the solders and flow media must still be investigated.

Additional experimental work was done in an effort to improve the properties of Teflon with respect to cold flow characteristics and resistance to propellant penetration. Limited test results showed that significant advances in this area are possible.

A study was made of the advantages and disadvantages of installing certain of the spacecraft valves internally instead of externally. Because of the additional protection from the space environments that would be afforded by this approach, it seems that advantages might be gained in some instances.

CONCLUSIONS

1. A need for a zero leakage shutoff valve exists. This valve must be capable of sealing liquid and gaseous fluorine, chlorine trifluoride and pentaborane in addition to the less corrosive bipropellants.

2. A vent valve required to vent the boiloff vapors in a zero gravity field without special design of the storage tanks is an immediate problem.

3. Space maintenance must be considered a major problem as techniques required for maintenance and repair in space are unknown. New design concepts will be necessary for valve component replacements, possibly utilizing "plug-in" modules.

4. Knowledge of the effect of radiation on polymers, lubricants and squibs is not conclusive, nor is the effect of radiation on the sealing properties of polymers known. The combined effect of radiation and propellant degradation on polymers is also unknown.

5. The effects of space vacuum on metal-to-metal seat closures is not fully understood. More information is required to predict the possibility of seizure (cold welding) between the various metals used on spacecraft.

6. No known polymers are compatible with many liquid propellants either for dynamic or static application. This problem could be especially critical for providing a no-leakage closure for many of the ultra-reactive propellants.

7. Valve manufacturers and users are not well informed of the effects on valves subjected to prolonged exposure to the space environments and to high performance propellants.

RECOMMENDATIONS

It is recommended that work be continued or initiated to accomplish the following:

1. Develop a satisfactory zero leakage metal-to-metal valve seat including a reclosure capability. This task may require additional studies to:

   a) Determine the mechanism of leakage in metal-to-metal seats.

   b) Determine the effect of generated and built-in contamination on leakage.

   Work should continue on the no-leakage fusion valve developed under this program.

2. Develop a zero-gravity vent valve capable of venting boil-off vapors without special design of the tank.

3. Study the impact of the space maintenance requirements on valves and consider new design concepts to alleviate repair and maintenance in space.

4. Determine the effects of space radiation on polymers used in valves including the combined effect of radiation and propellant degradation.

5. Determine the degree of cold welding that occurs between metals in sliding or static contact in high vacuum and for valve seats including the effect of the diffusion of the propellants between the seat interfaces.

6. Initiate studies to determine the effect of the various planetary atmospheres on the fatigue properties of metals and the engineering properties of polymers after being exposed to high vacuum and propellants.

7. Sponsorship of a program to apprise the valve industry of the state of the knowledge of the space environments. This work should be directed to the aerospace industry to promote an understanding of the valve problems associated with the space environments.

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I. INTRODUCTION

EARLY HISTORY

The history of valves in the aircraft industry dates back to the earliest airplanes. The valves used on those craft were simple, reliable enough, and few in number. As airplanes were developed, they became more complex and valve requirements became more stringent, which resulted in more complicated components. However, this evolution took place over a long period of time, which permitted an orderly development of the valves in keeping with the development of the aircraft. In the event of a valve malfunction during flight, alternatives were usually available to the pilot: thus, catastrophic failures because of malfunction were few compared with the number of missions carried out.

With the advent of the ICBM, the industry was confronted with vastly different and far more severe requirements. Permissible leakage was reduced, even though more difficult-to-seal media such as helium were being used. Cryogenic propellants used in conjunction with gaseous pressurization systems greatly extended the band of operating temperatures, ranging in some cases from -423° to -300° F. Higher acceleration and vibration levels were encountered, and aerodynamic heating imposed new requirements on designers. Because of the extremely high cost of missiles, great emphasis was placed on reliability to reduce the possibility of failure. Greater efforts were made to reduce weight and power requirements of the components. Thus, it became necessary to develop whole new families of valves and other components to satisfy the critical needs of missiles.

The developments were very costly, and did not preceed at a rapid enough rate to prevent numerous failures of the early missiles. In addition to the in-flight catastrophic failures, preflight failures added tremendously to the expense of the programs and caused serious delays.

A report on malfunctions of airborne valves, regulators, and disconnects covering the period of 1 January to 30 September 1959 showed a total of 431 failures of varying degrees of severity in these three categories alone (Ref. 1). New processes had to be developed to produce the necessary hardware, and on occasion apparently simple problems proved to be major stumbling blocks. Fittings were difficult to seal, especially when used over wide temperature ranges. Removal of contaminants such as oil vapors, water, air, and solids proved to be especially difficult. However, most of the problems were solved, or at least greatly mitigated, through the lavish expenditure of time and money.

Space vehicle requirements imposed an additional increment of performance and reliability upon components. Missile valves were required to operate for a maximum time of five minutes. Space valves were required which could operate for as long as two years and withstand the rigors of high vacuum, radiation, space debris, and temperature extremes. These environments, in general, deteriorate materials; hence functional performance is degraded. The very low pressures of space can cause evaporation and sublimation of materials to the point where the normal function is impaired or destroyed. For instance, liquid lubricants would boil away completely in a short time. The more volatile constituents of elastomers will escape, effecting a complete change in the mechanical properties of materials. Friction coefficients increase with the removal of the gas film that is always present on parts in the earth's atmosphere, and the loss of the electrical insulating properties of air tends to lead to the electric breakdown of insulators.

The effects of radiation on materials in vacuum have not been completely known, and it is known that certain polymers (e.g., Teflon) are adversely affected in the presence of oxygen to the point where its use has been prohibited on some projects.

Space debris has been a subject of much concern, since it can cause deleterious effects on missile performance ranging from total mechanical failure from a puncture to a less severe performance degradation such as upset of thermal balance by erosion of surfaces.

Since temperature extremes may range from near absolute zero to several hundred degrees, it is necessary to have accurate information on the probable temperatures to be encountered and to provide for proper operation of the equipment.

PROGRAM OBJECTIVES

The objectives of the Advanced Valve Technology program are to advance the state-of-the-art of valves used on space vehicle propulsion systems and to define the areas requiring further emphasis. The study was limited to valves used on liquid propellant engines and gaseous attitude control systems. The specific types of valves included in the study are as follows:

a) Liquid propellant flow-metering valves

b) Liquid propellant flow shutoff valves with electrical actuator, pneumatic actuator, and repeatable (6 cycles) squib actuator

c) Liquid propellant vent or relief valves

d) Pneumatic regulators for cold gases

e) Pneumatic regulators for hot gases

f) Liquid propellant fill valves (disconnects)

g) Pneumatic fill valves (disconnects)

PROGRAM PLAN

The steps taken to achieve the program objectives are as follows:

1) Evaluation of the state-of-the-art of the valves listed above

This was accomplished with the aid of the following surveys:

a) Literature Search
b) Patent Search
c) Prime Survey
d) Vendor Survey

2) Determination of the technical problems

The problems associated with valves were determined through the following steps:

a) An extensive study was made of the functional parameters and space environments to determine the nature of the requirements that the valves must meet in space.

b) Additional studies were undertaken to determine the effects of certain of the space environments on the materials used in valves.

c) With the information obtained in steps (a) and (b), a determination of the problems that would be encountered by valves and associated components was made.

3) Solutions to the problems

It was not the intention of this program to solve the problems identified during the program, as such an effort would be far beyond the scope of this contract. However, preliminary efforts were made toward the solution of several of the problems that were considered to be of particular concern.

Reference 1

Boeing Aircraft Company. "Propulsion System Optimization Study", Report No. DGR-TOR-33

II. SURVEYS

The initial efforts to ascertain the present state-of-the-art of spacecraft valves consisted of searches and surveys to determine the extent of existing data and evaluate major areas of concern to help supply the direction for the conduct of the program. These efforts included a literature and patent search, a survey of the manufacturing industry, and interviews with cognizant personnel of the prime contractors. A detailed discussion of this work follows.

LITERATURE SEARCH

A large amount of written material covering almost all conceivable aspects of space exploration and associated art has been produced. The volume is surprising if one considers the actual space age to date from the successful orbiting of the first Sputnik in 1957. The material, which is found in technical journals, in papers presented at the various symposia, in textbooks, and in numerous technical reports, is available from many sources.

Space environment was of primary interest on this program, and information relating to the various space environments, such as vacuum, radiation, meteoroids, and temperatures was obtained. This information was required for determination of the environmental problems that valves would encounter in space. The sources for the information included ASTIA documents, NASA Technical Publication Announcements, and scientific and technical journals, as well as reports in the STL Library.

From this survey sufficient information was extracted and compiled to present a reasonably accurate description of the space environments and their relationships to components used on space vehicles. The information on these environments is to be found in Section III of this report.

PATENT SEARCH

A search was made of the U. S. Patent Files to determine if any new and useful valve concepts not already applied to space vehicles might be discovered. The search was subject to the following limitations:

1) The search was limited to the classes of valves indicated in the original work statement, i.e., flow control, vent, relief, shutoff and disconnects.

2) Patents granted prior to 1945 were excluded.

Copies of approximately 600 patents were reviewed. The patent numbers are tabulated and presented in Table A-1. Each patent was examined to the extent necessary to determine its applicability. That is, a glance at some patents was sufficient to determine that no further attention was warranted. Other patents, however, required closer scrutiny and study. Of the entire list of patents examined, there was one or perhaps two basic ideas that might be of some interest to current valve technology. Because of this low yield of useful ideas, it must be concluded that the time and money could have been more profitably spent in other areas.

Some of the reasons for the low productivity of the patent search are as follows:

1) Age of Patents

   The average time between the filing and granting of letters of patent seems to have been approximately five years. When the time required to conceive and develop a patent to a point where a patent application could be made is added to the five years, it is probable that most of the patents available will predate the space age. While it is realized that the basic idea in a very old patent might be applicable in some ways to space age valve requirements, the probability of making a significant advance through this expensive procedure is not high.

2) Patent Claims

   The primary function of a patent is to protect the

> holder of the patent to the greatest degree possible. For this reason, it is standard practice with patent attorneys to word the claims in a patent in such a vague and general way that the greatest number of possibilities is covered. This verbiage probably serves the purpose of protecting the patent holder, but is certainly not conducive to presenting a concise, clearly understood concept to the reader. The direct result of this practice is that an inordinate amount of time is required to sift useful basic concepts from the welter of words. In a similar search conducted by another contractor on valve subcomponents, the project engineer estimated that it would require ten years to make a complete search and analysis on the one subcomponent area in which he was interested (Ref. 1).

In summarizing the patent search, it may be stated that such a procedure might produce useful results in some cases, but that a search in a general area such as valving will produce returns greatly disproportionate with the time and money expended.

Reference 1 - Rocketdyne, a Division of North American Aviation, Inc., "Poppet and Seat Program, Phase I - Survey Report," R-3819-1, AF04(611)-8392, October 1962.

PRIME MANUFACTURER SURVEY

Interviews were arranged with the cognizant personnel at most of the prime manufacturers' plants for the purpose of determining present and future valve requirements and to determine what current valve problems existed. As an aid to the conduct of the interviews, typical system schematics (Figures 2-1, 2-2) were used in the discussions and the data obtained were tabulated and are presented in Tables 2-1 through 2-6. Blanks on the charts indicate that information on that particular parameter was unavailable, usually because the program was in the early stages, and the detail requirements had not been defined. In addition to the specific requirements that were supplied by the contractors, many general comments of great value were received. In particular, the universal comment that contamination is probably the most severe single problem was instrumental in defining some of the major efforts of this program.

VENDOR SURVEY

The program, as originally conceived, included a proposal to survey the valve manufacturing industry to determine which firms were engaged in this field and then to determine by analysis and test how well the components met space vehicle requirements. Subsequently, it was mutually agreed upon between STL and NASA that such a program could not be completed within the time schedules of the contract. Therefore, the procurement and test portions of this plan were deleted. However, the procedures used and the results obtained in the vendor survey are of interest and are described below.

A list of approximately 500 valve manufacturers was compiled from the various buyers' guides that are printed periodically in trade journals and technical magazines. A form letter, including a questionnaire, was mailed to the manufacturers listed. The questionnaire requested that the recipient note the type of valve or valves that were produced, the type of operator that could be used with it, and the class of service for which the valve was intended, such as high temperature, high pressure, and cryogenic. From this mailing, approximately 320 replies were received, and of this number it is estimated that approximately 250 manufacturers are engaged in manufacturing valves suitable for aerospace applications. The information was coded on cards so that any combination of requirements could be selected to determine who the manufacturers of a particular item are. For example, the manufacturers of regulators for use with low-temperature, corrosive gaseous media and suitable for space application can be identified by isolating those cards that contain the parameters mentioned.

A tabulation showing the number of manufacturers that produce the various types of valves for different services is shown in Table 2-6.

Table A-3 presents a list of manufacturers who responded to the questionnaire. A number was assigned to each manufacturer in the order that the replies were received.

Table A-2 is arranged to permit identification of the vendors that make the various types of valves, and specifies the service or services for which the valve has been designed. The list excludes valves manufactured for other than space use. An example of the use of the table is as follows:

REQUIRED - A disconnect valve, suitable for low temperature corrosive service. Reference to the columns on Table A-2 under DISCONNECT, LOW TEMPERATURE and CORROSIVE SERVICE provides the code numbers of the manufacturers of this equipment. Identification of the vendors is then made through the listing given in Table A-3.

It should be noted that the information presented in Table A-2 was provided by the manufacturers and no attempt has been made to evaluate it for accuracy.

TABLE 2-1 TYPICAL REQUIREMENTS FOR LIQUID BIPROPELLANT SYSTEMS

	ATTITUDE CONTROL & LUNAR LANDING	REACTION CONTROL	PROPOSED SYSTEMS See Figure 2-1		
OXIDIZER	N_2O_4	N_2O_4	*RFNA	N_2O_4	
FUEL	UDMH	Aerozine 50	UDMH	Hydrazine	
FLOW RATE LBS/SEC	.322 to .1	.15	45	0 - 17	
RATIO: $\frac{\text{OXIDIZER}}{\text{FUEL}}$	1.5	2.0	2.0	1.0	
PRESSURANT	He 4800 psi 760 psi	He	He	He	
REGULATED PRESSURANT	660 psi	150 psi	900 psi	400-500 psi	
ENVIRONMENTAL TEMPERATURES	0-145°F 275°F Steril.	-65°F to 300°F	275°F Steril.	Zero	
LEAKAGE	Not Stated	1 cc/day	Zero Essent.	Zero	
RESPONSE (MILLISEC)	30-50	5-10	25 Start 30 Shutdown	10 Close	
RELIABILITY	.9995	.99998	.9995	---	
SERVICE LIFE	72 Hrs in space environ.	7 days in space	---	2 years in space	
TEST LIFE (CYCLES)	---	100,000	---	10,000	
NON-MAGNETIC	Yes	None	---	None	
FILTER (Microns)	5µ	10µ Abs. Liq. 5µ Abs. Gas			

*Note: RFNA is not considered to be an advanced propellant; however, it is included in the listing because the data shown were obtained in the survey. For a list of the propellants considered in this report, see Page 3-2.

TABLE 2-2 TYPICAL REQUIREMENTS FOR SHUTOFF VALVES, LIQUID BIPROPELLENT SYSTEMS

	ATTITUDE CONTROL & LUNAR LANDING	PROPOSED SYSTEMS See Figure 2-1			
OPERATOR	Pneumatic Pilot Control Integral Piston	Pneumatic Pilot He - Solenoid 3-way	Pneumatic 3-way NC Sol Pilot He	Solenoid Type Pulse-Oper.	—
OXIDIZER	*RFNA	N_2O_4	N_2O_4	N_2O_4	Storables
FUEL	UDMH	N_2H_4(Hydrazine)	UDMH	Aerozine 50	Storables
FLOW RATE	45 lb/sec	to 17 lb/sec	.322 lb/sec	.15 lb/sec	1 lb/sec
MIXTURE RATIO: $\frac{\text{OXIDIZER}}{\text{FUEL}}$	2.0	1.0	1.5	2.0	--
UPSTREAM PRESSURE (psi)	900	275(Static) 260(Dynamic)	660(Static)	150	250 to 1500 psi
DOWNSTREAM PRESSURE (psi)	Space Vac.	Space Vac.(Static) 210 (Dynamic)	Space Vac(Static)	Space Vac.	Space Vacuum
TEMPERATURE (°F)	10-90° Running Temp.	-50 to 170	0°-145° 275 Sterilization	-65 to 300	-35 to 150° F
RESPONSE (MILLISEC)	25 Start 30 Shutdown	5 to 10	30-50	5-10	---
LEAKAGE	Zero	1 cc/month	---	1 cc/day System	1 scc/y
NON-MAGNETIC	None	None	Yes	None	---
SERVICE LIFE	1 Restart 2 hrs-30 days shelf	50 with 1 yr. shelf life	1	7 Days in Space	---
TEST LIFE (CYCLES)	100		100	100,000	---
OTHER:			Radiation: Cosmic Ray 1 MR/hr Solar 10^4 Proton/cm^2/sec		---

*See Note on Page 2-7

TABLE 2-3

TYPICAL REQUIREMENTS FOR GAS OPERATED ATTITUDE CONTROL SYSTEMS

	Attitude Control Systems See Figure 2a		Attitude Control Reaction Type 2 System-Low & Hi	Attitude Control System See Figure 2-2
PRESSURANT	He, N_2	He, N_2	N_2	Argon
TANK PRESSURE	2500 to 3250 psi	2500 to 3250 psi	3250 psi	3000 psi
REGULATED PRESSURANT	50 psi	50 psi	Lo 5 psi Hi 35 psi	50 psi
FLOW RATE OR THRUST	≈.09 lb Thrust	.09 lb Thrust	~ .1 lb Thrust ~.002 lb Thrust	.0005 to .004 lb/sec
TEMPERATURE °F	77° Controlled	77° Controlled	-20° to 77°	--
LEAKAGE	30 cc/hr	36 cc/hr	.5 scc/hr Shutoff 2 cc/hr Max. Reg.	.5 scc shutoff
RESPONSE (MILLISEC)	200	75	15	12 Open 15 Close
RELIABILITY	.997	.997	.997	.9965
SERVICE LIFE	6 Mo. to 2 Yrs	3 Yrs	--	1 Yr
TEST LIFE (CYCLES)				
NON-MAGNETIC			---	Yes
FILTER (MICRONS)	5 Nominal	5 Nominal	5 Nominal 12 abs	10 Nominal
OTHER		Radiation: 3.7 rads/hr	Radiation: 3 r/yr	

TABLE 2-4 TYPICAL REQUIREMENTS FOR SHUTOFF VALVES, GAS SYSTEMS

	PROPOSED SYSTEMS (SEE FIGURE 2-2)				
OPERATOR	Integral Coaxial Solenoid Type	Integral Coaxial Solenoid Type			
GAS	N_2, He	N_2, He	N_2	Argon	
UPSTREAM PRESSURE (psi)	35	35	5 and 35	50 $\Delta P = 2.5$ psi	
DOWNSTREAM PRESSURE (psi)	Space Vac. 10^{-5} mmHg	Space Vac. 10^{-5} mmHg	Space Vac.	Space Vac. 10^{-6} mmHg	
FLOW RATE LBS/SEC OR THRUST	≈ .1 lb thr.	≈ .1 lb thr.	≈ .1 lb thr. ≈ .002 lb thr.	.001	
TEMPERATURE (°F)	77	77	--	70	
RESPONSE (MILLISEC)	200	75	15	12 Max Close 15 Max Open	
LEAKAGE	30 cc/hr subsystem	36 cc/hr subsystem	.5 scc/[illegible] across seat	.5 scc	
SERVICE LIFE	To 2 yrs in orbit at 500 nm	3 hrs in orbit	--	--	
TEST LIFE (CYCLES)	--	--	--	500,000	
NON-MAGNETIC	No	No	No	Yes	
OTHERS		Radiation: 3.7 rads/hr	Radiation: .3 r/hr [illegible]		

TABLE 2-5 TYPICAL REQUIREMENTS FOR GAS PRESSURE REGULATORS, VARIOUS SYSTEMS

	ATTITUDE CONTROL See Fig. 2-2	PRESSURIZED GAS FOR LIQUID SYSTEM	ATTITUDE CONTROL	PRESSURIZED GAS FOR LIQUID SYSTEM	
GAS MEDIA	Argon	He, N_2	N_2	He	
UPSTREAM PRESSURE (psi)	4000	3500	3250	4800 to 762	
DOWNSTREAM PRESSURE (psi)	50 Nominal	200 to 300 Lockup <3% of Regulated	5 to 35	600	
FLOW RATE LBS/SEC	.0005 to .004	.15	---	---	
TEMPERATURE (°F)	40 to 115	-35 to 150	---	0 to 145 245 Steril.	
LEAKAGE	2 scc/hr	1 scc/hr N_2	---	---	
SERVICE LIFE	1 Year	--	---	---	
TEST LIFE (CYCLES)	250,000	--	---	---	
NON-MAGNETIC	Yes	--	---	---	
OTHERS:	Teflon is not acceptable material		Radiation: .3 r/hr for 1 year		

Table 2-6 Number Of Manufacturers Producing Valves For Various Services.

Valve Type	Space	High Pressure	High Temperature Application	High Vacuum	Cryogenic	Corrosive Media
Disconnect	32	32	17	10	29	24
Pierce Diaphragm	18	15	11	11	12	15
Regulator	45	62	29	17	33	33
Relief	60	77	48	25	59	46
Vent	39	35	25	22	43	38
Flow Metering	2	1	1	1	--	--
Attitude Control	2	--	--	--	--	--

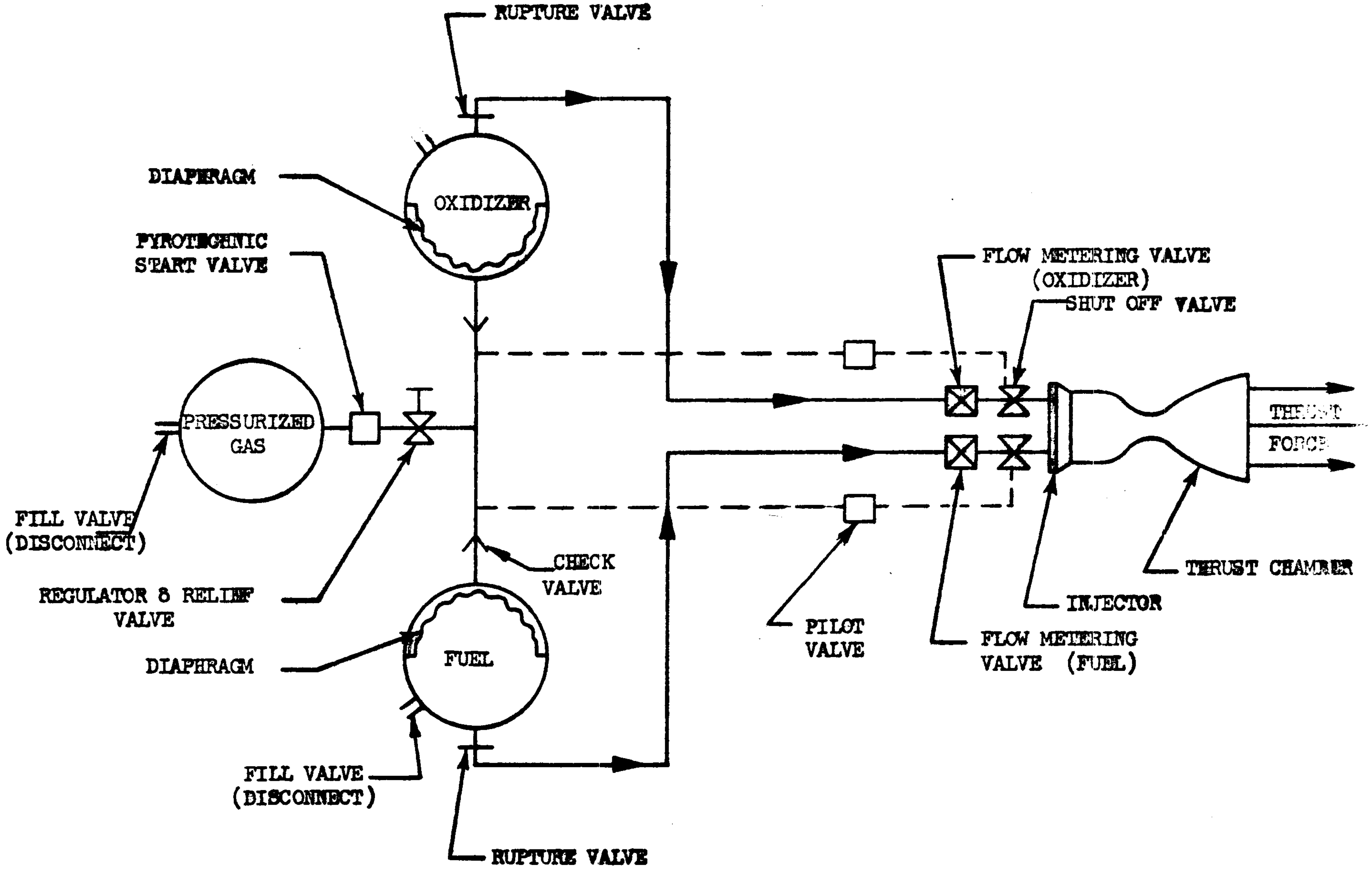


FIGURE 2-1 **TYPICAL BIPROPELLANT PROPULSION SYSTEM FOR SPACE VEHICLE**

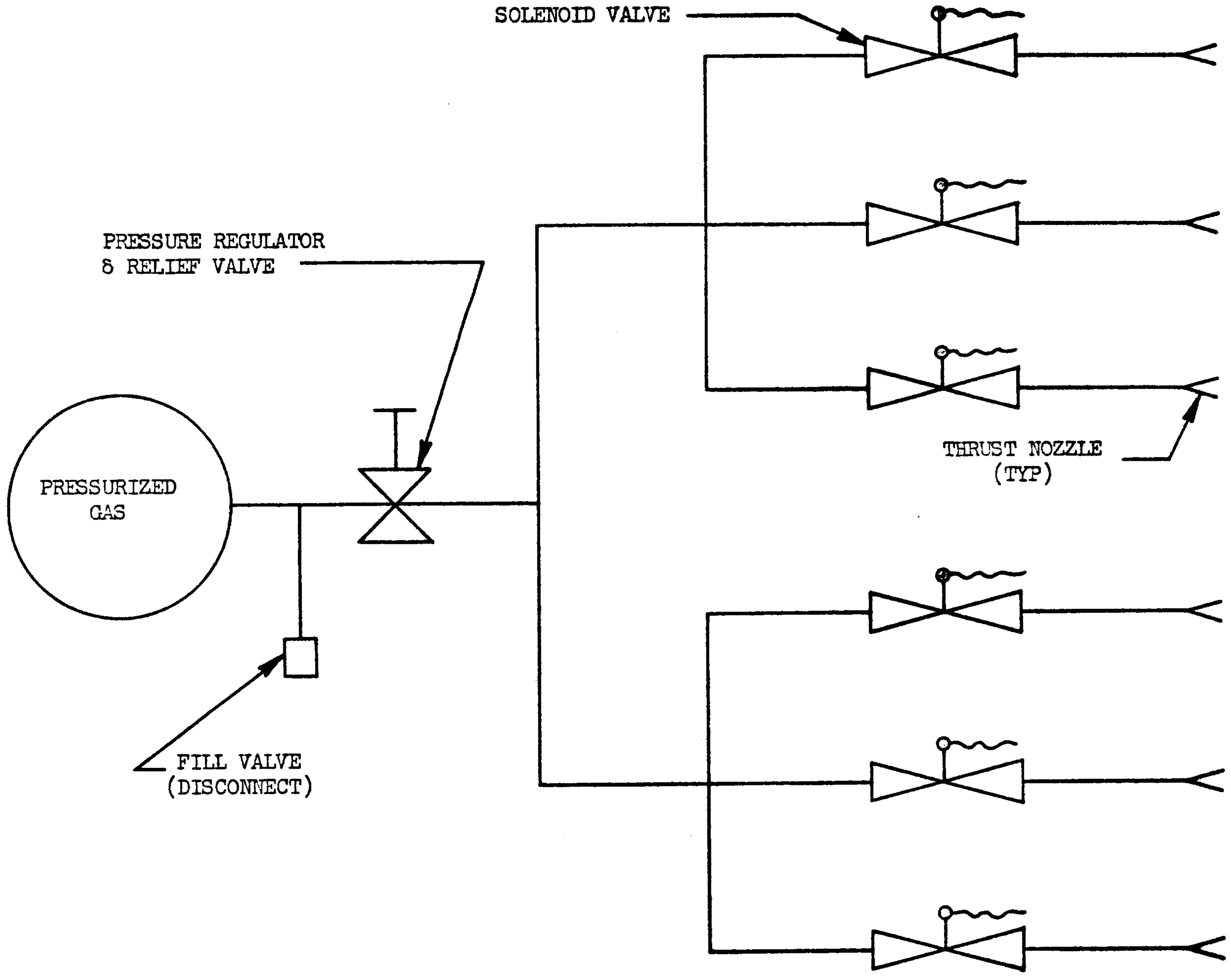


FIGURE 2-2 TYPICAL ATTITUDE CONTROL SYSTEM FOR SPACE VEHICLES

III. FUNCTIONAL PARAMETERS AND SPACE ENVIRONMENT

This section presents the results of a study of the functional parameters and of the space and planetary environments that affect valve operation. The plan used to formulate this study included the following steps:

1. Identification of the parameters
2. Determination of the magnitude of the parameters
3. Discussion of the effects of the parameters on valves

FUNCTIONAL PARAMETERS

FLOW MEDIA

Liquid Media

In most cases a more difficult problem exists with a liquid flow medium than with a gas, usually because of more stringent compatibility problems with the valve materials, especially the seals. Difficulty can arise because of chemical reactions, as in the case of storables, or because of temperature extremes as in the case of cryogenic fluids. The flow media considered in this report include the following:

Nitrogen Tetroxide (N_2O_4)
Unsymmetrical Dimethylhydrazine (UDMH)
Liquid Oxygen (LOX)
Hydrazine (N_2H_4)
Pentaborane (B_5H_9)
Chlorine Trifluoride (ClF_3)
Liquid Fluorine (LF_2)
Aerozine-50 (50% Hydrazine/50% UDMH)
Liquid Hydrogen (H_2)

Purity of liquid flow media must be maintained to avoid problems. This is of special significance in the case of cryogenic fluids that may become contaminated with gases whose melting point is above the temperature of the cryogenic fluid. For example, CO_2 solidifies at -110°F, which is well above the boiling point of LOX at atmospheric pressure (-297°F).

Excess CO_2 in liquid oxygen has been known to clog filters in transfer systems, and if its presence is not suspected will pose a difficult problem for diagnosis, as the filter will appear to be perfectly clean when it is allowed to warm up to permit dismantling for inspection. The same condition could be experienced in a liquid hydrogen system, with the added possibility of having solid air as a contaminant in addition to CO_2.

A detailed discussion of the compatibility of these various liquids with commonly used valve materials is presented in Section IV of this report.

Gaseous Flow Media

Commercial gases commonly used in spacecraft for pressurization and component actuation are hydrogen, helium, nitrogen, oxygen and argon. In addition to these, boiloff vapors from propellants such as N_2O_4 and F_2 may be used, and combustion product gases from engines and squibs find applications. It is essential that the commercial gases be free of contaminants such as fine rust particles because of the erosive effects these particles may have upon component parts in the gas stream, e.g., valve seats. This is especially true of hydrogen and helium because of the very high velocities that are attained under sonic conditions. Normal care in maintaining system cleanliness and use of adequate filters will obviate problems with such particulate contamination. Chemical impurities in the gases, such as water vapor, carbon dioxide and air can create contamination problems that are more difficult to identify and correct. As is the case with liquid flow media, care must be taken to avoid contamination of the gases with traces of other gases, such as air or carbon dioxide. In some space applications gases are cooled in heat exchangers operating at cryogenic temperatures, to facilitate loading and storage. Ice crystals formed from water vapor or CO_2 flakes can interfere with the process by clogging filters and orifices. Significant amounts of contamination can also cause erroneous readings on flow meters that are calibrated on the basis of a pure gas as the flowing medium.

Among the problems peculiar to the individual gases are the following: Hydrogen and helium are extremely difficult to seal and will leak through exceedingly fine openings in threaded connectors, body seals, and valve seats. The erosive effects of these gases on seats in the nearly closed position can be very significant.

Boiloff gases from the various propellants such as N_2O_4 and Fluorine may be both corrosive and toxic, and adequate provisions must be made to insure compatibility of the materials in contact with the vapors and to prevent hazard to personnel. Section IV of this report presents detailed data on fluid compatibility.

Products of combustion contain sizable particulate matter, and the gases may or may not be corrosive. However, devices that normally use these gases, e.g., turbine-driven power supplies, are designed to cope with this type of contamination.

Sterilization

One important consideration in those space vehicles and probes with even a remote possibility of extraterrestrial impact is that of complete biological sterilization. NASA, the Russian Government, and generally, all major international scientific bodies agree as to the requirement for such sterilization (Refs. 1, 2).

Reasons for Sterilization - The arguments may be summarized in this manner. Biology today is fast approaching the time when it may gather direct evidence on the age-old question of the origin of life. Examination of the moon and the nearby planets may tell us whether life in spore form drifted through space, seeding suitable planets upon which it came to rest, or whether life would be expected to arise spontaneously on any world where physical conditions suitable for the emergence of life were maintained for a sufficiently long period for such a development to occur (Refs. 3, 4, 11). The latter theory is the preferred one at this time.

Examination of the moon could help answer some of these questions. It is generally believed that the proper moisture and atmosphere were not maintained on the surface of the moon for a long enough period for life to have arisen there spontaneously (Refs. 5, 11). On the contrary, the moon is thought to have existed for several billion years as an airless, barren body sweeping up the debris of outer space. Organic matter floating through this region would have collected on the moon's surface, being preserved particularly in the cracks and crevices hidden from the activity of the sun. Contaminating its surface with living microorganisms from earth, or even with organic debris from earth, before man has had a chance to examine the "moon dust" for evidence of interstellar organic compounds, could destroy a priceless chance to determine whether or not there is indeed any living organic matter in the dust of interstellar space. Thus it is desirable to avoid contaminating or polluting the moon before such examinations can occur. There is no reason to suppose that all microorganisms would be killed in a hard landing on the moon, or that the survivors would be located relatively near the point of impact, since there is no atmosphere to slow the velocity of particles expelled by the impact.

With Mars, and possibly Venus, another situation exists. To the best of our present knowledge, microorganisms from earth not only might survive on those planetary surfaces, but they might find nutrient there, thrive and multiply. Indeed an experiment has already been performed (Ref. 6) in which bacteria did multiply when introduced into chambers that reproduced what were believed to be the most likely conditions prevailing on Mars. Thus, with these planets, there is concern with the problem of possible infection, as well as pollution (Ref. 11).

Scientists believe from spectroscopic evidence and from the seasonal changes in color of Mars that some form of life, possibly similar to low forms of vegetation on earth, already exists there. If so, there may be the priceless opportunity of conducting the first exobiological experiments, to examine life forms other than those which arose on earth. Caution must be taken, if life is there, that it is not destroyed before it can be studied. To prevent the possibility of such a biological accident it has been stated (Ref. 7) that no probe should be launched toward Mars or Venus if there is as much as a one-in-a-million chance that it will land a viable organism on their surfaces. It has also been pointed out (Ref. 8) that if it is possible that earth forms could infect our neighboring planets, the reverse is also true, and here much more is at stake than the loss of an unparalleled opportunity for scientific investigation (Ref. 11).

If it is granted that it is desirable to prevent contamination, the problem of sterilization arises. The resistance of various life forms to harsh environmental conditions when in a state of suspended animation of anabiosis, has been carefully reviewed by Keilin (Ref. 4) in his Leeuwenhock Lecture before the Royal Society in 1958. The conditions believed to exist in outer space were recently reviewed by Newell (Ref. 9). A comparison of the information in these two documents can lead only to the conclusion, which has been presented before in considerably more detail (Refs. 7, 8) that spores or other forms of life on earth could indeed survive such a journey. Even vegetative microorganisms are much more resistant to adverse effects, such as heat, when dry and in vacua than they are in an earth environment, as shown in the recent experiments of Zamenhoff (Ref.10). Briefly, the penetrating radiations of outer space are not of sufficient intensity to assure sterility. The ultraviolet radiation is intense enough, but is so easily shielded that only organisms uncovered on the surface of the space vehicle would be exposed. Cold, even down to a slight fraction of a degree above absolute zero, has no lethal effect (Ref. 4). Heat is lethal, even if the resistance of organisms in an evacuated dehydrated state is greater than was supposed (Ref. 10), but the temperature within space vehicles is carefully controlled at more or less room temperatures so that instruments will perform satisfactorily. Vacuum has not resulted in a deleterious effect on all microorganisms (Ref. 12). As for the hazards in landing on an extraterrestrial body, the momentary heat and pressure of a high-velocity landing on a hard surface should not exceed those achieved for brief fractions of a second in explosions, which bacteria have survived, nor can it be assumed that the atmosphere of Mars or Venus will consume a space vehicle coming in at a high speed, as micro-meteorites are heated and consumed in earth's atmosphere. In short, only by seeing that the space vehicles are sterile as they leave earth can it be assured that living earth forms will not be transported to other celestial bodies.

Methods of Sterilization - The possible methods of sterilization include heat, chemical, and radiation. In choosing the optimum method one must consider the materials of construction, the methods of fabrication and assembly, and the handling necessary following fabrication and assembly.

The presently accepted heat sterilization methods consist of soaking the components, subassemblies, or perhaps the entire vehicle at temperatures of 125°C (257°F) to 132°C (270°F) from 24 to 36 hours (Ref. 13). Jet Propulsion Laboratories Mariner B and Hughes Aircraft Company Surveyor both utilize such a schedule. The principal advantage of heat is its ability to permeate hermetic seals, container walls, and encapsulated components or assemblies. This allows sterilization of commercial components such as valves, actuators, motors, solenoids, capacitors, resistors, and transformers. It has been demonstrated that such components are not internally sterile and could be a source of extraterrestrial contamination should they fracture upon impact. Other advantages of heat sterilization are the absence of personnel hazards and the availability of the necessary facilities and technology.

Disadvantages of the heat sterilization method include the degradation in performance and reliability of valves, some electronic components and assemblies, materials, propellants, and pressurized propellant storage systems. Data are currently available describing time-temperature effects on the physical properties of most materials and components; consequently further discussion is omitted. An additional disadvantage, and one less susceptible to solution, arises from the difficulties that would be incurred in sterilizing cryogenic propellants, e.g., liquid oxygen and liquid hydrogen. Bacteria and spores are not killed by cryogenic temperatures, and as it may be possible to impact the earth's moon with residual propellants on board, contamination of the moon could result. Producing sterile cryogenic propellants would require extra steps in the manufacturing process (e.g., heating the gas in a sterilizing heat exchanger prior to liquefaction). Such a process would be difficult and expensive, at best; perhaps impossible in the case of liquid hydrogen. If sterilization of the vehicle is to be effective, a means must be found to sterilize those cryogenic propellants in which bacteria and spores could survive.

The effectiveness of chemical sterilizers is limited in that they must contact the surfaces to be sterilized. This rules out their usage in sterilizing hermetically sealed components, valves or subassemblies as well as in cases of bulk contamination of a solid such as encapsulated electronic modules where heat may be the only effective sterilizer. Of the chemicals, gaseous sterilizers, such as ethylene oxide mixtures, readily lend themselves to surface sterilization (Refs. 14, 15, 16).

The ease of handling, storage, applications, and above all the ability to sterilize a probe or a spacecraft mounted on the booster vehicle immediately prior to launch are among the advantages of a gaseous sterilizer. Compatibility of ethylene oxide mixtures with most materials and components (Ref. 17) has led to its general acceptance. Typical compatibility data for various engineering materials as reported in reference 17 are shown in Tables 3-1 through 3-5.

Further work will indicate whether all engineering materials are as negligibly affected as those tested to date.

The use of hard radiation as a sterilizer is limited currently due to the radiation sensitivity of various materials and components as well as the handling and facilities requirements (Ref. 1).

Applying the previous discussion to a propulsion system, it is evident that a combination of sterilization techniques would be necessary. These sterilization techniques would impose certain design requirements.

Three alternative methods exist for insuring sterilization of a complete propulsion system including the associated valving. These are:

1. Terminal heat sterilization of a complete system without fuel and oxidizer, which were added subsequently under aseptic conditions.
2. Terminal heat sterilization of a completely fueled system.
3. Subassembly sterilization using various techniques and subsequent assembly and propellant loading under aseptic conditions.

In the first two cases, while valves, with the possible exception of squibs, do not pose any unusual problems outside of insuring the valves can withstand a heat sterilization cycle, the following problem areas exist:

1. <u>For liquid propellant systems:</u>
    a. Insuring that no leaks occur due to differential expansion at sealing points and valves.
    b. Venting the increased tank pressure due to the increased temperature during sterilization or over-designing the tankage to accommodate this increase. Both methods impose a payload penalty.
    c. Accounting for the decrease in the strength of the structural materials at the higher temperature.
2. <u>For solid propellant systems:</u>
    a. The state-of-the-art solid propellants cannot physically withstand the sterilization heating

requirements, and the long-term requirements for bringing the internal portion of the grain up to temperature compound this problem.

b. Stresses caused by heating the solid propellant grain can cause physical rupture.

c. Problems arise in the reliability of case bonding.

d. The high temperature storage period aggravates propellant degradation following heating.

e. Propellants which can possibly be heat-sterilized have performance characteristics lower than the best state-of-the-art propellants.

The third method of sterilization of a propellant system, involving the sterilization of subassemblies and final assembly under aseptic conditions, requires the sterilization, by heat, of all the subassemblies or components with surfaces not accessible to a chemical sterilizer. Those components such as flared tubing, nuts and bolts in which before assembly all surfaces are exposed and are internally aseptic, may be sterilized by either heat or chemical sterilizers. Storage and final assembly procedures must be devised to insure the maintenance of these aseptic conditions until the assembly is hermetically sealed to prevent internal recontamination.

After installation of the system in the space vehicle, surface resterilization may be effected by the use of a gaseous sterilizer such as ethylene oxide.

Certainly separate sterilization of subsystems with subsequent sterile assembly implies more complicated ground equipment and ground operations than does terminal sterilization. However, the reliability and performance to be gained by the use of highly developed propulsion systems and propellants makes the former method worthy of strong consideration.

REFERENCES - STERILIZATION

1. Development of International Efforts to Avoid Contamination of Extraterrestrial Bodies, Science, V. 128, 887-889, 1958.

2. Contamination of Extraterrestrial Exploration, Nature 183, 925-928, 1959.

3. Lederberg, J. and Cowie, D.B. "Moondust", Science 127, 1473-1475, 1958.

4. Keilin, D. The Leeuwenhock Lecture. The Problem of Anabiosis or Latent Life: History and Current Concept. Proc. of Royal Society 150, 149-191, 1959.

5. Firsoff, V.A. "Strange World of the Moon", Basic Book, New York, 1959.

6. Davis, I. and Fulton, J.D. "Microbolic Studies on Ecologic Considerations of the Martian Environment". Aeromedical Reviews. Review 2-60. School of Aviation Med., USAF, Brooks AF Base, Texas, 1959.

7. Daview, R. W. and Communtizis, M.G. "The Sterilization of Space Vehicles to Prevent Extraterrestrial Biological Contamination". Tenth International Astronautics Congress, London. (External Publication No. 698, Jet Propulsion Laboratory, Pasadena, California) 1959.

8. Lederberg, J. "Exobiology - Experimental Approaches to Life Beyond the Earth". Proc. First International Space Science Symposium (13 January 1960) Nice, France. In Press.

9. Newell, H. E. "The Space Environment". Science 13, 385-390. 1960.

10. Zamenhof, S. "Effects of Heating Dry Bacteria and Spores on Their Phenotype and Genotype". Proc. National Academy Science 46, 101-105, 1960.

11. Phillips, C.R., Hoffman, R.K. "New Practical Developments in Gaseous Disinfectants". Society of American Bacteriologists. 4 May 1960.

12. Personal Communication with Hughes Aircraft Company. 2 January 1963.

13. Personal Communication with Rolf Hastrup of JPL. 3 January 1963.

REFERENCES - STERILIZATION

14. Phillips, C. R. Gaseous Sterilization. In "Antiseptics, Disinfectants, Fungicides and Sterilization". Edited by G. F. Reddish, Lea and Febiger, Philadelphia, Penn. 1957.

15. Phillips, C. R. and Warshowsky, B. "Chemical Disinfectants". Ann Rev. Microbiol. 12, 525-550, 1958.

16. Schley, D. G., Hoffman, R. K., and Phillips, C. R. "Simple Improvised Chambers for Gas Sterilization with Ethylene Oxide". Applied Microbiol, 8, 15-19. 1960.

17. Willard, M., Entreken, V. K., and Alexander, A., Hughes Research Studies RS 277, RS 283, RS 292, RS 293 Surveyor Sterilization Parts 1 to 4, 1962.

Elastomer	% Weight Change	% Volume Change	Hardness Shore "A"		Tensile Strength, psi			Ultimate Elongation		
			Unexposed	Exposed	Unexposed	Exposed	%Δ	Unexposed	Exposed	%Δ
Neoprene, Parco 363-70	0.00	+0.02	68	70	1583	1324	-16.4	313	251	-19.8
LS-53, TH1057	-0.09	-0.48	66	67	841	691	-17.8	105	86	-18.4
Buna N, Precision 758-70	+0.21	+0.33	not measured	not measured	1142	1133	- 0.7	272	234	-13.9
Viton A	+0.1	+0.5	-	-	2467	2267	- 8.1	137	137	0
AMS 3302 Silicone Rubber	-0.08	-	-	-	-	-	-	-	-	-

Table 3-1 - **Properties of Elastomers Exposed to 12% Ethylene Oxide - 88% Freon 12 for 24 Hours**

Lexan		
%Weight change		+3.3
Elastic Modulus,	Control	3.81×10^5 psi
	Exposed specimens	3.61×10^5 psi
Kel F		
%Weight change		0.0
%Volume change		-0.1
Hardness, Shore D	Control	81
	Exposed specimens	79
DC 4 Silicon Grease		
%Weight change		-0.37%

Table 3-2 - Properties of Lexan and Kel F and DC 4 Grease Exposed to 12% Ethylene Oxide-88% Freon 12 for 24 Hours

Resin System	% Weight Change	% Volume Change	Insulation Resistance, ohms		Dielectric Constant		Dissipation Factor	
			Unexposed	Exposed	Unexposed	Exposed	Unexposed	Exposed
Stycast 1090	-0.07	-0.25	2×10^{11}	2×10^{11}	4.21	4.23	0.0438	0.0438
Epon 826, anhydride cured	-	-	$>10^{12}$	$>10^{12}$	3.46	3.50	0.0042	0.0036
Epon 826, amine cured	-	-	5×10^{11}	$>10^{12}$	4.38	4.39	0.0010	0.0089
Epon 828, anhydride cured	-	-	$>10^{12}$	$>10^{12}$	3.37	3.39	0.0044	0.0046
Epon 828, amine cured	-	-	$>10^{12}$	$>10^{12}$	4.30	4.29	0.0098	0.0096
DC 881	-0.2	-0.2	22×10^{11}	15×10^{11}	2.97	3.32	.102	.101

Table 3-3 - **Properties of Potting and Encapsulating Resins Exposed to 12% Ethylene Oxide-88% Freon 12 for 24 Hours**

Specimen	Insulation Resistance After 96 Hours at 90-95% Relative Humidity, MΩ	
	Before Exposure	After Exposure
Copper Clad Epoxy Glass Laminate	$> 1 \times 10^6$ $> 1 \times 10^6$	1×10^6 1×10^6
Copper Clad Phenolic Paper Laminate	1×10^5 1×10^5	1×10^6 6×10^5

Table 3-4 - Insulation Resistance of Phenolic and Epoxy Copper Clad Test Comb Patterns Exposed to 12% Ethylene Oxide - 88% Freon 12 for 24 Hours.

Specimen	Weight Change mg/cm^2	Film Adhesion Test	
		Unexposed	Exposed
MIL-A-8625, Type I Anodized Al	+0.01	-	-
MIL-A-8625, Type II Anodized Al	+0.04	-	-
Molybdenum disulfide lubricant on MIL-A-8625, Type I anodized Al	0.00	No removal of film	No removal of film
Molybdenum disulfide lubricant on MIL-A-8625, Type II anodized Al	-0.06	No removal of film	No removal of film
AZ 31 B Magnesium	+0.01	-	-
DOW 17 lite on AZ 31B Magnesium	0.00	-	-
DOW 17 heavy on AZ 31B Magnesium	+0.01	-	-
DU lead teflon coating on steel	0.00	No removal of coating	No removal of coating
Rokide on 321 CRES	+0.02	-	-
Rokide on Molybdenum	-0.03	-	-

Table 3-5 - Effect of Exposure to 12% Ethylene Oxide-88% Freon 12 for 24 Hours on Metals and Metal Coatings.

OPERATING TEMPERATURES

The operating temperatures discussed under this heading refer to the temperatures of the flowing media and are considered independently of temperature effects from space environments. The latter are discussed in this section under the heading "Temperature in Space."

Cryogenic Temperatures (-300°F to -423°F)

Values of boiling points (measured at standard pressure) for gases used in spacecraft are as follows:

Helium	- 423°F	N_2	-320°F
Argon	- 302°F	O_2	-297°F
H_2	- 423°F	F_2	-306°F

The effects of cryogenic temperatures on valves and valve materials may be summarized as follows:

a. Dimensional changes in subcomponents, such as seats and seals.

b. Greatly increased viscosity in lubricants with conventional lubricants reaching the solid state.

c. Change in the structural properties of materials with some properties being enhanced and some being degraded.

d. Contamination resulting from the solidification of gases. Carbon dioxide solidifies at -110°F, and air or nitrogen becomes solid at approximately -350°F.

Moderate Temperatures (-100°F to + 400°F)

If devices such as gas generators are excluded from consideration, the temperature range of the various flow media encountered on spacecraft using storable propellants may vary from approximately -100°F to + 400°F. These flow media include pressurant gases which may be heated by engine exhaust to obtain an increase in the specific volume, which serves to reduce the weight of gas required for pressurizing applications.

Valves have been in operation in missile applications for several years in which temperature ranges of -423°F +450°F have been successfully employed. Because of the extensive development work that has been accomplished in this field, valves operating at these temperatures are within the state-of-the-art.

High Temperature (400° - 2000°F)

Requirements for valves to operate in the range of 400°F to 2000°F arise from the use of products of combustion, obtained either from rocket engine exhaust or from gas generators that burn fuels for the purpose of generating hot gases. The gases may be used to operate mechanical devices such as pumps or may be used as tank pressurants in fluid transfer systems.

The effects produced by these hot gases vary with the materials that are being used and with the duration of the exposure. The significant effects are as follows:

1) Reduction strength All metals experience a reduction in strength as the temperature is varied. Additional material must therefore be provided for operation at high temperature, thus incurring a weight penalty.
2) Changes in dimension Extreme changes in temperature can cause relatively large changes in dimensions, which may be critical for a given part. If severe gradients exist across the valve, seizure of movable parts can occur because of differential expansion.
3) Erosion and Corrosion Rocket exhaust and gases produced by generators may contain large quantities of particulate contaminants. These contaminants, in conjunction with gases that may be corrosive in nature, can produce severe erosion on surfaces on which they impinge.

OPERATING PRESSURE (INTERNAL)

The internal pressure at which a valve is required to operate will govern several aspects of the design of a given component, for example, the types of seals to be used and the structural strength of the housing. When the pressure is sufficiently high to require significant actuating forces, a balanced poppet design may be required. In addition to internal pressure, external or ambient pressure must be considered if the valve or system is to be operated in atmospheres such as those of Venus or Jupiter. The atmosphere of Venus is estimated to be 16 earth atmospheres, and that of Jupiter is estimated to be as high as several thousand psi. For these operating conditions the initial system pressure would have to be higher by the increment of the planetary ambient pressure to permit overboard discharge of a gas, as is done with an altitude control valve. In the event that system pressure is depleted prior to entry into a high-pressure planetary atmosphere, the structural design of the tanks, valves, tubing, etc. would have to be such that components would not be collapsed because of the high external ambient pressure. Care must be taken to insure that seals used on the various components are effective in both directions of pressure application if seepage of planetary atmosphere into any part of the system would be objectionable.

Gas pressures of 300 to 600 psia are normally required for a gas-pressure-fed system. These pressures are determined by the thrust-chamber pressure and the propellant feed line drops. For a turbopump fed system gas pressures as low as 25 to 85 psia are usually required. Typical requirements taken from Table 2-1 indicate pressurants up to 4800 psi regulated from 150 to 660 psi for pressurizing the liquid propellants. From Table 2-3 tank pressures as high as 3250 psi regulated from 5 to 50 psi are given for attitude control systems.

WEIGHT

Until recently, direct component, development and manufacturing costs of the missile and space programs have been considered to be of secondary importance, with the mission success as the dominant factor controlling design and manufacture.

One method of increasing the useful payload per given launch vehicle for equivalent launch cost is by reducing the weight of the components in a payload, such as valves, lines, brackets, flanges, fittings, etc. A subcontractor may have little or no incentive or direction for an extra and costly machining process if the process reduces weight but does not affect system performance or reliability. This fact is borne out on several current space payloads which had intensive "weight economy drives." These drives have resulted in substantial weight reduction. It is believed, however, that there should be improved weight/cost criteria applied in designing and manufacturing spacecraft components in the early phases of the program. A simple criterion is difficult to obtain because of the myriad space payloads and boosters. Currently most payloads are designed and mated to a specific booster for a specific mission. Therefore, in this case if a payload is not overweight, no additional expenditure in effort or money is made to decrease unnecessary weight. On the other hand, if the payload is too heavy for a mission, a weight reduction analysis is made, usually at great cost of engineering time. In the future, however, designers must have a greater awareness of the importance of weight early in the design, and also some rule by which funds and effort should be expended in minimizing weight.

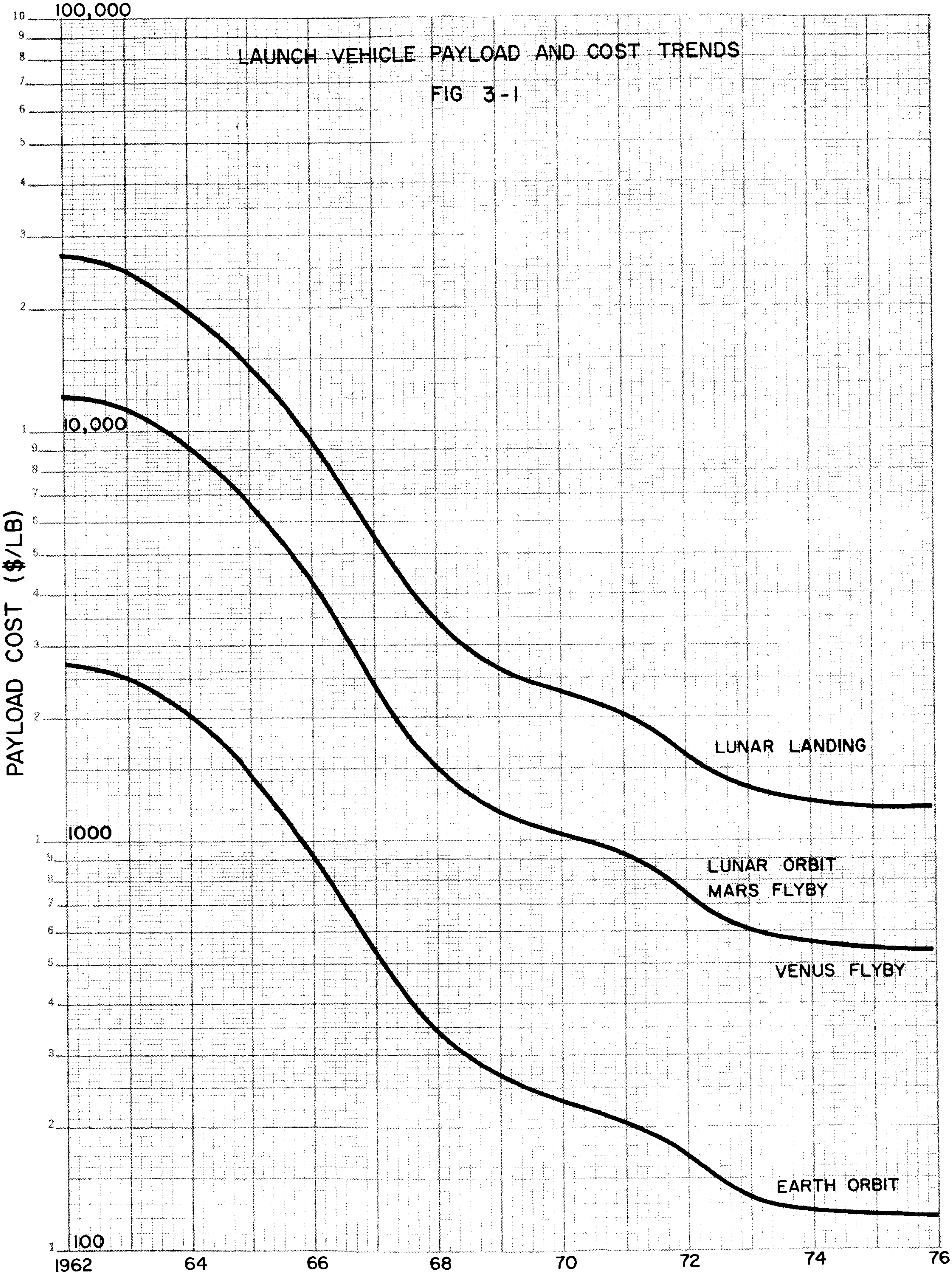
One attempt to provide a basis for the design and manufacture of subcomponents on space payloads is presented in this study. Figure 3-1 graphs the current and projected launch vehicle costs on the basis of dollars per pound of payload for five space missions: earth orbit, lunar orbit, lunar landing, Venus flyby and Mars flyby. For example, if an engineer designing a gas regulator or valve for an earth-orbited satellite which is to be launched in 1968 or 1970 could, by an additional machining process, reduce the valve weight by one pound, the additional machining process would be worth approximately $150 to $200 because this is the additional launch vehicle cost to place that amount of material into orbit.

Similarly, if the payload were placed into lunar orbit or a Venus or Mars flyby, then this same machining process would be worth approximately $800 to $1000. This method of optimizing the space program payload to cost ratio would be of doubtful value if applied to only one or two satellites; however, when applied and used by all designers throughout the space industry, the effect can become significant.

Reference:
H. H. Koelle. "Missiles and Space Systems - 1962," Astronautics, Vol. 7, No. 11, November 1962.

LAUNCH VEHICLE PAYLOAD AND COST TRENDS

FIG 3-1



POWER REQUIREMENTS

Present sources of power available for operation of components include the following:

1) Batteries and Fuel Cells
2) Solar Cells
3) Compressed Gas
4) Hydraulic Accumulators
    a) Liquid gas combination
    b) Liquid compressibility devices
5) Mechanical Springs
6) Chemical devices (Gas generators and squibs)

Each source of power has its advantages and limitations, and the choice of system depends upon the specific requirements. Batteries have a relatively short life, do not operate well at low temperature or under heavy loads, and are essentially low-voltage devices. Solar cells depend upon constant input from the sun and thus are used in conjunction with batteries to provide power during periods in which the spacecraft is in the shade. Power from a solar cell is expensive--approximately $100 per watt (Ref. 1, pages 61-68). A system to provide a kilowatt of power with a combination of solar cell and battery will weigh approximately 700 lbs.

A limited amount of energy may be stored in pressure vessels as compressed gas, or a combination of gas and liquid can be used, as in a conventional hydraulic accumulator. Cocked mechanical or liquid springs may also be used as a source of energy. Finally, chemical devices such as squibs are useful for some applications.

Efforts are required to determine means of reducing electrical power requirements for spacecraft applications. It is quite probable that improvements could be obtained in the efficiency of solenoid actuators by taking measures that are available but not generally considered because of the added cost that would be incurred. However, as is shown in the section on weight (page 3-20), it may be well worthwhile to pay more for a lighter component through additional machining steps to reduce the total payload weight, as the extra cost of the machining may be insignificant compared to launch costs per pound of the total system. Therefore, a reduction in total power requirements, which would result in a reduction in weight through use of lighter equipment, appears to have a very attractive potential. Specific areas to be investigated include the following:

Electrical and Magnetic

a) Use of silver or aluminum wire
b) Use of higher permeability material in flux path
c) Variation in coil shape, wire shape, flux path size
d) Improvement of insulation - reduction of bulk

General

Care in specifying the operating temperature is required to achieve optimum efficiency and lowest weight. Military specification values should not be used if the temperature range of the specification is greatly different than the expected operating range of the actuator. For example, a specification requiring a range of -65°F to 160°F will impose a needless weight requirement if the actual operating temperature will be significantly below the upper limit of 160°F, because a smaller unit can be constructed for a given force requirement if the operating temperature is reduced.

Reference 1
R. W. Buchheim and the Staff of The Rand Corporation, Space Handbook Astronautics and its Applications, Random House, New York, 1959

Leakage

Leakage is a primary problem in most valves, and a difficult one to solve. Soft seats give better leakage control than hard seats where fluid compatibility and temperature limits are suitable, but hard seats must be used in cases where fluid media and operating temperature would cause problems.

The detrimental effects associated with leakage include the following:

1. Loss of propellants and pressurants
2. Corrosive effect on materials
3. Interference with experiments
4. Fire and explosion hazard
5. Toxic properties of propellants

The loss of propellants may or may not be a serious problem, depending upon the system and mission duration. For example, a leakage of 1 cc/day at 20°C of N_2O_4 would equal 2.3 lbs in two years. For a vehicle with a relatively large amount of N_2O_4 stored initially, this loss may not be significant. For a lunar mission of a few days' duration the loss of the propellant may not be a serious problem; however, for a Mars fly-by, the loss could be intolerable.

The corrosive effects resulting from propellant loss may be a more severe problem than would be the reduction in total thrust. A significant leak could envelop components within the spacecraft with corrosive vapors and cause failure of the mission. Such an envelope could cause interference with experiments and perhaps degrade materials and equipment. For manned missions and ground handling, possible danger from toxic vapors would have to be considered.

In addition to macroscopic leakage, seepage permitted by permeability of materials must be considered. Bell Aerosystems (Ref. 1) give permeability data for Teflon TFE 7 and Teflon FEP with nitrogen tetroxide as follows:

Specimen	Thickness Mils	Density $82^{\circ}F$ (gm/cc)	Transmission Rate -- Air	N_2O_4 (cc/100 $in.^2$ per 24 hr)
TFE 7	10.0	2.186	20.0	275.9
FEP	10.6	2.138	30.0	81.8

Additional work on permeability is being conducted by the Stanford Research Institute under NASA Contract NAS 7-105.

Establishment of a tolerable leak rate is dependent upon two factors:

1. Weight penalty incurred because of the necessity of larger tankage and additional propellant to offset the loss
2. Detrimental effects to personnel or materials

Criteria for (1) is readily established. However, more information is required to determine the effects on materials and personnel from vapors of varying concentration in the vacuum of space.

Leakage requirements for unmanned missions, obtained from interviews with the prime manufacturers, are tabulated in Tables 2-1 through 2-5. Requirements varied from 1 cc/day to zero for N_2O_4 and from 30 cc/hr to 0.5 cc/hr for gases. In the cases where "no leakage" is stated, it is not known precisely what this means because of the lack of an accepted definition for this term.

Reference 1 - Bell Aerosystems Status Report AFBSD TDR-62-6

OPERATING LIFE

Operating life can vary from one cycle for a pierce diaphragm valve to many hundreds of thousands of cycles for a properly designed solenoid valve. Many factors and combinations of factors affect the life expectancy of a valve, among which are operating temperature, operating pressure, rate of cycling, number of cycles, loads on members, materials of construction, and exposure to space environments.

Pressure will govern seat loads required, and operating temperature in the higher ranges has a very direct bearing on the life of the valve. The rate of cycling may be important if the temperature rise as a result of the operation becomes significant. As with any piece of mechanical equipment, the higher the structural loads, the shorter the life.

Exposure to the space environments will tend to shorten the life of valves because of the deleterious effects of vacuum, radiation and erosion from space debris. The degree to which this occurs depends upon the design of the valve and the location and length of time in the environment.

The survey of prime manufacturers indicated life requirements varying from several hours in the space environment and one cycle of operation to three years in space and 500,000 cycles. The requirements for a particular application must be carefully analyzed and the appropriate compromises or "trade offs" must be made to permit specification of an optimum life requirement for a component.

Contamination

There are normally two sources of contamination, "built-in" and system generated. The built-in contamination is caused during the manufacture and handling of the parts and at installation of the components in the system. Also, contamination may be introduced by the propellants and pressurants. Generated contamination is contamination created within the system, and is caused by wear and chemical action of the propellants on the materials. Also, freezing of small amounts of water or other constituents mixed with the propellants can cause serious problems. Internal spalling which results from meteoroid impact can also be a source of contamination.

Filters are normally used to protect the mechanical function of the valve from contamination and are usually found in the line and sometimes in the valve itself. Filters, however, can be a contamination source in that the filter industry has not yet solved the problem of producing a clean filter. Also, filters cannot protect the moving parts from the wear particles created by the parts. The valve seats themselves will contain wear particles created by bearings, actuators, etc. upstream of the seats. Three separate, extensive test programs have recently been conducted on filters of various types. In one program conducted by STL for the Air Force at a commercial laboratory, filters of sixteen separate manufacturers were tested and evaluated. The filters ranged in size from small airborne hydraulic filters to 12" line size filters used in propellant loading systems. In general, the filters were examined for initial cleanliness, bubble point, cleanliness after vibration, differential pressure and rated flow, filtration efficiency and dirt-holding capacity. A similar but completely separate test was conducted by the Army Corps of Engineers, and a third test was conducted by the Materials Section of the Structures and Mechanics Laboratory, Marshall Space Flight Center at Huntsville, Alabama. A remarkable agreement among these three separate test programs was obtained at one point in particular, e.g., the initial cleanliness of the filters in the as-received condition. The essence of the test results with regard to this point is this: almost all of the filters contained built-in dirt or contamination particles that were greatly in excess of the absolute rating of the filter. This dirt is a result of a general disregard among the manufacturers for even elementary care with respect to cleanliness during the manufacturing process. While the reports of these tests that have been recently issued have been very critical of the filtration industry's product and may be expected to initiate reforms, it must be recognized that considerable time will elapse in the normal course of events before corrective action is taken. It is necessary, therefore, to be aware of the fact that it is possible for a filter to be a contaminant generator and thus defeat the very purpose for which the filter was installed. Cognizant personnel should also be aware of a recently approved SAE document, ARP 599, which defines the various procedures in cleaning and inspecting filters.

Wear particles are products of adhesive wear and are discussed in this report under Wear Particle Study. Much work has been done on the determination of wear particle size under atmospheric conditions at room temperature and without lubrication. Lubricated surfaces or surfaces exposed to various gaseous atmospheres will produce smaller wear particles. At present no information is available on wear particles produced in a vacuum, but it is estimated that the wear particle size would not be greater than two times the wear particle produced in atmosphere. Materials in contact and their generated wear particle sizes are given in Section IV under the Wear Particle Study.

SPACE MAINTENANCE

Maintenance and repair of both manned and unmanned spacecraft is a requirement that will demand new designs, techniques, and procedures. Periodic service of communication and other unmanned satellites is envisioned, in which rendezvous and docking techniques would be employed to permit personnel to effect the necessary maintenance or repair. Inflight maintenance will be necessary during interplanetary space travel or in orbiting space stations. Repairs of a major nature may be required of vehicles that have landed on the moon or other celestial body.

Conventional threaded tubing fittings may not be satisfactory in systems where replacement of components may be probable, because of the possibility of cold welding. Means of joining tubing to components and tubing to tubing must be devised that will permit uncoupling of fittings under the numerous handicaps imposed by the space environment. A weightless environment imposes unusual difficulties on an astronaut who is attempting to exert a torque on a fitting in that the man will tend to rotate about the fitting unless he is anchored in some manner to the surrounding structure. Space clothing, required because of the vacuum conditions, is bulky and cumbersome and thus not conducive to performing mechanical tasks that would be simple routine on earth. Validation of the repair by a component on system check will require ingenious test procedures and equipment.

Conventional shop processes, e.g., filing, drilling, sawing, gas welding, and brazing may require modifications to varying degrees of space applications. The effects of vacuum on such operations as filing, sawing, and drilling are not well understood. Some preliminary drilling tests were conducted on this program, and the results of that work are presented in Section IV.

Gas welding and brazing techniques may require attention because of a combination of effects of vacuum and zero gravity. Lack of atmospheric pressure may significantly alter the size and shape of the flame, which may require resizing or redesign of the tips for a given task.

Special problems in maintenance may be encountered on the various planets and these problems may differ from those encountered in interplanetary space. For instance, the problems caused by maneuvering in a zero gravity field would be mitigated on the moon and Mars because of the existence of gravity fields on these bodies. The atmosphere of the moon is essentially the same as that of interplanetary space. However, the atmosphere of Mars is presumed to be 90% nitrogen and 5% carbon dioxide at 0.1 earth's atmospheric pressure. This atmosphere may conceivably pose maintenance problems that differ from those encountered in space or on the moon.

One possible problem that might be encountered on either the planets or in space is that of igniting a gas torch in the absence of oxygen, as conventional lighters, e.g., flints and matches, depend on oxygen for operation. A possible solution to this problem might be an electrically heated wire. This, and other potential problems, will require further investigation.

RESPONSE

The response time of a solenoid valve is affected by the following variables:

1) Mass of moving parts
2) Pressure differential
3) Armature travel
4) Coil winding
5) Applied current
6) Friction of moving parts

An examination of the above variables suggests that a requirement for a higher response than is actually necessary will incur penalties in cost and weight, as the size of the coil and the power required to operate it is related to the time required to open or close the valve.

It should be further noted that associated with high response are high seat and poppet loads, as a suddenly applied load will produce a much higher stress than if the load had been applied gradually. A valve having a higher poppet velocity will incur high seat stresses which tend to reduce the life expectancy of the unit.

Modulating Valves

The speed with which a modulating valve can respond to a signal will be governed by actuator force available, mass of moving parts, spring force, friction forces, and forces due to dynamic effects of the flowing medium.

In addition to these factors, the signal transport time must be included in the case of a valve having pneumatic actuation if the sensing point is remote from the valve and the signal is transmitted by pneumatic lines.

The response of a regulator or a vent valve must be sufficiently fast to compensate for the most rapid change that could occur in the system. Normally, a vent or regulator valve is subjected to relatively slow changes in demand. However, at the instant of application of inlet pressure to a regulator, a high speed transient may be imposed, especially if the downstream ullage is very small. Similarly, a vent valve could be subjected to a transient condition if a sudden application of pressure could be effected in a small ullage. The response of the valves would therefore have to be equal to the rise time of these pressure applications.

Typical response requirements taken from Tables 2-2 and 2-4 are 5 to 50 milliseconds for liquid bipropellant shutoff valves and 12 to 200 milliseconds for gaseous shutoff valves. However, one requirement from a prime manufacturer of space propulsion systems was for a response time of 2 milliseconds.

ACCELERATION, VIBRATION AND SHOCK

Launch Loads

Acceleration is usually considered to be more severe in the launch phase than for the space flight condition. Acceleration levels measured on the engine dome range from 10 to 30 g with the maximum occurring between 600 to 1600 cps. Valves attached to the combustion chamber of the launch missile may experience up to four times greater loads through amplification depending on the mounting. Valves located in the tankage area may experience from 5 to 20 g; however, amplification due to other structure may occur.

During the first few seconds of firing, acoustical noise is usually responsible for the severe excitation of most of the valves located at some distance from the missile rocket engine.

Space Flight Loads

Vibration and shock may be more serious for the space flight phase within varying degrees depending on the orbit or space mission, such as lunar landing. At present, vibration and shock requirements are usually most severe under rocket engine test conditions.

Acceleration is normally considered more pronounced in the launch phase than for the space flight condition. It should be noted, however, that the valve used on the space vehicle will not be operating at the time of the earth launch, but will be operative in the space orbit and under this condition the valve is more susceptible to adverse effects from the acceleration.

Re-entry and Recovery Loads

Accelerations and dynamic pressures up to 10 times the launch values can be experienced by spacecraft in re-entry of the planets' atmospheres. Shock loads imposed by parachute recovery of equipment would have to be considered, although ascent loads usually predominate.

Expected values for deceleration experienced during expected entry to the planets are as follows: (Ref. 1)

Planet	Direct Entry at Escape Velocity			Direct Entry at Orbital Velocity			Entry by Decay From Satellite Orbit
	$\Theta = 5^\circ$	20°	90°	$\Theta = 5^\circ$	20°	90°	
Venus	28.6	112	326	14.3	56	163	8.9
Earth	28.3	111	324	14.2	55.5	162	9.5
Mars	1.6	6.3	18.3	0.8	3.2	9.2	9.2

where Θ is the re-entry angle with the horizontal, and the decelerations are given in earth g's.

Other Loads

An important shock source could be the impact on the valve or spacecraft from meteorites and consideration of this possibility should be included in the design analysis. Additional information on meteorites is given in this report in Section III.

Representative values of acceleration, vibration and shock for space vehicles are given in Table 3-6 (Ref. 2).

References

1. H. H. Koelle, Ed. Handbook of Astronautical Engineering, McGraw-Hill, New York, (1961).
2. T. M. McCoy and W. H. Coop. "Handbook of Aerospace Environments and Missions" Report No. NSL 62-152, NAS 8-2550, Nov 62, Northrop Space Laboratories.

Table 3-6 Representative Values of Acceleration, Vibration and Shock

Mission	Acceleration or Deceleration	Vibration	Shock	Acoustical Noise
Earth Launch	up to 7g to 775 sec. 20-30 g for 150 sec.	10g rms 600 to 1600 cps	15 to 20g for 6 to 12 milliseconds	Field outside of payload 150 db 60 sec. duration
Low Earth Orbit	1 to 3g longitudinal for increments of 5 min. or longer	to 50g peak > 1000 cps 5 min. duration	Secondary stage ignition shock levels to 50g for approximately 10^{-3} sec.	None
Lunar Orbit	Deceleration to 2g up to 10 min. for lunar injection	50g peak to > 1000 cps for 10 min. duration	Engine ignition levels to 40g for 6-12 ms	None
Lunar Landing	0.5 to 72g for landing approach		Engine ignition levels to 40g for 12 ms Soft landing shock of 10 to 100g for several ms - Hard landing shock to > 1000g for several ms	None

SPACE ENVIRONMENTS

Vacuum of Space

Interplanetary space consists of a low-density gas mixture consisting primarily of hydrogen and helium. The estimated gas pressure in interplanetary space is about 10^{-16} mm Hg, and in interstellar space, pressures lower than 10^{-25} mm Hg may be encountered. The lowest pressure that has been produced in the laboratory is about 10^{-14} mm Hg; however, pressures of 10^{-9} to 10^{-10} mm Hg are currently considered practicable for the best vacuum pumps available (Ref. 20).

In order to maintain an orbit in the gravitational fields of the planets, the space vehicle must be traveling at some determined velocity, and as a result, the pressure near the spacecraft will be different than the static pressure of space. Also, streams of molecules will emanate from the sun and thereby influence the space vacuum. Gas molecules leaving the surface of the space vehicle will for the most part escape into space, but some may collide with other gas molecules and return.

A vacuum environment may affect the functional characteristics of valves and their related equipment. The following is a summary of the parameters that may be considered by the designer of valves operating in a space vacuum:

1) Sublimation and evaporation of materials
2) Cold welding
3) Friction and wear
4) Strength of materials

1. Sublimation and Evaporation of Materials

The effects of high vacuum on the sublimation rates of metals can be calculated from the Langmuir Equation, assuming that none of the molecules leaving the surface return to it.

$$G = \frac{P}{17.14}\sqrt{\frac{M}{T}}$$

where

G = rate of loss per unit area of exposed surface in $g.cm^{-2}sec^{-1}$
P = vapor pressure at temperature T in mm Hg
M = molecular weight of the metal in the gas phase
T = absolute temperature (^{o}K)

The higher the vapor pressure of the material, the higher the rate of sublimation. A plot of vapor pressure against temperature is presented in Figure 3-2. Cadmium, which is often used for plating of parts, is a poor material to use in space vacuum. Metals that sublimate from a warm surface will have a tendency to plate on a cooler surface, possibly causing electrical short-circuiting, change of surface emmissivities, or change of optical properties of mirrors and lenses. Sublimation can be retarded by selection of surface coatings with low-vapor pressures or inorganic coatings such as oxides, which often have lower vapor pressures than the metals from which they are formed.

The Langmuir Equation is not applicable to the organic materials of interest to the valve designer; therefore, experimental studies of weight loss of organic materials are necessary.

In recent years considerable study has been devoted to the investigation of the mechanisms and kinetics of the degradation of polymers. Such degradation or breakdown can be caused by various factors, including heat, light, and nuclear radiation, as well as various substances, such as oxidizing agents (Ref. 1).

Of direct interest is that work covering the thermal degradation of polymers in vacuum. Much of this work is described in Reference 1 through 11. In general, a review of this work indicates that polymers of relatively high molecular weight useful in spacecraft applications do not evaporate or vaporize in a vacuum, but when supplied with sufficient thermal energy, decompose or depolymerize by one of several possible mechanisms. That is to say, these polymers have such low vapor pressures that the thermal energy required to cause evaporation exceeds that required to break chemical bonds of the polymer. It may be concluded that many polymers of engineering importance do not sublime or evaporate in high vacuum environments and will probably not decompose at the moderate interior temperatures anticipated in many spacecraft applications. Furthermore, since in a high vacuum environment many deleterious contaminants such as oxygen and moisture will not be present, at least in the quantities found in the earth's atmosphere, it might be further concluded that the thermal stability of these polymers should be at least as good in high vacuum as at earth ambient conditions.

The very pure polymers necessary for scientific investigation and research are not those commonly used in engineering applications. Most commonly used polymeric materials are commercially formulated products. Investigation of these products in vacuum environment has revealed varying results. From these data it becomes immediately evident that the purity variations of molecular weight and formulation additives significantly influence the weight-loss characteristics of a plastic. Low molecular weight, high vapor pressure fractions of the polymer may be expected to evaporate from the surface of the material. Also, a wide variety of additives may be expected in many instances to evaporate from the surface. Common additives include diluents, plasticizers, dyes, antioxidants, flexibilizers, flame retardants, accelerators and catalysts. For most plastics of engineering interest the quantities and vapor pressures of these materials and other contaminants such as adsorbed and absorbed gases, moisture, solvents, cleaners, and mold releases will be primarily responsible for the weight loss or outgassing which is detected in engineering studies. Additional factors which may influence the weight loss of materials in vacuum are the degree of cure of the material and any by-products of the polymerization reaction. If the material is inadequately or improperly cured, fragments of low molecular weight and high vapor pressure may remain uncombined in the product. These will evaporate when the material is subjected to a vacuum environment. The same effect may be anticipated for reaction by-products, such as water in many condensation polymerization reactions.

It is obvious that property changes may be expected to occur as a result of the loss of these various additives and contaminants. First, there is the loss or degradation of that property for which the additive was initially placed into the formulation. For example, the loss of a flexibilizer by evaporation in a vacuum environment will produce a more rigid, perhaps brittle, plastic with a corresponding decrease in elongation and impact strength and increased tensile and flexural strength. On the other hand, loss of a dye may result merely in a color change, which may not be significant.

The loss of an antioxidant or fire retardant may not result in any serious property degradation since these factors are not generally considered to be serious problems in space applications. On the other hand, the loss of a radiation-resistant (anti-rad) compound may result in a very definite change in the ability of the material to withstand the space radiations, certainly a serious problem for some materials.

The loss of accelerators or catalysts from materials may result in a beneficial effect. These materials are generally of high reactivity added initially to initiate and/or accelerate the polymerization of the material and are also capable of serving to accelerate any depolymerization or degradation reaction (Ref. 1). Consequently, the loss of these materials could prove to be quite beneficial in many instances.

In addition to degrading that property for which an additive may have been used in the formulation, other property changes may be produced and must be considered. For example, the loss of these materials may change significantly the electrical properties of the polymer, such as dielectric strength, dielectric constant, dissipation factor, and resistivity. Because of the loss of contaminants, moisture, and absorbed gases, many polymers, such as Teflon, used as seals in a valve may experience an increase in their permeability to the propellant.

Based on the postulates that the thermal stability of the basic pure polymers is at least as good in vacuum as in air and that the molecular weights of these polymers are too great to allow evaporation, the rate at which the various materials (additives and contaminants) will evaporate from the plastic is dependent upon at least two factors: the vapor pressures of these various constituents and their diffusion rates through the plastic to its surface. It is to be expected that the weight-loss rate of materials in vacuum will be initially high during the time that surface "contaminants" evaporate and then should steadily decrease to the rate determined by the diffusion rates of these "contaminants" to the surface.

Section IV gives some experimental data obtained by Space Technology Laboratories in sublimation studies which follow this form, although this in itself cannot be used as proof of the above postulate, since similar curves are to be expected if chemical degradation occurred.

2. Cold Welding

"Cold welding" or pressure bonding, as the term implies, refers to the joining of two solid objects without the presence of a gross liquid or melt phase at the interface. If the bulk temperatures of the objects in question are near ambient, the problem is of great concern to the spacecraft designer utilizing components or subsystems relying on the process of mechanical motion at some specific time in the space environment.

A further restriction to the static case is imposed, thus eliminating friction and wear, which from the first principles, involve, in part, the same atomistic processes. Actually, the designer is only concerned with the question of bringing two solid objects into contact, or having already established a contact, placing them in the space environment.

Examinations of the controlling factors in considering such a rate phenomenon reveals at least the following for consideration:

1) The atomic species and interatomic bonds
2) The surface energy

Clearly the greatest difficulty lies in qualitatively and quantitatively describing the variables associated with the surface energy condition. Three of the most obvious are:

a) The absolute temperature - for both the bulk and differential volumes at the surface
b) Contamination of the surface
c) Crystalline perfection of the surface

Since under the stated conditions in the earth atmosphere "solid state bonding" does not occur in the same time scale the designer is to be concerned with, the role of surface contaminants is indeed important. Likewise, it is quite clear that if clean surfaces are established in space, they will remain so.

Thus, two rate processes must be quantitatively described to reliably predict either joining or nonjoining of two surfaces by solid state bonding: First, if contaminated surfaces are placed in the space environment, how rapidly and by what mechanisms may the contaminations be removed? Second, if the contaminants are removed, will the two surfaces in question form a bond of sufficient strength, during the contact period, to be of consequence?

Absorbed contaminants are conventionally described as physisorbed or chemisorbed on the surface. Physisorption does not involve the species in question by any strong chemical bond and only rather long-range but relatively weak Van der Waal type forces are involved. Chemisorption does involve strong atomic bonds. The difference in energy between the two types of bonding is very significant - Van der Waal bonds have energies of less than one electron-volt and chemical bonds involve energies of a few electron-volts (Ref. 12). The exact role played by contaminants is not clear or necessarily simple. In some cases, the most important role may be satisfaction of available surface bonds. In other instances, an equally important role might be the presentation of an inert barrier serving to retard or prohibit diffusion across the interface.

With this very simple background, examination of desorption mechanisms to be found in space is possible.

a. Mechanical Motion. A highly efficient means of breaking down or providing sufficient energy to the surface to be desorbed is mechanical motion. What happens to the contaminants upon this additional energy could be one of several processes or combinations thereof. Microscopic plastic deformation can produce short-time, high-surface temperatures without a detectable change in bulk temperatures. Continuous mechanical motion is a different situation than one-time contact. However, in both cases small volumes at the interface will develop high instantaneous surface temperatures resulting in desorption.

b. Ultraviolet and/or Low Energy Electron Desorption. Radiation of suitable character to interact at the surface has been demonstrated (Ref. 13) as a suitable mechanism for producing clean surfaces. If two surfaces are in static contact with each other in the contaminated condition, such desorption mechanisms would not operate since the penetrating power of such radiation limits desorption to exposed surfaces.

c. Sublimation. Sublimation, dissociation, diffusion, and chemical reaction are all removal mechanisms. Each process is temperature dependent and usually one is the dominant rate-controlling process. The limitation on the assessment of the loss rate of contaminants in the use of bulk thermodynamic criteria applies to very thin layers. The problem is further complicated by lack of any reasonable estimates of the initial thicknesses of surface contaminants associated with engineering surfaces. An excellent, brief dissertation has been given by Ham (Ref. 14).

Any rationalization of loss rates in a specific experiment will have a significant geometrical factor. Solid-angle considerations must then be taken into account. The question of two-dimensional mobility and surface diffusion clearly is significant in determining the loss rate process for the contaminants in many instances.

Examination of the bonding processes between two clean surfaces indicates bulk diffusion[*] to be the most probable. Before this is discussed in more detail, one other possibility will be considered. This will be termed coherent bonding. Coherent bonding would involve no diffusion. The joining would be effected by attachment of surface bonds by both interfaces which were previously involved in the first monolayer. If the first monolayer bond strength is not pure Van der Waal, then the bond strength could be significant. For coherent bonding, a number of surface conditions must be considered in determining how many individual bonds contribute to the gross bond strength. Consideration of the degree of registry required for appreciable bond formation shows that only lattices with metallic bonds could conceivably establish at least an initial joining of this sort. Lattices consisting of covalent or ionic bonds would require such a precise degree of registry as to make such a bond highly improbable (Ref. 15).

Coherent bonding of this nature would be nearly instantaneous. However, three-dimensional atomic mobility of few atom distances could likewise be almost instantaneous compared with the time span of a few

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[*] Bulk diffusion is considered only to involve three-dimensional atomic mobility, at least at small microscopic sites at the interface, not necessarily gross diffusion.

seconds to minutes representative of the most rapid experiments which have been reported. Contemporary experiments do not permit distinguishing between the two mechanisms.

Of significance is that neither short-time diffusion bonds nor coherent bonds have occurred for metallic elements placed in contact in which the metals in question were immiscible with each other as determined from the appropriate phase diagram. Also all couples in which adhesion has been demonstrated have had either complete or partial solid solution exhibited in their phase diagrams.

A few experimental observations which have been performed in vacuo are summarized as follows:

OFHC copper (Ref. 16) fractured at a bulk temperature of 200°C could be rejoined under high compressive pressures to strengths of approximately 95 percent of the original in repeated operations. Bonding was achieved in seconds in some cases. Gross plastic deformation was incurred during the compressive cycle of rejoining the surface.

Other materials tested by the same investigator with similar techniques were 1018 steel and 52100 steel; only 1018 steel showed measurable rebonding. Steel by another investigator also showed adhesion (Ref. 17).

Copper was also the subject of investigation in other studies (Ref. 18), in which the copper in question was the needles of Project Westford. Subjection to ultra-high vacuum resulted in partial cold welding of the needles.

The primary investigations supporting a solubility-immiscibility hypothesis were performed by Spalvins and Keller, in which adhesion was found only where solubility of some degree was indicated by the phase diagrams. Conversely, no joining was noted in the remaining couples, which showed no solubility or, in one instance, had covalent bonds.

Complete Adhesion	No Adhesion
FE-AL	Cu-Mo
Ag-Cu	Ag-Mo
Ni-Cu	Ag-Fe
Ni-Mo	Ag-Ni
	Ge-Ge (single crystal)

Because of the uncertainty in predicting rate processes, practical techniques to minimize the possibility of cold welding can only be generalized.

1) Based on the present state of experimental verification, the use of the solubility-immiscibility model seems warranted. Thus, the use of immiscible materials in combination is recommended to prevent in-vacuo cold welding.

2) Reliance on maintaining a contaminated surface may be more suitable or mandatory in some instances. This could be in the form of strictly natural chemisorbed layers or preferentially treated solid lubricants, oils, or greases. With exception of the naturally occurring contaminants, other forms could be placed on the surface to permit and justify to a greater extent use of bulk thermodynamic properties in predicting loss rates.

Studies which quantitatively describe the loss rate of contaminants on engineering surfaces seem essential if the desired technique to avoid cold welding is by such a method.

Many additional studies between clean metal surfaces are necessary to establish conclusive evidence of the actual manner in which bonding can or cannot occur. If immiscibility is the dominant feature, then proper materials selection will in itself preclude bonding.

3. Friction and Wear

The tendency of a vacuum to permit clean surfaces (surface contamination removed) will, as a result, increase the friction forces between metals in sliding contact. After initial sliding has begun, the oxide film is broken, and because of the absence of an oxidizing atmosphere, these oxide layers are not reformed and consequently many more metallic junctions are formed at the interface. Since adhesive friction is considered to be the result of shearing of these cold welded metallic junctions, any methods that can be devised to prevent the junction formations will be helpful in reducing friction.

If the oxide films are completely removed from the metal surfaces, the metal can weld together and sliding is impossible. Any amount of gases or vapors produces some contamination to a surface whereby the friction will decrease. For valve closures exposed to vacuum, leakage through the seat interface would alleviate cold welding and decrease the friction on seats which are in sliding contact, such as the ball-type configuration.

Wear is aggravated when the oxide layers are removed between surfaces in sliding contact. The wear debris formed between metallic surfaces in contact also change in size, depending on the atmosphere the wear surfaces are exposed to. With the absence of an atmosphere, the wear particle size is believed to be a maximum. The surfaces in contact and exposed to the vacuum of space, such as a valve closure or valve actuator part, may experience larger wear debris than is found when they are operated in the earth's atmosphere. Because of a change in wear particle size, a change in leakage in the "last" valve in the system (shut-off valve) may occur, or seizure may develop between the surfaces of the moving parts of an actuator. A more thorough explanation of wear debris is given in Section IV under the Wear Particle Study.

4. Strength of Materials

The absence of an oxidizing atmosphere and the loss of the initial oxide films on the surface of structural parts may influence the fatigue strength of the parts.

Investigators have shown that the fatigue life of many metals increased substantially when the metals were tested in a vacuum, as compared to when they were tested in air. A flexure pivot is an interesting application to a mechanism that requires a bearing or hinge supports. A flexure pivot is basically a thin, flat beam which will bend easily under a load and thereby act as a hinge point. An increase in fatigue properties of metals in a vacuum supports this means of providing a pivot joint and also eliminates the need for lubricants.

The tensile strength of fine metal wires in a vacuum is slightly greater than in air, but in general the strength of metals in a vacuum does not differ significantly.

The Effects of Vacuum on Electrical Components

For many electrical components the effect of vacuum must be considered. A motor that operates satisfactorily in air may not perform its task in vacuum. A switch may short-circuit in vacuum because of the change of the dielectric. A motor or solenoid winding, when exposed to vacuum, may fail because of the loss of insulation. Capacitors may change in value if the insulation materials used in their construction lose moisture or other contaminants entrapped during their manufacture. Preliminary studies have indicated changes in the electrical characterisitcs of some components (Ref. 21). Section IV presents test data on materials considered for electrical applications in vacuum.

Additional problems may be presented when the components must operate in the atmosphere of another planet. A component may have to meet test procedures in air, but in addition, work in the vacuum of space and then again operate satisfactorily in the atmosphere of Mars, Venus, or Jupiter.

Some of the various environmental problems may be eliminated, for instance, by providing the solenoid actuator for a valve with its own atmosphere, such as the propellants. An actuator buried in the propellant would not be exposed to vacuum, but care should be taken to ensure that the materials exposed to the propellants are compatible. Section VI discusses a design concept wherein an actuator is installed inside the propellant or pressurant tank.

Bibliography and References - Vacuum of Space

1. Jellinek, H. H. G. Degradation of Vinyl Polymers, Academic Press Inc. New York, 1955.

2. Beasch, C. F., Harvey, M. R., and Ackhammer, B. G. "Heat and Ultraviolet Aging of Poly (Vinyl Chloride)" Journal of Research - National Bureau of Standards 60, 1958, pp 481-488 (RP 2863).

3. Florin, R. E. and others. "Factors Affecting the Thermal Stability of Polytetrafluoroethylene", Journal of Research - National Bureau of Standards 53, 1954, pp 121-130 (RP 2524).

4. Madorsky, S. L., and Straus, S. "Thermal Degradation of Polychlorotrifluoroethylene, Poly-a, β, β-trifluorostyrene, and Poly-p-xylylene in a Vacuum", Journal of Research - National Bureau of Standards 55, 1955, pp 223-230 (PR 2624).

5. Madorsky, S. L., and Straus, S. "Thermal Degradation of Polymers as a Function of Molecular Structure", Journal of Research - National Bureau of Standards 53, 1954, pp 361-370 (RP 2553).

6. Madorsky, S. L., Hart, V. E., and Straus, S. "Pyrolysis of Cellulose in a Vacuum", Journal of Research - National Bureau of Standards 56, 1956, pp 343-354 (PR 2685).

7. Madorsky, S. L., Hart, V. E., and Straus, S. "Thermal Degradation of Cellulosic Materials", Journal of Research - National Bureau of Standards 60, 1958, pp 343-349 (RP 2853).

8. Straus, S. and Madorsky, S. L. "Pyrolysis of Styrene, Acrylate, and Isoprene Polymers in a Vacuum", Journal of Research - National Bureau of Standards 50, 1953, pp 165-176 (RP 2405).

9. Straus, S. and Wall, L. A. "Pyrolysis of Polyamides" Journal of Research - National Bureau of Standards 60, 1958, pp 39-45

10. Wall, L. A. and Florin, R. E. "Effect of Structure on the Thermal Decomposition of Polymers", Journal of Research - National Bureau of Standards 60, 1958, pp 451-458 (RP 2860).

11. Wall, L. A. and Michaelsen, J. D. "Thermal Decomposition of Polytetrafluoroethylene in Various Gaseous Atmospheres", Journal of Research - National Bureau of Standards 56, 1956, pp 27-34 (RP 2644).

12. Goldman, J. W. (ed.). The Science of Engineering Materials, J. Wiley δ Sons, Inc. 1957.

13. Lange, W. J., and Riemersma, H. "Desorption of Gas by Photons", Transactions of the Eighth Vacuum Symposium and Second International Congress, Vol. 1, 1961.

14. Hamm, J. L. "Mechanisms of Surface Removal of Metals", Aerospace Engineering, May 1961.

15. Spalvins, T., and Keller, D. V. Adhesion Between Atomically Clean Metallic Surfaces, Final Report, NSG-159-61, NASA, July 1962.

16. Private Communications with J. L. Ham, NRC, Cambridge, Mass.

17. Colner, W.H. "Space -- A New Environment for Materials", Materials Research and Standards, August 1962, p. 656.

18. Farkass, I., Gould, P. R., and Horn, G. W. 1×10^{-11} Torr in Large Metal Chambers, Its Attainment and Application Results, Paper presented at Ninth National Symposium of the American Vacuum Society, October 31 - November 2, 1962.

19. Clauss, F. J. Lubricants and Self-Lubricating Materials for Spacecraft Mechanisms, Lockheed Technical Report LMSD-894812, Lockheed Missile and Space Division, Sunnyvale, Calif. 18 April 1961.

20. Gray, P. D., Christensen D. and Howard, W. W., Engine Operating Problems In Space, Contract No. NAS7-98, Report No. 0629-01-1 and 0629-01-2, Vol. 1 15 February through 14 May 1962, Vol 2 15 May through 14 August 1962, Aerojet-General Corporation, Space Propulsion Division.

21. Brueschke, E.E. "The Effects of the Space Environment on Electronic Components and Materials", Special Research Study SRS-367, Hughes Aircraft Company, Culver City, California, 15 June 1960.

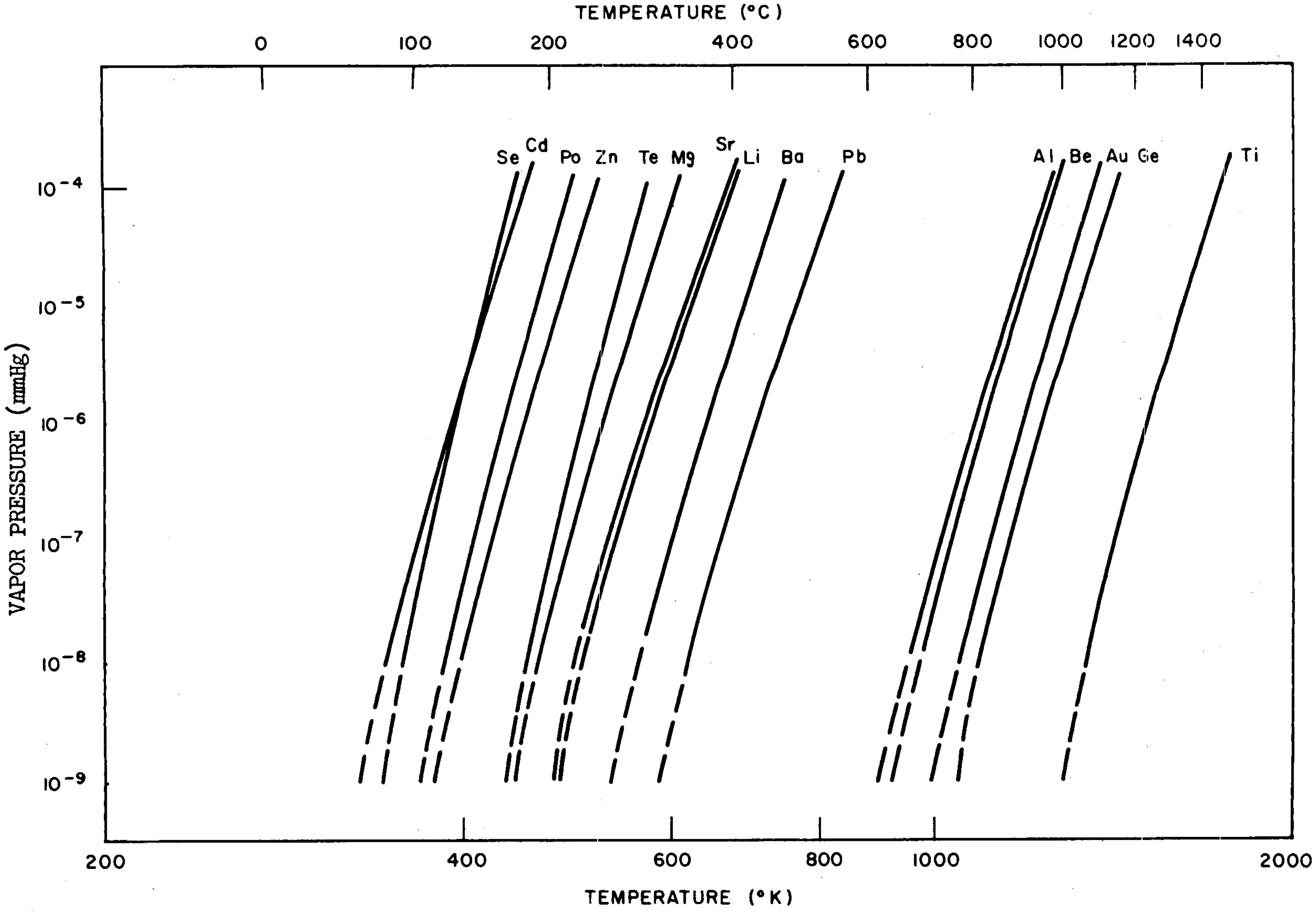


Figure 3-2 Temperature Vs Vapor Pressure

Radiation

Introduction - The usual division of the space radiation environment is into four zones, described as follows:

The Inner Radiation Zone
The Outer Radiation Zone
The Auroral Zone
The Interplanetary Zone

The characteristics of each of these zones will be discussed below in terms of the type and energy spectrum of the radiation present, as well as the temporal and spacial variations of this radiation. A few brief definitions of the units employed in the following calculations will first be presented.

Definitions: -

Flux - The omnidirectional flux of particles at any point in space is the number of particles of a particular type that would traverse a test sphere of 1 cm^2 cross sectional area in one second. It has the units of particles/cm^2 sec. The unidirectional flux is the flux arriving at the test sphere per unit solid angle from any particular direction and has the units of particles/cm^2 sec steradian. If the incident radiation is isotropic, the unidirectional flux equals the omnidirectional flux divided by 4π. Under this same assumption, the flux of particles incident from one hemisphere on a plane surface is one-fourth the omnidirectional flux.

The results of laboratory radiation damage experiments are usually quoted in units of particles/cm^2 required to produce some effect in a given sample. This unit should not be confused with the omnidirectional flux, however, since the laboratory measurements are almost always made with a unidirectional beam of particles. Thus, to obtain the omnidirectional flux corresponding to this laboratory flux, the laboratory flux should be multiplied by four.

Dosage Units - There are four units generally used to describe the amount of energy lost in a material by incident radiation. The roentgen (r) is defined precisely as the quantity of gamma radiation that will produce one electrostatic unit of electrical charge in 1 cc of dry air at standard conditions of temperature and pressure. This corresponds to the absorption of 87.7 ergs of energy per gram of air. A more useful unit, the roentgen-equivalent-physical (rep), which is independent of the type of radiation, refers to tissue damage and is defined as the radiation dose which produces an energy absorption of 93 ergs/cm^3 in aqueous tissue. Still more useful is the rad which is independent of the material being irradiated and the type of radiation and is the radiation dose which produces an energy absorption of 100 ergs/cm^3. The roentgen-equivalent-man (rem) is useful in discussing biological effects and will not be considered here.

Geomagnetic Coordinates - Since the trapping of charged particles and the behavior of extraterrestrial particles in the earth's vicinity is characterized by the shape and strength of the earth's magnetic field, it is quite convenient to plot the radiation intensities in geomagnetic rather than geographic coordinates. The origins of these coordinate systems coincide, but the geomagnetic axis is tilted by 11.5 degrees with respect to the axis of rotation of the earth. Since isointensity contour maps presented herein, as well as the sample vehicle trajectories, are in geomagnetic coordinates, it will be necessary to consider the differences between the two systems when the radiation in an actual trajectory is being predicted.

The Inner Radiation Zone - Until recently the inner radiation zone was primarily characterized by a high proton flux. However, the high altitude nuclear test bomb blast of July 9, 1962 above Johnston Island resulted in the trapping of a large number of fission electrons in this zone. Measurements of these fission electrons indicate a peak omnidirectional intensity of 10^9 electrons/cm^2 sec extending from an altitude of 1300 km to an altitude of 5500 km (Ref. 1). The differential spectrum of fission electrons, shown in Figure 3-3, can be approximated by $N_o \exp [-0.575\, E - 0.055E^2]$ for the range $1 \leq E \leq 7$ Mev, N_o being the normalizing factor. Approximately half of these fission electrons have energies below 1 Mev. The figure of 10^9 electrons/cm^2 sec quoted above represents the total number of electrons of all energies that are trapped, based on the assumption that a fission spectrum does indeed exist. The isointensity contours of this artificial electron belt based on this assumption are shown in the bottom half of Figure 3-4. There have not yet been any measurements of the temporal decay of the fission electrons in the inner zone. (For the sixty days following July 7 no decrease was observed.)

The proton isointensity contours for $E>40$ Mev are shown in the top half of Figure 3-4. The spectral distribution of these protons is based on data analyzed by Freden and White (Refs. 2, 3), Naugle and Kniffen (Ref. 4), and Heckman and Armstrong (Ref. 5) from vehicles skirting the edge of the inner radiation zone, which is shown in Figure 3-5. The most reasonable assumption that can be made at this time is that the spectral distribution in the heart of the inner zone is given by the spectral distribution observed on the fringes. The distribution is well approximated by an integral spectrum of the shape

$$kE^{-0.8} \text{ for } E \geq 20 \text{ Mev}$$
$$k'E^{-3.5} \text{ for } \geq 20 \geq E \geq 8 \text{ Mev}$$

Observations during magnetically quiet days indicate that changes in intensity in the inner radiation zone are of the order of several percent. However, time variations involving as much as a factor of 3 increase in intensities have been observed to occur in temporal correlation with major solar events and/or major geomagnetic storms (Ref. 6). On the other hand, the geomagnetic field acts as an excellent shield in deflecting solar protons from the inner radiation zone, since protons of energies less than 6.8 Bev are excluded from the equatorial plane at altitudes below 1.25 Re (earth radii).

The Outer Radiation Zone - The outer radiation zone is characterized by the absence of high intensities ($>$ 100 particles/cm^2 sec) of geomagnetically trapped protons with energies greater than 10 Mev. The trapped radiation consists principally of electrons and soft protons ($E<10$ Mev). In the equatorial plane the outer zone begins at 2.3 Re and extends to 8 to 10 Re. In a meridian plane the outer zone boundary dips down to lower altitudes with increasing geomagnetic latitude. The intensities at the heart of the outer zone (3.6 Re) are:

Electrons	$E>500$ kev	2×10^7 electrons/cm^2 sec
Protons (Ref. 7)	$E>100$ Mev	<1 proton/cm^2 sec
Protons	$E>140$ kev	$\sim 10^8$ protons/cm^2 sec

The isointensity electron contours are plotted in the top half of Figure 3-6. In the bottom half of this figure are shown the contours after the magnetic storm of August 16, 1959, which increased the intensities 20-fold to 4 x 10^8 electrons/cm^2 sec of energy greater than 500 kev. In addition to these large changes wrought by magnetic storms, 3-fold increases and decreases not clearly correlated with solar activity are observed above 6 Re. In the heart of the outer zone the spectrum of electrons is given by an expression of the form const. x exp (-4.26 E), and is shown in Figure 3-7.

The Auroral Zone - The auroral zone is located roughly between 60 and 65 degrees geomagnetic latitude, but moves toward lower latitudes during strong magnetic disturbances. The auroral displays are caused by energetic electrons entering the atmosphere, although protons may or may not be present.

Since the particle flux, the energy spectrum of each component, and the directional characteristics of the particles are characteristics of the observed aurora, the auroral zone cannot be described in as definite a fashion as the inner and outer radiation zones. The maximum proton intensity seen in the auroral zone, which was observed during an aurora with the fading ray structure, is given by an integral spectrum of the form $J(>E) = 75E^{-3.2}$ protons/cm^2 sec steradian where the energy is in Mev. For this type of aurora the electron spectrum is of the form $J(>E) \alpha \frac{1}{E}$ for energies where 5 kev $\leq E \leq$ 50 kev. The intensity above 10 kev was measured to be $(4 \pm 2) \times 10^7$ electrons/cm^2 sec ster. Since the particle fluxes in the auroral zone are much smaller than those observed in the equatorial radiation zone, the damage done to these particles has been neglected in the calculations below. Of course, for special trajectories that leave the earth near a geomagnetic pole, the auroral zone radiation could become important.

The Interplanetary Zone - Energetic radiation in interplanetary space consists of an extremely high energy, temporally stable component, the primary cosmic flux, and pulses of radiation of a few days' duration associated with solar flares which occur at random intervals. The largest flares, designated 3+, include the relativistic flares in which enormous amounts of energy are carried away by highly relativistic protons. These flares are extremely rare, only nine having been observed in the last 23 years. However, the smaller flares occur with increased frequency--the smallest, a flare of importance occurring eight times per day (Ref. 1). In addition to these two sources of interplanetary radiation there also exists a continuous ejection of low energy particles (primarily protons and electrons) from the sun to form what is called the solar wind. These particles generally have energies of the order of a few kev and need not be considered in any radiation damage estimates.

Galactic cosmic rays consist primarily of protons ($\sim$93%) and alpha particles ($\sim$7%) along with small amounts of heavier elements (Ref. 8). The energy spectrum (Ref. 9) of the galactic protons is well represented by $N(>E) = 0.3/(1+E^{1.5})$ protons/cm^2 sec ster for energies where 500 Mev $\leq E \leq$ 20 Bev. The energy E is in Bev. This gives the free space flux of particles as 2.5 particles/cm^2 sec. This flux is quite small and needs to be considered only in very long space flights; although shielding such high energy particles would be extremely difficult to achieve, since small thicknesses are likely to cause increased damage from the secondaries produced.

The effect of solar flares is very difficult to estimate because of time variations in their intensity and the temporal randomness of their occurrence. The integral energy spectrum at peak intensity of the type 3 solar flare of September 29, 1961 was measured to be $N(>E) = kE^{-\gamma} = 6.33 \times 10^4 E^{-1.77}$ protons/cm^2 sec ster for E between 100 and 1000 Mev. The temporal variation of this spectrum is shown in the series of spectra in Figure 3-8. Solar flares of intensity 3 or higher have a frequency of approximately 1 per 20 days. To obtain the radiation intensity in space from solar flares one could take 1/20 of the intensity of the above flare as an average for flights of long duration away from the earth. This is, of course, only a very rough approximation because any particular flight may see radiation from flares that is far from average.

Typical Maximum Intensity Orbits - Several circular orbits, passing through either the heart of the inner or outer radiation zone, have been considered in making calculations of the integrated radiation intensity on a spacecraft. For a circular orbit the period is given by

$$T = 2\pi\sqrt{\frac{R_E}{g}} \left(\frac{R}{R_E}\right)^{3/2}$$

where g is the acceleration due to gravity at the earth's surface, R_E is the earth's radius and R is the radius of the orbit (altitude + R_E). This expression leads to $T = 85\ (R/R_E)^{3/2}$ minutes, for $R_E = 6370$ km and $g = 9.8 \times 10^{-3}$ km/sec.

There are, in all, six different orbits that were considered. The first two were the equatorial and polar orbits passing through the heart of the inner zone. The next four were the equatorial and polar orbits passing through the heart of the outer zone, two for before the storm and two for after the storm. All these orbits are shown on Figures 3-4 and 3-6. Note that the outer zone equatorial orbit before the storm is identical with the outer zone equatorial orbit after the storm. Calculations of the radiation intensities in these orbits lead to the results presented in Table 3-7.

Dose Rates

Bremsstrahlung - The calculation of the dose rates produced by an incident electron flux is complicated by the existence of gamma rays that are produced whenever electrons pass through an absorber. The gamma radiation thus produced is termed "Bremsstrahlung." An exact calculation of the dose rate produced by the Bremsstrahlung is complicated by a number of factors:

1. Angular dependence of the Bremsstrahlung with respect to the incident electron,
2. Partial absorption of the Bremsstrahlung by the electron absorber,
3. Variation of the mass absorption coefficient with Bremsstrahlung energy, and
4. Electron straggling and scattering in the absorber.

To simplify the calculation a number of approximations can be made which will lead to results that for reasonable absorber thicknesses, e.g., less than 5" of aluminum, will yield answers accurate to approximately ±50%, a result probably more accurate than the estimates of the incident electron intensity. The calculation will assume that

1. The Bremsstrahlung is produced isotopically,
2. None of the Bremsstrahlung is absorbed in the material that produces it,
3. The mass absorption coefficient for aluminum is taken as a constant, and
4. The electrons are all assumed to stop in the absorber.

Of these assumptions, the last is the only one that will yield a large error in the answer, and this only for those cases where the shielding thickness is less than 1 g/cm^2 (approximately 0.17 inches). In any case, assuming that all the electrons are stopped can only lead to a dose rate estimate that is larger than one that is calculated without using this assumption. That assumption (2) is an excellent approximation can be seen by referring to Figures 3-9 and 3-10 which present the absorption of gamma rays in various materials. As can easily be seen, gamma rays suffer very small absorptions in aluminum, 1 inch of which decreases the intensity by only 20%. Under the above assumptions, the expression for the dose rate becomes

$$R = 6.1 \times 10^{-8} \int_{E=O}^{\infty} \int_{T=E}^{\infty} (T-E)\, N(T)\, dTdE$$

where R is in rad/day, N(T) dT is the differential incident electron spectrum as a function of the kinetic energy T, and E is the Bremsstrahlung energy. If the electrons are not stopped in the absorber, the upper limits in this double integral will be T_{MAX}, the energy of an electron whose range is the thickness of the absorber. Figures 3-11 and 3-12 indicate this range as a function of electron energy. For the outer zone one can use

$$N(T)\ dT = 36ke^{-4.26T}dt$$

and for the inner zone

$$N(T)\ dT = 1.1ke^{-0.93T}dT$$

where k is the number that appears in Table 3-7 in the column labeled "Electrons/cm^2 Day." Using these two expressions, we obtain:

$$R = 3.3 \times 10^{-13}k \text{ rad/day (Outer Zone)}$$

$$R = 9.7 \times 10^{-12}k \text{ rad/day (Inner Zone)}$$

Electrons

A calculation of the dose rates produced by an electron flux after passing through an absorber is complicated by the energy variation of the range. If, however, we approximate the range as proportional to the energy, the calculation becomes much simpler. This is a quite good approximation for electrons as can be seen by studying Figure 3-11 and 3-12. With this approximation the dose rate becomes:

$$R = 3.2 \times 10^{-8}k\beta\int_0^{\infty} e^{-\alpha(E + 13.3t)}dE \text{ rad/day}$$

where k again is obtained from the column labeled "Electrons/cm^2 Day" in Table 3-7 , t is the thickness of the aluminum shield in inches, and $\alpha = 4.264$, $\beta = 36$ in the outer zone, $\alpha = 0.93$, $\beta = 1.1$ in the inner zone. For a thickness of aluminum absorber $t = 0.06$ inches, the above integral for R gives

$$R = 8.9 \times 10^{-8} \quad k \text{ rad/day (outer zone)}$$

$$R = 1.8 \times 10^{-8} \quad k \text{ rad/day (inner zone)}$$

Protons

The calculation for protons is more difficult than that for electrons because the range energy relation and energy loss rate for protons cannot be approximated by as simple an expression as was used above for the electrons. A power law fits the curves of Figures **3-13** and **3-14** quite well, but a function of this form will not yield an answer in closed form. A sample calculation has been previously performed for an inner radiation zone orbit that can be used here, however (Ref. 10). The calculation was carried out quite accurately for a shielding thickness of 1 g/cm^2, which gave, for an integral energy spectrum of $1.8 \times 10^4 E^{-0.8}$ protons/cm^2 sec for E between 27 and 1000 Mev, a dose rate of 1.00 rad/hr. To use this number for the orbits chosen here we simply note that the integral spectrum used in the calculation referred to gives an intensity of 9.4×10^2 protons/cm^2 sec of energies greater than 40 Mev. The dose rate for the orbits of Table **3-7** thus becomes:

$$R = 2.9 \times 10^{-7} k \text{ rad/day.}$$

This result is for an aluminum thickness of 1 g/cm^2 or 0.146 inches of aluminum. Looking at Figures **3-13** and **3-14** we note that this thickness of aluminum will just stop 28 Mev protons. A thickness of 0.060 inches will stop 15 Mev protons. Thus $(28/15)^{0.8} = 1.65$ times as many protons penetrate 60 mils of aluminum as penetrate 146 mils. Since the energy loss rate for protons of this energy is not strongly energy dependent, a good approximation for the dose rate under 60 mils of aluminum would be:

$$R = 4.6 \times 10^{-7} k \text{ rad/day.}$$

Interplanetary Space

The dose rate in interplanetary space due to galactic cosmic rays was measured on the Pioneer V space probe below 1 g/cm^2 of low Z shielding materials, and was found to be 14 mrad/day. The dose rate from solar flares, on the other hand, cannot easily be measured and so must be calculated. Calculating this dose rate is a formidable task because (1) the temporal variations of the particle intensities as well as the energy spectrum of these ejected particles are not known accurately, and (2) calculations would be difficult, requiring a computer, even if the flare characteristics were well known.

An estimate of the dose rate can be made by fitting the differential energy spectrum of 0412 U.T. in Figure 3-8, to a power law in energy of the form $kE^{-\gamma}$ which gives a value for γ of 1.7. In the inner radiation zone a value of $\gamma = 1.8$ has been used for the differential energy spectrum to give the dose rates reported under Protons above. To obviate the necessity of performing a separate computer calculation for the solar flare contribution to dose rates, an approximate result can be obtained using $\gamma = 1.8$ for this case as well. With this approximation and assuming the peak flare intensity yields twenty times the average intensity, the average number of protons/cm^2 sec greater than 40 Mev is 6.3. The dose rate is thus

$$R = 4.6 \times 10^{-7} \times \left[6.3 \times 8.64 \times 10^{4}\right] \text{ rad/day}$$

or

$$R = 0.25 \text{ rad/day}$$

Section IV discusses the effects of space radiation on valve materials, and includes a sample problem illustrating application of the equations in this section.

REFERENCES - RADIATION

1. Project Relay Quarterly Technical Progress Report of 1 June 1962 to 31 August 1962, Space Technology Laboratories Report No. 8614-6037-SU-000.

2. Freden, S. C., and R. S. White. "Protons in the Earth's Magnetic Field." Phys. Rev. Letters, 3, 9-10, 145, 1959.

3. Freden, S. C. and R. S. White. "Particle Fluxes in the Inner Radiation Belt," UCRL-5877-T.

4. Naugle, J. E., and D. A. Kniffen. "Flux and Energy Spectra of the Protons in the Inner Van Allen Belt," Phys. Rev. Letters, 7, 3-6, 1961.

5. Heckman, H. H., and A. H. Armstrong. "Spectrum of Geomagnetically Trapped Protons," J. Geophys. Research, 67, 1255 (1962).

6. Pizzella, G., C. E. McIlwain, and J. A. Van Allen. "Time Variations of Intensity in the Earth's Inner Radiation Zone, October 1959 Through December, 1960," J. Geophys. Research, 67, 1235-1253, 1962.

7. Fan, C. Y., P. Meyer, and J. A. Simpson. "Dynamics and Structure of the Outer Radiation Belt," J. Geophys. Research 66, 2607-2640, 1960.

8. Peters, B. "Progress in Cosmic Ray Research since 1947, J. Geophys. Research, 65, 155-173, 1959.

9. Winckler, J. R. "Primary Cosmic Rays," Radiation Research, 14, 521-539, 1960.

10. Rosen, A., C. A. Eberhard, T. A. Farley, and J. L. Vogl. "A Comprehensive Map of the Space Radiation Environment," Space Technology Laboratories, Inc. Report No. 8644-6003-RU-000.

11. Gray, P.D., et al, Rockets in Space Environments - Phase I: Parameter Study, Report No. 2112, 27 October 1961, Aerojet-General Corporation.

12. Gray, P.D., et al, Rockets in Space Environments - Phase II: Individual Component Investigation, April 1962, Report No. 2263 Aerojet-General Corporation.

13. Gray, P.D., et al, Engine Operating Problems in Space, Report No. 0629-01-2 (Quarterly), Contract NAS7-98, 29 May 1962, Aerojet-General Corporation

14. Gray, P.D., et al, Engine Operating Problems in Space, Report No. 0629-01-2 (Quarterly), Contract NAS7-98, 29 August 1962, Aerojet-General Corporation

TABLE 3-7 RADIATION DOSE RATES FOR VARIOUS ORBITS

TYPE	RADIUS	PERIOD	ELECTRONS/CM^2 ORBIT	PROTONS/CM^2 ORBIT	ELECTRONS/CM^2 DAY	PROTONS/CM^2 DAY
Polar	1.5 R_e	156 min	2.3×10^{12}	1.7×10^{8}	2.1×10^{13}	1.55×10^{9}
Equat	1.5 R_e	156 min	9.4×10^{12}	9.4×10^{8}	8.6×10^{13}	8.6×10^{9}
Polar Before	3.5 R_e	557 min	2.45×10^{11}	———	6.2×10^{11}	———
Equat Before	4.2 R_e	731 min	6.8×10^{11}	———	1.7×10^{12}	———
Polar After	4.2 R_e	731 min	4.8×10^{12}	———	9.5×10^{12}	———
Equat After	4.2 R_e	731 min	1.8×10^{13}	———	3.4×10^{13}	———

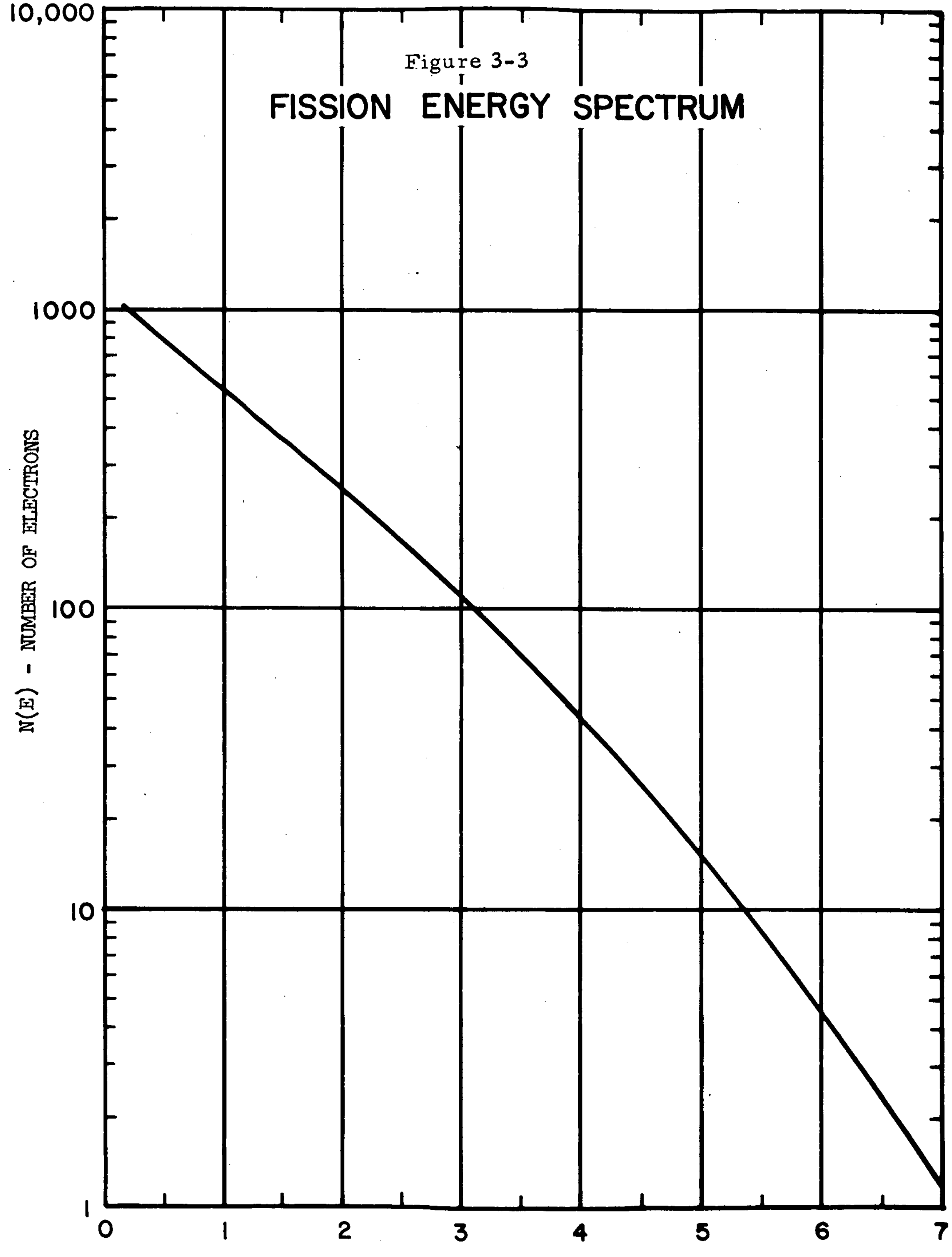


Figure 3-3

FISSION ENERGY SPECTRUM

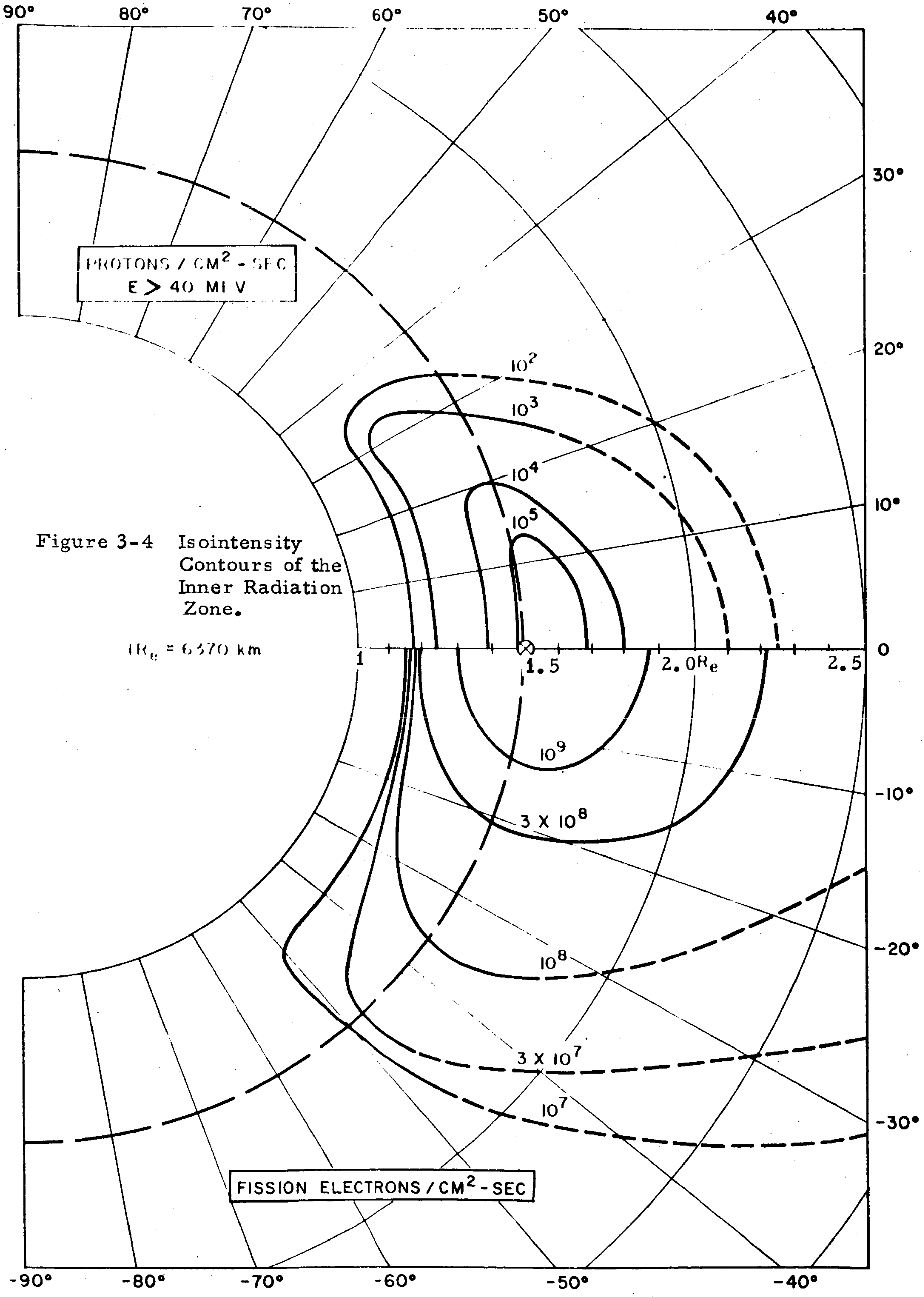


Figure 3-4 Isointensity Contours of the Inner Radiation Zone.

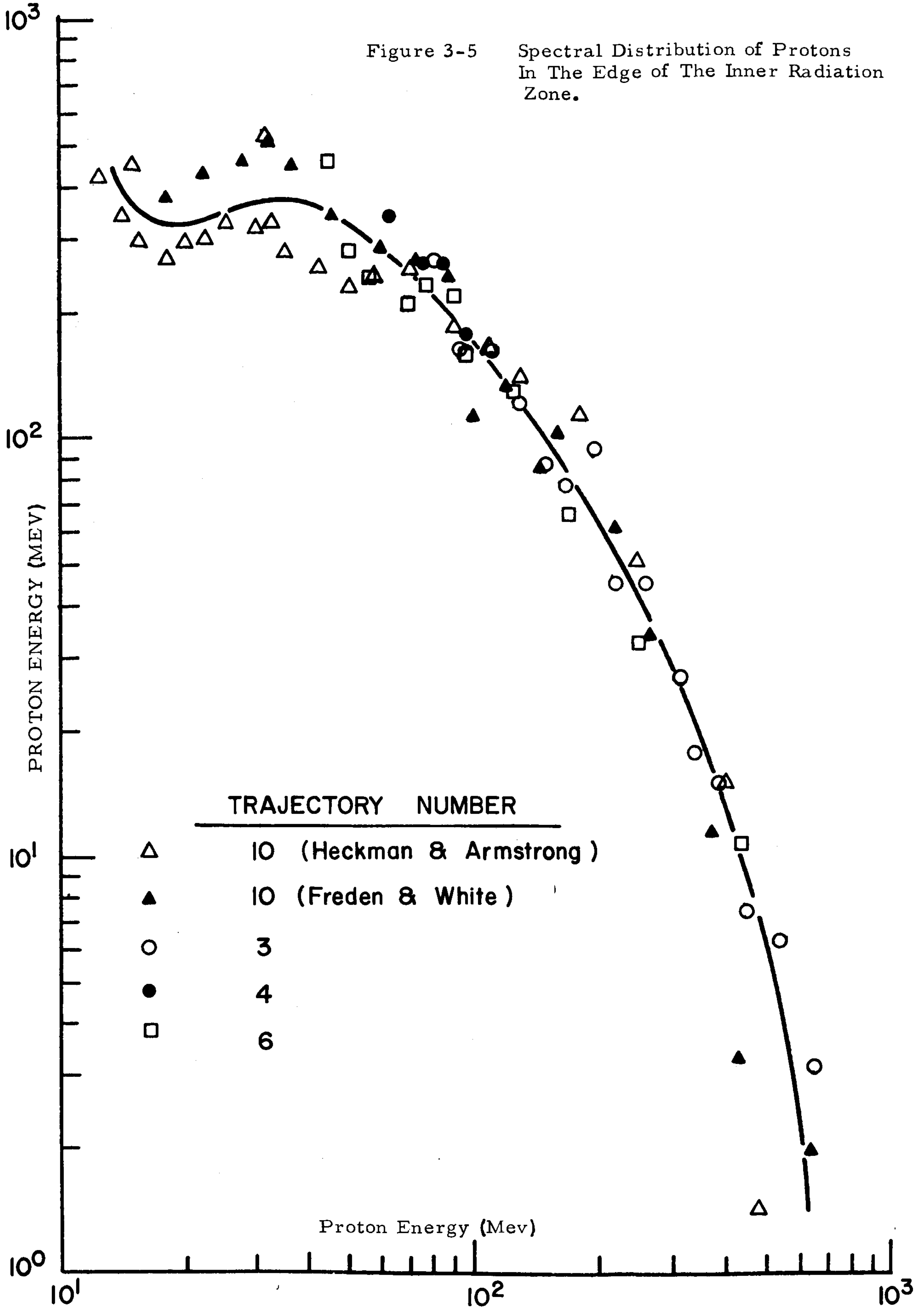
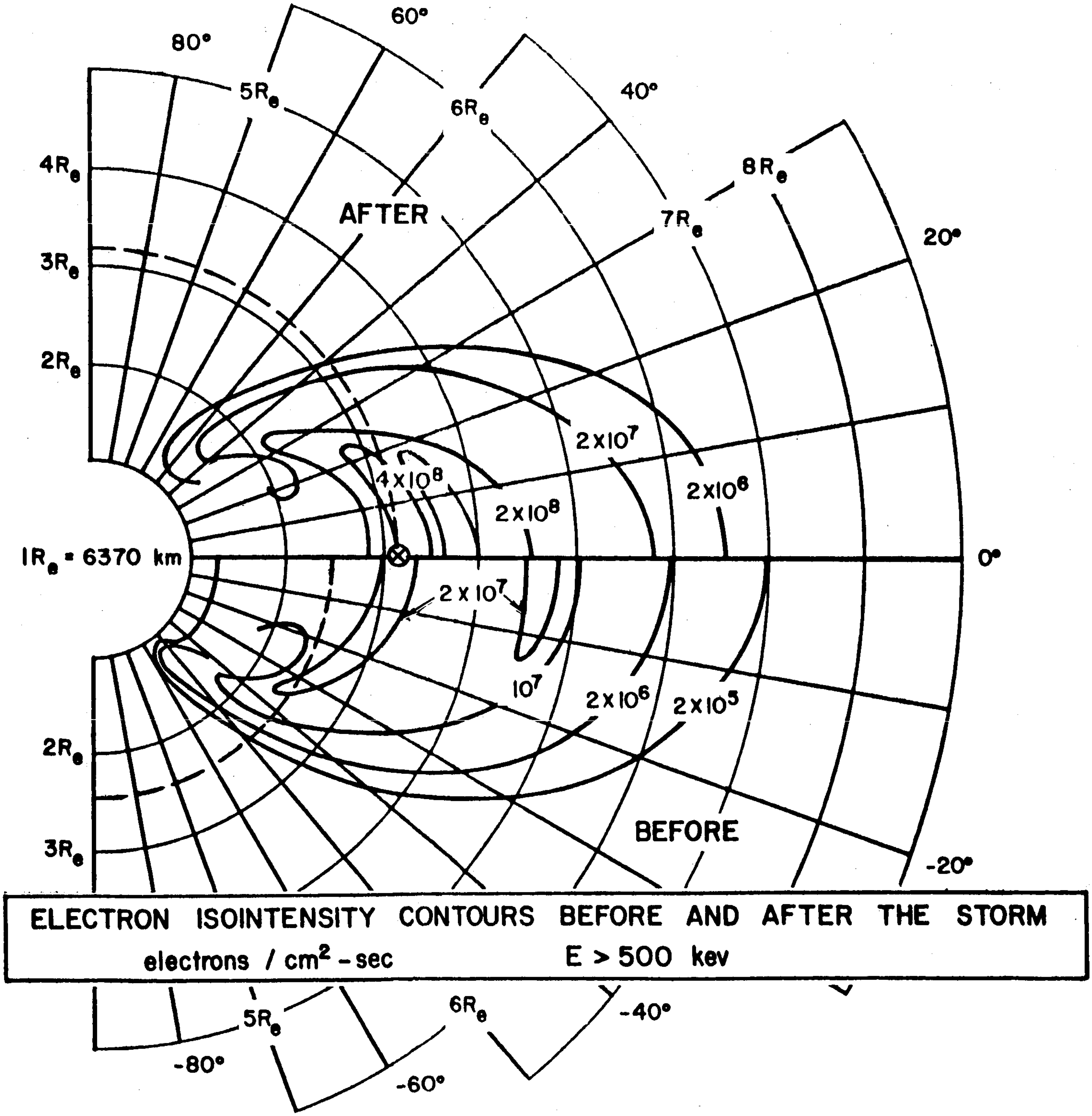


Figure 3-5 Spectral Distribution of Protons In The Edge of The Inner Radiation Zone.



ELECTRON ISOINTENSITY CONTOURS BEFORE AND AFTER THE STORM

electrons / cm^2 - sec E > 500 kev

Figure 3-6

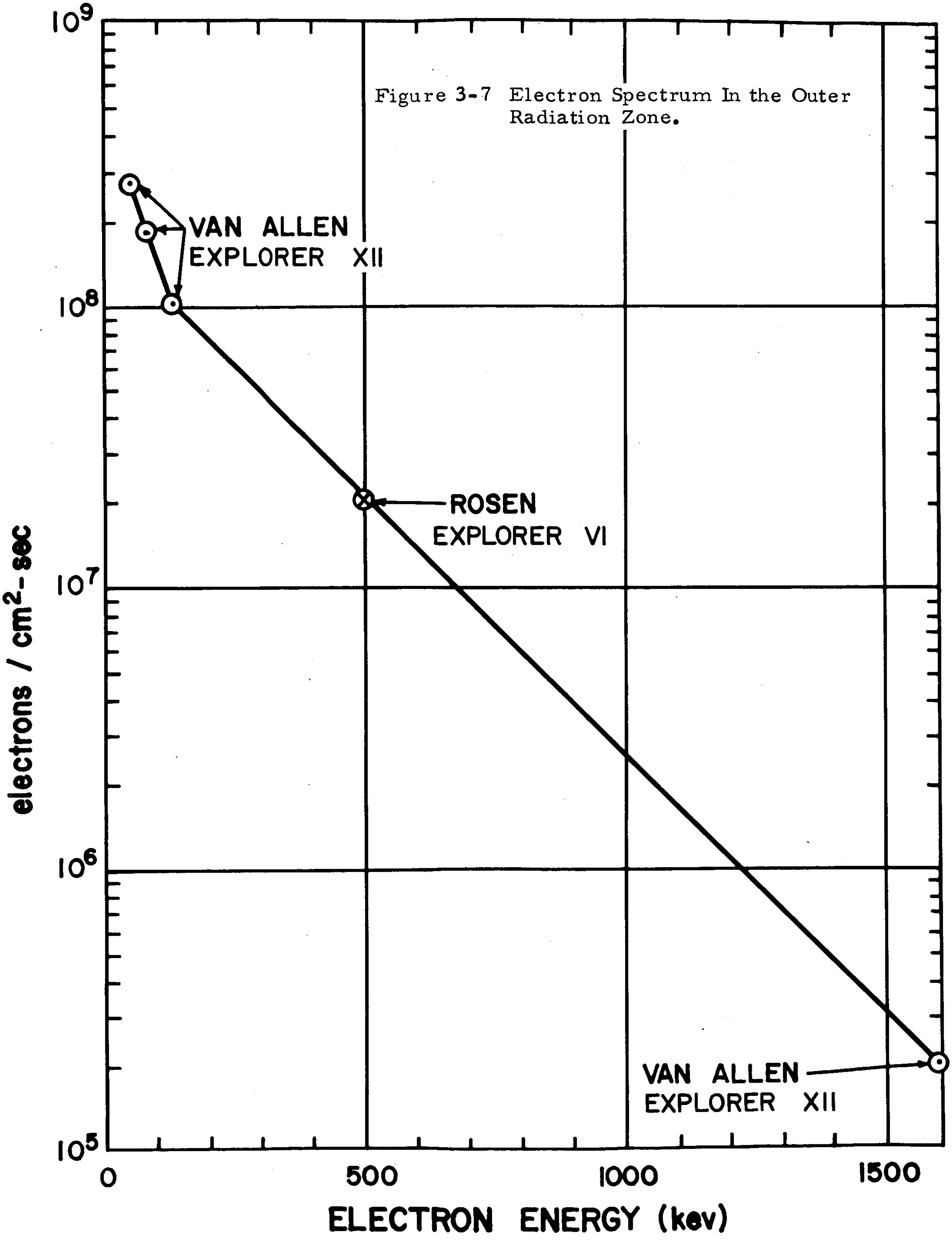


Figure 3-7 Electron Spectrum In the Outer Radiation Zone.

Figure 3-8 DIFFERENTIAL ENERGY OF DECAY OF SEPT. 28 EVENT

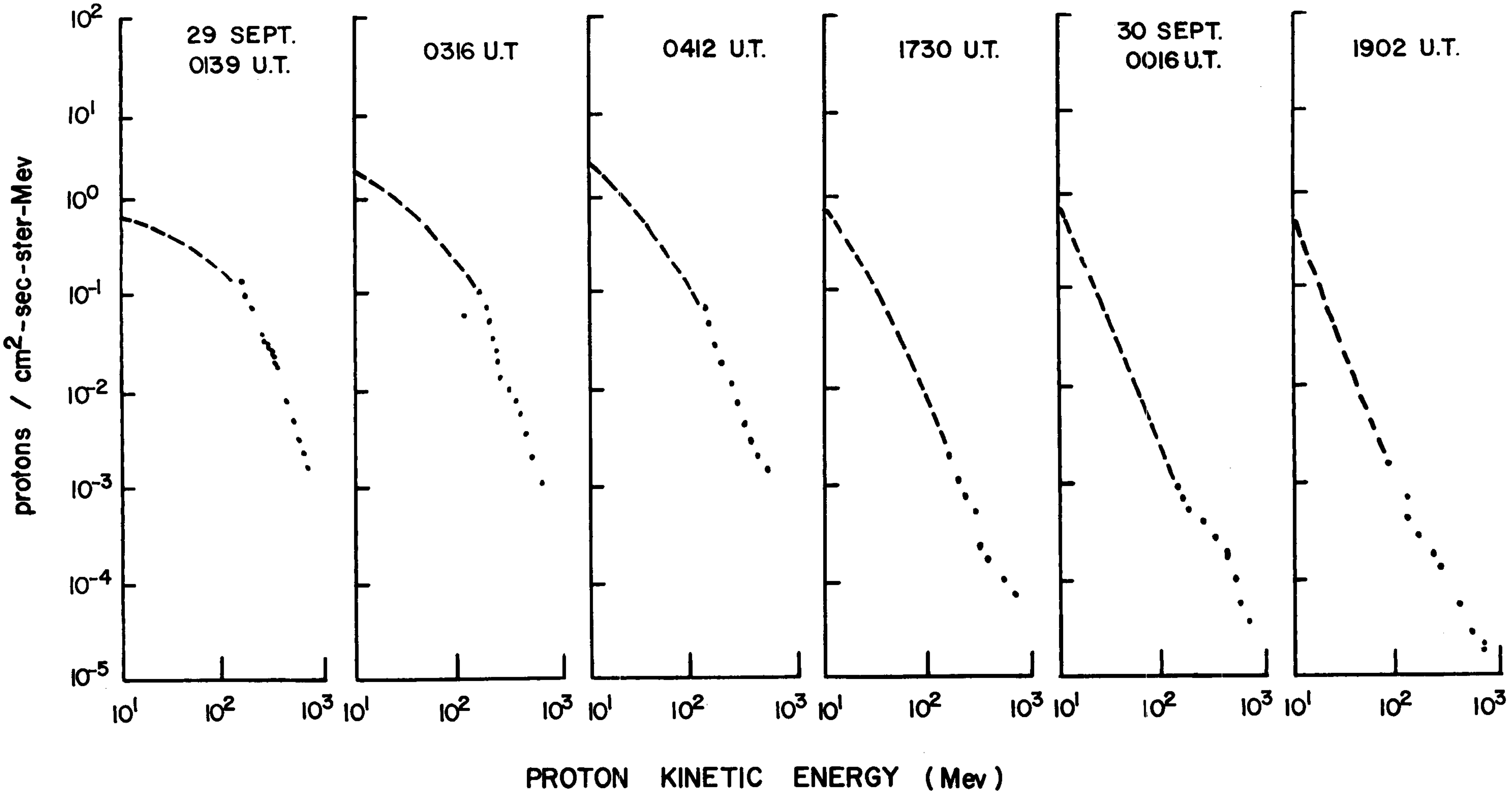


Figure 3-9 GAMMA-RAY ABSORPTION AT I MEV ENERGY

I_o = INITIAL RADIATION INTENSITY

I = RADIATION INTENSITY AT A DISTANCE X

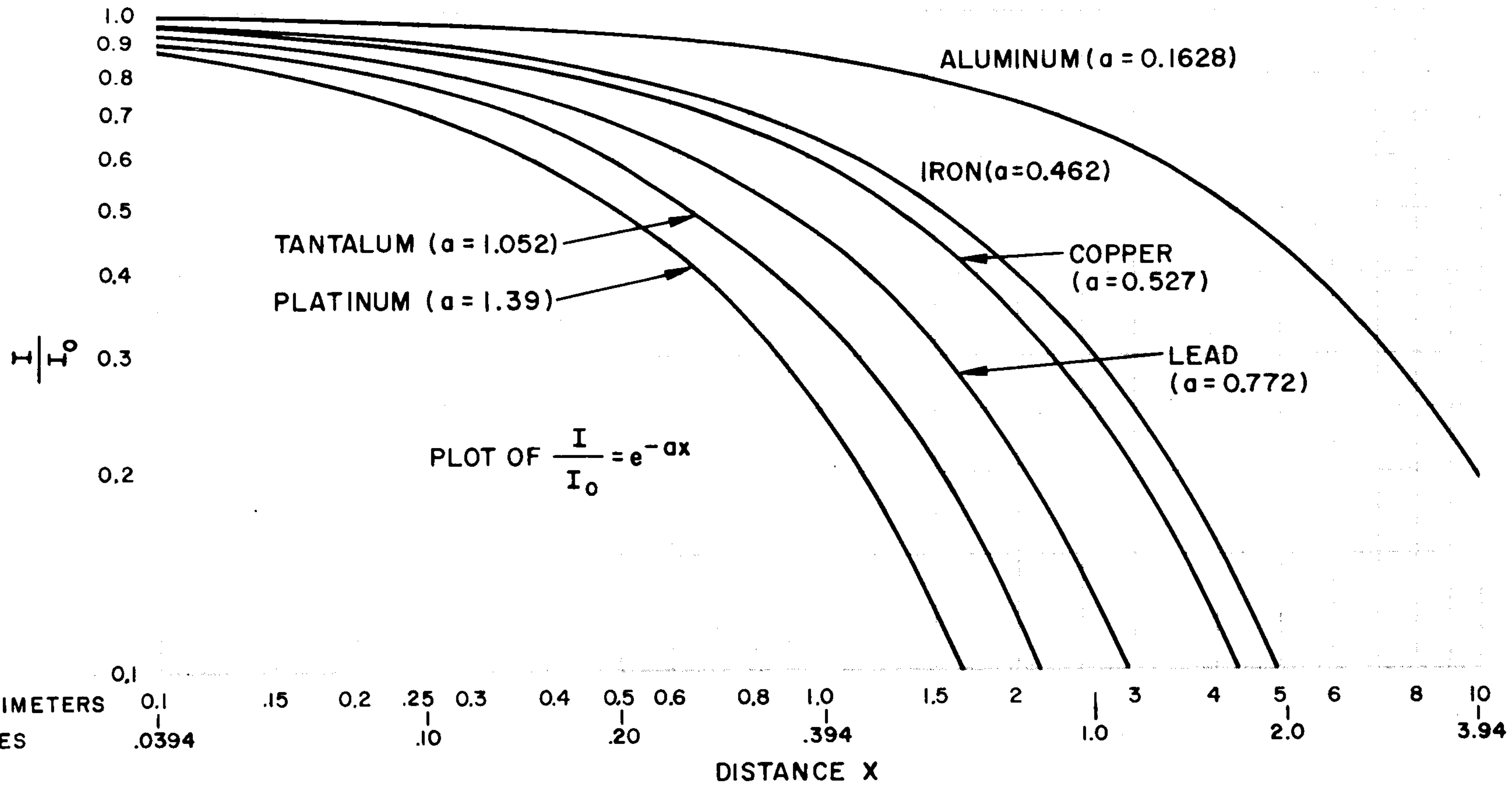


Figure 3-10 GAMMA-RAY ABSORPTION AT 4 MEV ENERGY

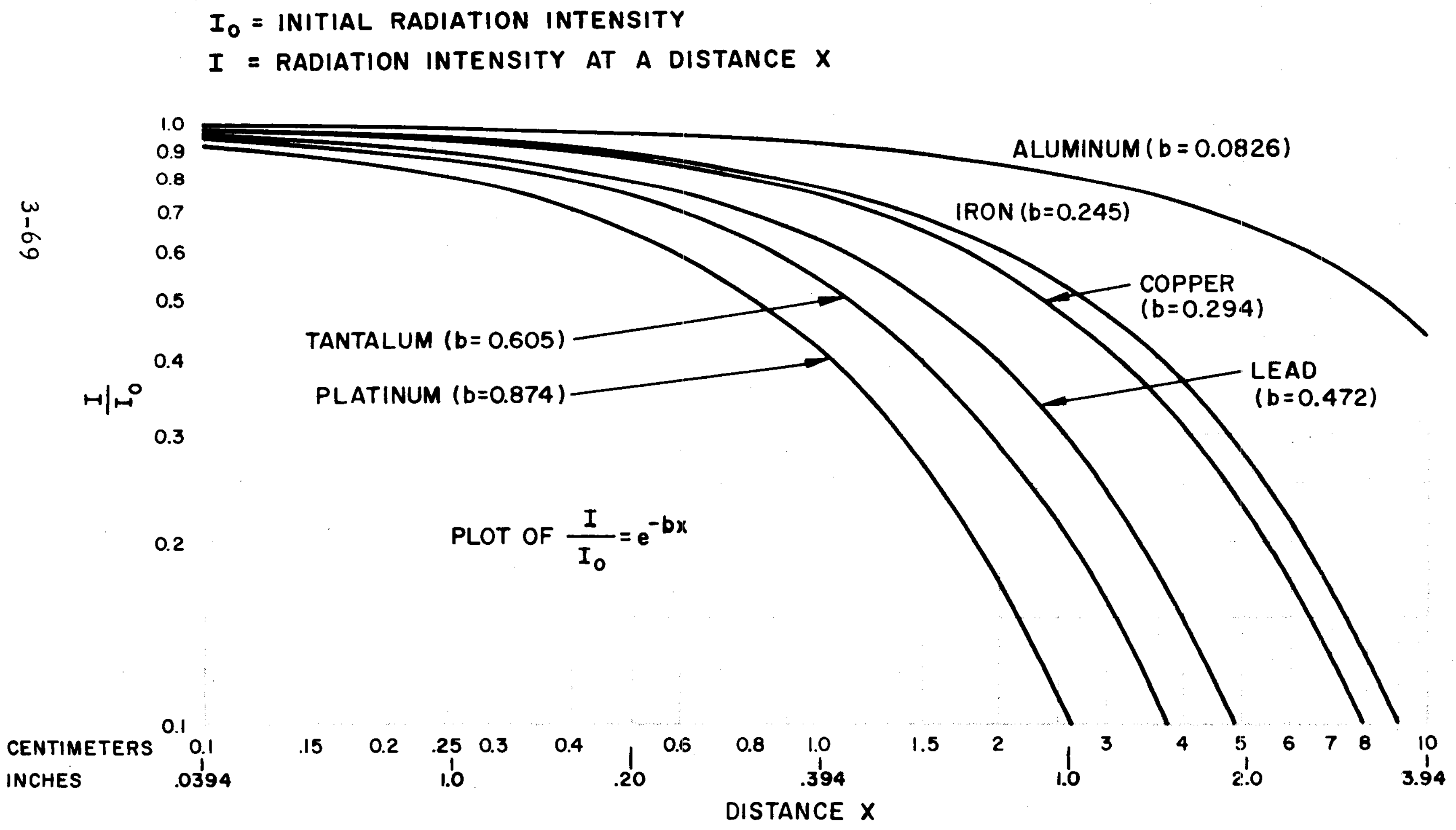
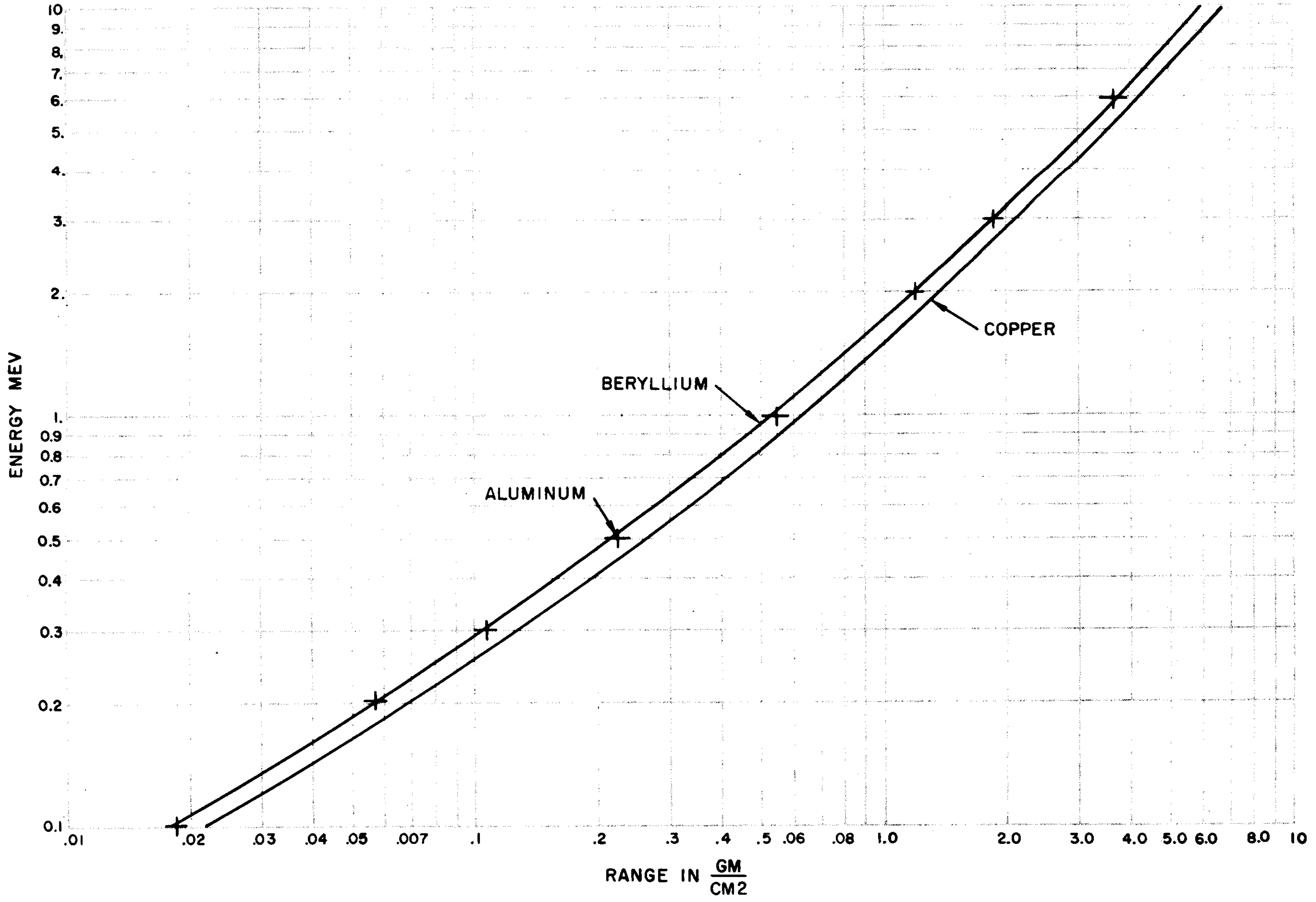


Figure 3-11 RANGE-ENERGY RELATION FOR ELECTRONS TO 10 MEV



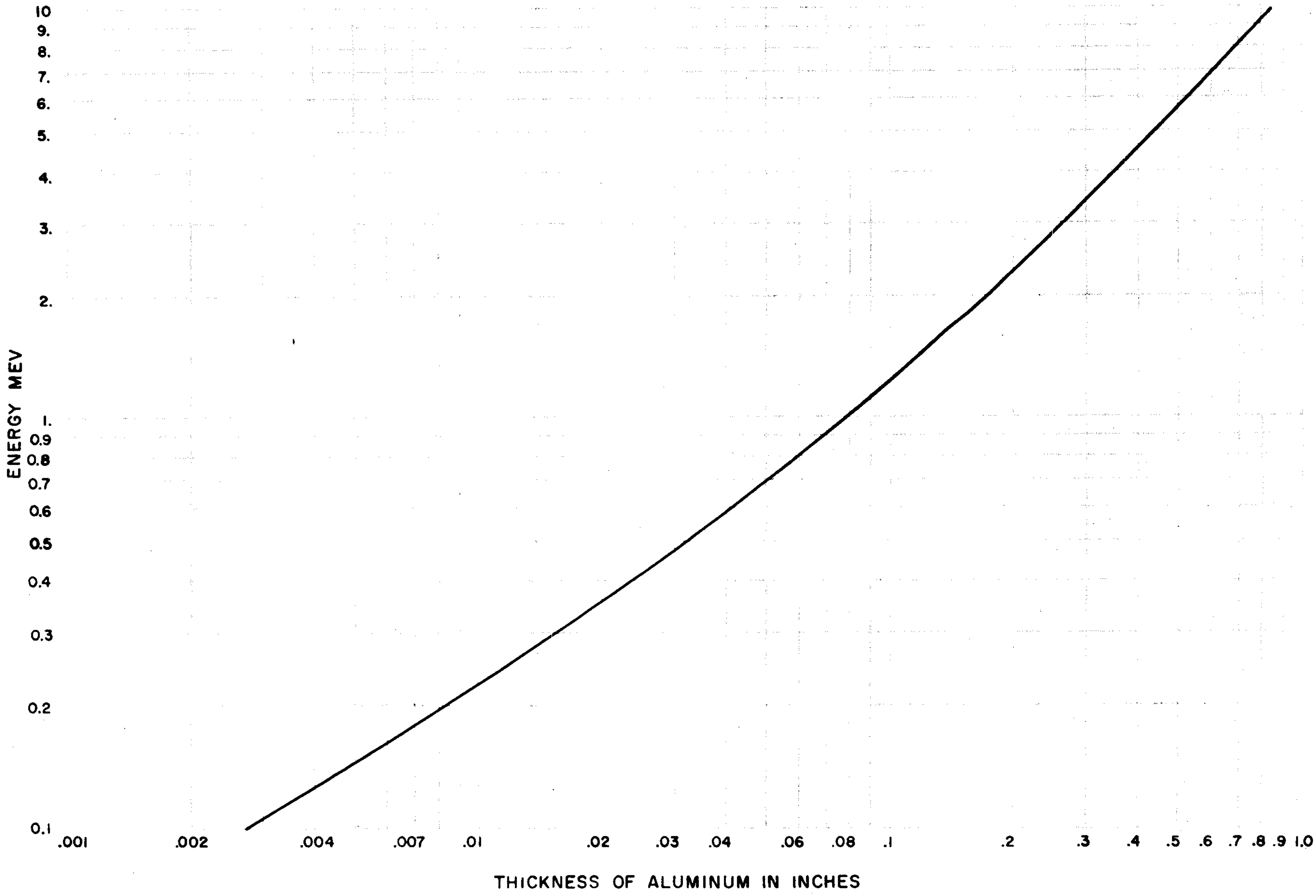


Figure 3-12 RANGE-ENERGY RELATION IN ALUMINUM FOR ELECTRONS TO 10 MEV

RANGE THICKNESS IN INCHES VS ELECTRON ENERGY IN MEV

Figure 3-13 RANGE-ENERGY RELATION FOR PROTONS TO 100 MEV

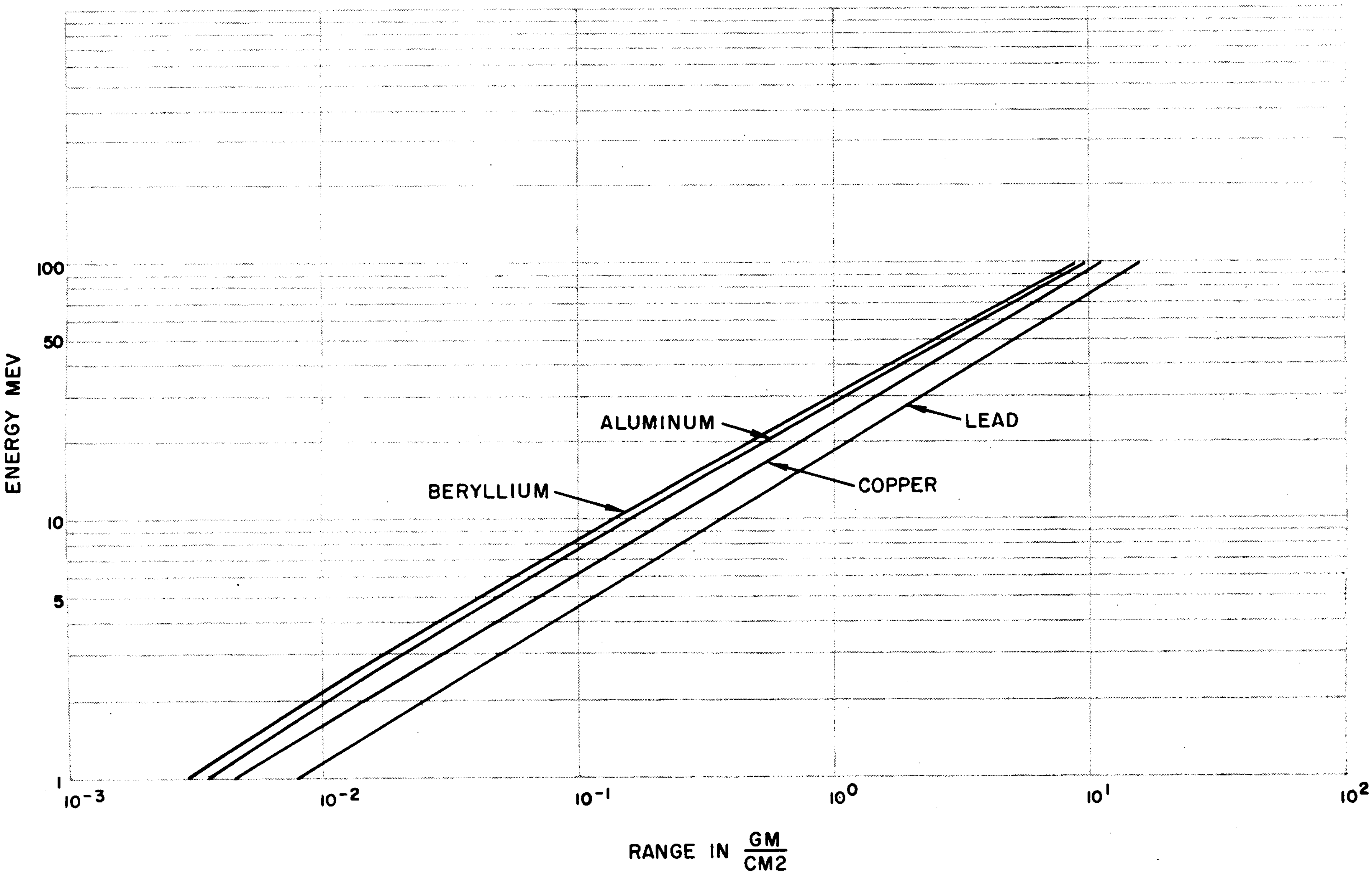


Figure 3-14 RANGE-ENERGY RELATION FOR PROTONS TO 100 MEV

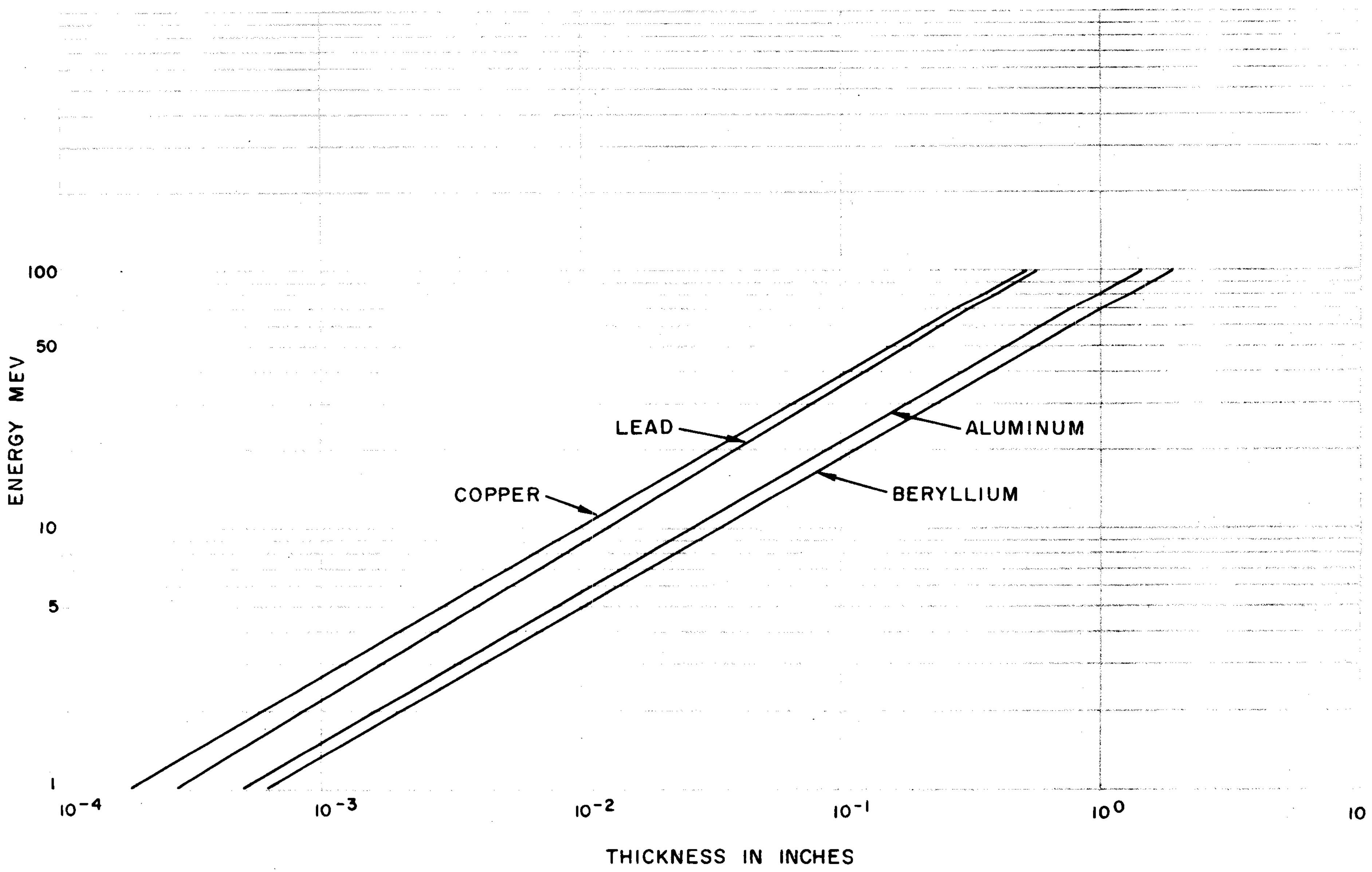
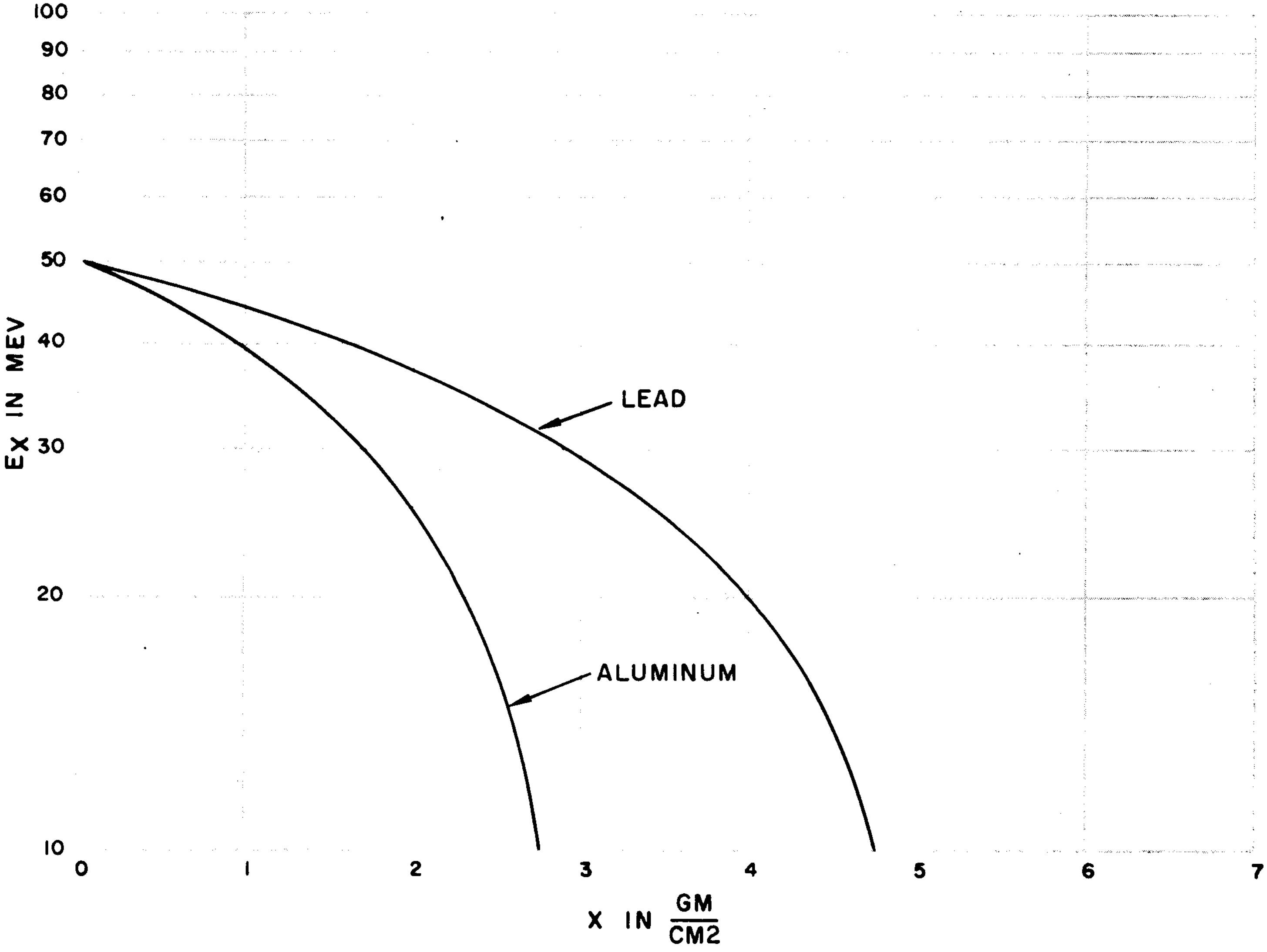


Figure 3-15 **PROTON ENERGY DEGRADATION**



Eo = 50 MEV-INITIAL PROTON ENERGY
Ex = PROTON ENERGY AT DISTANCE X

Zero Gravity

The absence of gravity is impossible to duplicate on earth except for short periods of time. At present testing in a zero-gravity field is very difficult or impossible; therefore, very little information is available on this environmental parameter. There are some generalizations that can be made, however.

It is generally believed that no significant effects on materials will be encountered due to the zero-gravity condition in space. Heat transfer by convection is not possible in a zero-gravity field. Design depending on weights and liquid-liquid or liquid-vapor separating to some predictable orientation will be useless in the zero-gravity field.

The behavior of contained liquids in a zero-gravity field may depend on the wettability of the liquids with the container walls. Liquids which do not wet the container walls will tend to contract to a spherical shape and leave the wall to be suspended in space. Liquids which do wet the container walls will tend to spread out over the wall, leaving the gas pocket in the center.

Other forces will act on a space vehicle whereby the problems associated with zero gravity are alleviated to some degree. The forces that may produce an artificial gravity force are:

1. Orbit transfer or correction forces
2. Spinning or tumbling of the spacecraft
3. Solar radiation pressures

Noted below are several problems associated with a zero-gravity field:

1. Fluid heat transfer must depend on mechanisms other than convection, such as film boiling, conduction and diffusion.

2. Venting the gas from a liquid-vapor phase requires techniques to prevent loss of the liquid. A vent valve capable of this without special design of the tank is an immediate problem.

3. Transfer or flow of fluids, such as propellants and lubricants, must be made without dependence upon gravity.

4. Spring mass system characteristics are subject to change. For example, the resultant force on a regulator controller could be altered in going from a 1g field to a zero-g field, with a consequent shift in the regulator output values.

TIME

Although time is not usually thought of as an environmental parameter, it will be considered as such for purposes of this report. Probably in all cases time works in the direction of performance degradation, and its effect is, of course, more pronounced with less stable materials such as the polymers than with metals.

Several mission durations are presented as follows. (Ref. 1)

	Nominal Velocity (ft/sec)	Nominal Duration
Earth Orbit, 300-n. mi. Orbit	30,000	90 minutes
Earth Escape, Circumlunar	40,000	5 days
Lunar Landing, One Way	50,000	2-1/2 days
Lunar Landing, Earth-Return	60,000	1 - 2 weeks
Mars Cargo Mission, One Way	64,000	9 months
Mars Reconnaissance Mission (1-Year Duration, No Landing, No Martian Orbit)	85,000	12 months
Close Solar Probe, One-Way Instrumented	90,000	4-1/2 months
Mars Reconnaissance, Planetary Orbit and Return to Earth	98,000	2-1/2 years
Venus Reconnaissance, Planetary Orbit and Return to Earth	104,000	1-1/4 years
Solar System Escape, Ecliptic	120,000	-----
Mercury Reconnaissance, Planetary Orbit and Return to Earth	150,000	1-1/2 years

	Nominal Velocity (ft/sec)	Nominal Duration
Solar System Escape, 45° out of Ecliptic	245,000	-----
Jupiter Reconnaissance, Planetary Orbit and Return to Earth	250,000	3-2/3 years
Saturn Reconnaissance, Planetary Orbit and Return to Earth	400,000	4-1/2 years

Table 3-8 presents the functional and environmental parameters with related comments on the effect of the time parameter.

Ref. 1. The Space Mission Planning Chart by Allyn B. Hazard, Staff Specialist, Space-General Corporation, El Monte, California.

Table 3- 8 Relationship of Time ane Effects of Functional and Environmental Parameters

Functional and Environmental Parameter	Effects of Parameter	Time Relationship
Meteoroids	Penetration and Erosion	Probability increase with exposure to time
Radiation	Degradation and surface changes on materials	Direct and cumulative relationship; also periodic depending on space flight path
Thermal radiation	Temperature balance and gradients	Constant or varying for heliocentric orbits and periodic for planetary orbits
Zero gravity	Venting of gases, spring mass systems, and fluid systems	Independent
Space vacuum	Sublimation and evaporation of materials and increase in friction	Direct relationship
Planetary atmospheres	Material effects and friction variations	Direct and periodic relationship
Flow media	Corrosion of materials, chemical changes and boil-off of propellant	Increases with exposure to time
Leakage	Loss of propellant corrosion and loss of range	Direct relationship
Contamination	Decreases reliability of the valves	Direct relationship due to corrosion; periodic due to meteoroidal impact and generated wear debris
Space maintenance	———	Direct relationship
Acceleration, vibration, shock	Valve performance	Periodic

TEMPERATURE IN SPACE

The primary sources of thermal energy for a space system within the solar system are the sun and the internal energy generated by the equipment housed within the space vehicle. Other sources may be the earth, moon, or other planets, and may be of greater importance for orbiting vehicles or re-entry conditions.

Temperature control is attained primarily through heat transfer by radiation and may be accomplished by the use of reflecting materials or reflection devices such as rotating louvers. In some instances the temperature requirements for valves are governed by the temperature control requirements of the space vehicle, since the propulsion control system is normally housed within the space vehicle.

Heat energy derived from the total electromagnetic spectrum is 7.4 Btu/ft^2 min. at a distance of 1 au (astronomical unit). At any given distance, the amount of heat energy is inversely proportional to the square of that distance from the sun. The propellants such as those used in cryogenic systems or hot gas systems may be the most important source of heat energy or in some cases the sterilization temperatures may be the most critical design temperature. These temperatures are discussed in this report under "Operating Temperature" and under "Sterilization".

A thermal analysis on a spinning or perfect conducting body in space is given, including conditions of earth reflection and radiation. Because of the complexity of an analysis directed toward a particular case (such as a valve mounted to a rocket engine and exposed to space), emphasis will be on the more general case.

A general approach was taken to allow estimations of the temperature of bodies exposed to the thermal environment in the proximity of Earth, Mars, and the moon. Results were also derived for a body away from any planet's influence such that the sun was the only energy source. Internal power dissipation of the body was considered negligible. The curves could be used for a power dissipating body, however, provided that the power was not large compared to the energy absorbed by the body and that great accuracy is not required. The analysis also assumes that the heat leak into the body from other components can be considered to be small.

With above model definition it is possible to write a heat balance equation that describes the steady state thermal balance of the body. The factors to be considered are:

1) Solar irradiation
2) Planet emission
3) Planet reflectance

The earth's distance from the sun is relatively constant with the aphelion distance only about 4% greater than perihelion. The solar flux for Mars was taken at perihelion so that the maximum temperature condition results. All heat balances for the curves showing body temperatures near the earth, moon or Mars (Figures 3-16, 3-17, 3-18) are for the sub-solar position and represent the highest temperature condition. The influence of the two planets and the Moon on the temperature of a body in their proximity is quite small at a distance of 10,000 statute miles. This is simply the result of the emitted and reflected radiation intensity varying inversely as the square of the distance. From a distance of 10,000 statute miles and greater, the body temperature can be read from Figure 3-19, which gives body temperature as a function of distance from the sun, and away from the thermal influence of any planets.

Figure 3-20 is a generalized heating curve that allows determination of the temperature-time relation for a given body, exposed to the sun after having been shadowed or eclipsed, and away from the thermal influence of a planet. The equation for cooling of the body has not been put in the form of a curve since it is readily usable as derived.

Thermal Data

	Temperature, *°F	Albedo	H_s, Btu/hr ft^2
Earth	-12	.35	442
Moon	255	.07	442
Mars	90	.15	231

*Effective black body temperature at sub-solar point

General Energy Balance, Steady State

For a body in vicinity of Earth, Moon, or Mars, the steady state energy balance is as follows:

Energy absorbed from planet + Energy absorbed from sun
(emitted and reflected) (emitted)

= Energy from body
(emitted)

$$A_{p,\oplus e}\,\alpha H_{\oplus e} + A_{p,\oplus r}\,\alpha_s H_{\oplus r} + A_{p,s}\,\alpha_s H_s = A_t \epsilon \sigma T^4$$

This equation was solved in terms of the distance from the planet with the ratios α_s/ϵ and the total area/projected area as parameters (Figures 3-16, 3-17, 3-18). For the case of a body far from a planet and influenced by the sun only, the first two terms drop out of the above balance, resulting in the equation

$$A_{p,s}\,\alpha_s H_s = A_t \epsilon \sigma T^4 \qquad \text{(Figure 3-19)}$$

General Energy Balance, Transient

For a body away from the thermal influence of the planets the energy balance is as follows:

Heating: energy absorbed = energy stored + energy emitted

$$A_{p,s}\,\alpha_s H_s = Wc\frac{dT}{dt} + A_t \epsilon \sigma T^4$$

letting:

$A = Wc$

$B = A_t \epsilon \sigma$

$C = \alpha_s A_{p,s} H_s$

$$C = A\frac{dT}{dt} + BT^4$$

$$\int_{T_o}^{T} \frac{A/B}{T^4 - C/B}\,dT = -\int_o^t dt$$

Solving and setting $T_o = o$

$$\ln\frac{(C/B)^{1/4} + T}{(C/B)^{1/4} - T} + 2\tan^{-1}\frac{T}{(C/B)^{1/4}} = \frac{4(C/B)^{3/4}}{A/B}t$$

This equation is graphically presented in Figure 3-20 in terms of significant parameters Wc, $A_t \epsilon \sigma$, and $\alpha_s A_{p,s} H_s$. The results give the temperature of a body versus time after entering sunlight from an eclipsed condition. An example of the use of the curves is presented at the end of this chapter.

Cooling: Cooling of body = energy emitted

$$- \frac{dT}{dt} (Wc) = A_t \epsilon \sigma T^4$$

$$-dT \left(\frac{1}{T^4} \right) = \frac{A_t \epsilon \sigma}{Wc} dt$$

$$- \int_{T_o}^{T} \frac{dT}{T^4} = \frac{A_t \epsilon \sigma}{Wc} \int_{t}^{t} dt$$

$$T = \frac{1}{\left[\frac{1}{To^3} + \frac{3A_t \epsilon \sigma t}{Wc} \right]^{1/3}}$$

Nomenclature:

A = area, ft^2
H = irradiance, Btu/hr ft^2
c = specific heat, Btu/lb ^oR
T = temperature, ^oR
t = time, hrs
W = weight, lbs
α = absorptivity
ϵ = emissivity
σ = Stefan-Boltzmann constant = 0.1714×10^{-8}

Subscripts

e = emitted energy
o = original condition
p = projected
r = reflected energy
s = solar
t = total
$\oplus$ = earth

EXAMPLE 1

Use of Curves:

Consider a spinning sphere in a subsolar orbit on an Earth to Moon mission. The distance traversed is approximately 240,000 miles. The surface temperatures of the body are given in Figures 3-16, 3-17, 3-18) depending on the position of the body in the orbit. For a black body where $\alpha_s/\epsilon = 1$ then from Figure 3-16 and at a distance of 100 statute miles from the earth

$$T\,(A_t/A_p)^{1/4} = 800$$

$$T = 800(A_p/A_t)^{1/4} = 800(1/4)^{1/4} = 566^\circ R$$

or $\quad T = 106^\circ F.$

At a distance of 10,000 statute miles from the earth

$$T = 720(1/4)^{1/4} = 510^\circ R$$

or $\quad T = 50^\circ F$

Figure 3-19 shows that the temperature should remain essentially constant until the body is influenced by the moon's thermal emittance and from Figure 3-17 and at 100 statute miles from the moon

$$T = 870(1/4)^{1/4} = 615^\circ R$$

or $\quad T = 155^\circ F$

The temperature history of a spinning black body sphere on a subsolar lunar mission is then:

Position of Body	Temperature
100 sm to 10,000 sm Earth altitude	106°F to 50°F
1 au from Sun	50°F
10,000 sm to 100 sm Lunar altitude	50°F to 155°F

EXAMPLE 2

The use of the cooling equation and heating curve, Figure 3-20 is explained by the following example: Consider a sphere of 1 pound and 3 inches in diameter that is dissipating negligible power. The vehicle will be assumed in a 10,000 nm circular earth orbit without thermal coupling to the sphere (valve).

$$A_t = \pi D^2 = 0.196 \text{ ft}^2$$

$$A_{ps} = \frac{\pi D^2}{4} = .049 \text{ ft}^2$$

$$c = 0.15 \text{ Btu/lb R (assumed effective value)}$$

$$H_s = 442 \text{ Btu/hr ft}^2$$

$$\alpha_s = 0.15$$

$$\epsilon = .05$$

$$W = 1 \text{ lb (1/2 available)}$$

$$A = Wc = .5(.15) = .075$$

$$B = A_t \, \epsilon \, \sigma = .0017 \times 10^{-8}$$

$$C = \alpha_s A_{ps} H_s = 3.24$$

It is assumed for illustrative purposes that one half of the sphere mass is perfectly coupled thermally with the remainder unavailable as heat sink. The period is 10.85 hours with maximum eclipse time of 0.895 hours. From Figure 3-19 read steady state body temperature of 660°R. It is then found from the cooling equation that the body temperature will be 270°R. Entering Figure 3-20 at 270°R and with the parameter $(C/B)^{1/4} \doteq 660$, it is found that the time parameter on the abscissa is 1.68. The corresponding real time, i.e., the time required to bring the body from 0°R to 270°F is found from the parameters A, B and C and the abscissa to be 6.42 hours. After 9.95 hours of sunlight orbit the abscissa would then correspond to $\left(\frac{6.42 + 9.95}{6.42}\right) 1.68 = 4.77$. The temperature is then found to be 600°R at the end of the illuminated part of the orbit, or 60 degrees less than its steady-state temperature. A second iteration would use the cooling equation with a starting temperature of 600 rather than 660°R.

This example illustrates the necessity for either exterior surface finish thermal control for the valve, or good thermal coupling with a temperature controlled region of the vehicle, since 270°R is too low a temperature for most valves.

A vehicle with a shorter orbital period would have a much higher ratio of eclipse to sunlight such that steady-state conditions would not be reached. For convenience note that $(C/B)^{1/4}$ is equal to the steady-state temperature of the valve.

Also, a temperature cycle for a valve could be plotted by solving for temperature versus time through several periods until a recurring temperature cycle is established.

Conclusions

For the general case of heat energy to a body in space, the design parameters to consider are the α_s/ϵ ratio and the A_t/A_p ratio. For any specific valve on a spacecraft, the heat transfer analysis is more complicated and each case should be analyzed separately. However, considering the general case of spheres, cylinders and parallelepipeds, the α_s/ϵ ratio is important and the analyses given here indicate that the finish and the surface materials should be selected for optimum temperatures. Hard anodized aluminum closely represents a black body, but for many materials used in valves, organic coatings or insulation such as aluminized mylar ($\alpha_s/\epsilon \approx .25$) should be considered.

Figure 3-16 GENERALIZED BODY TEMPERATURE, NEAR EARTH

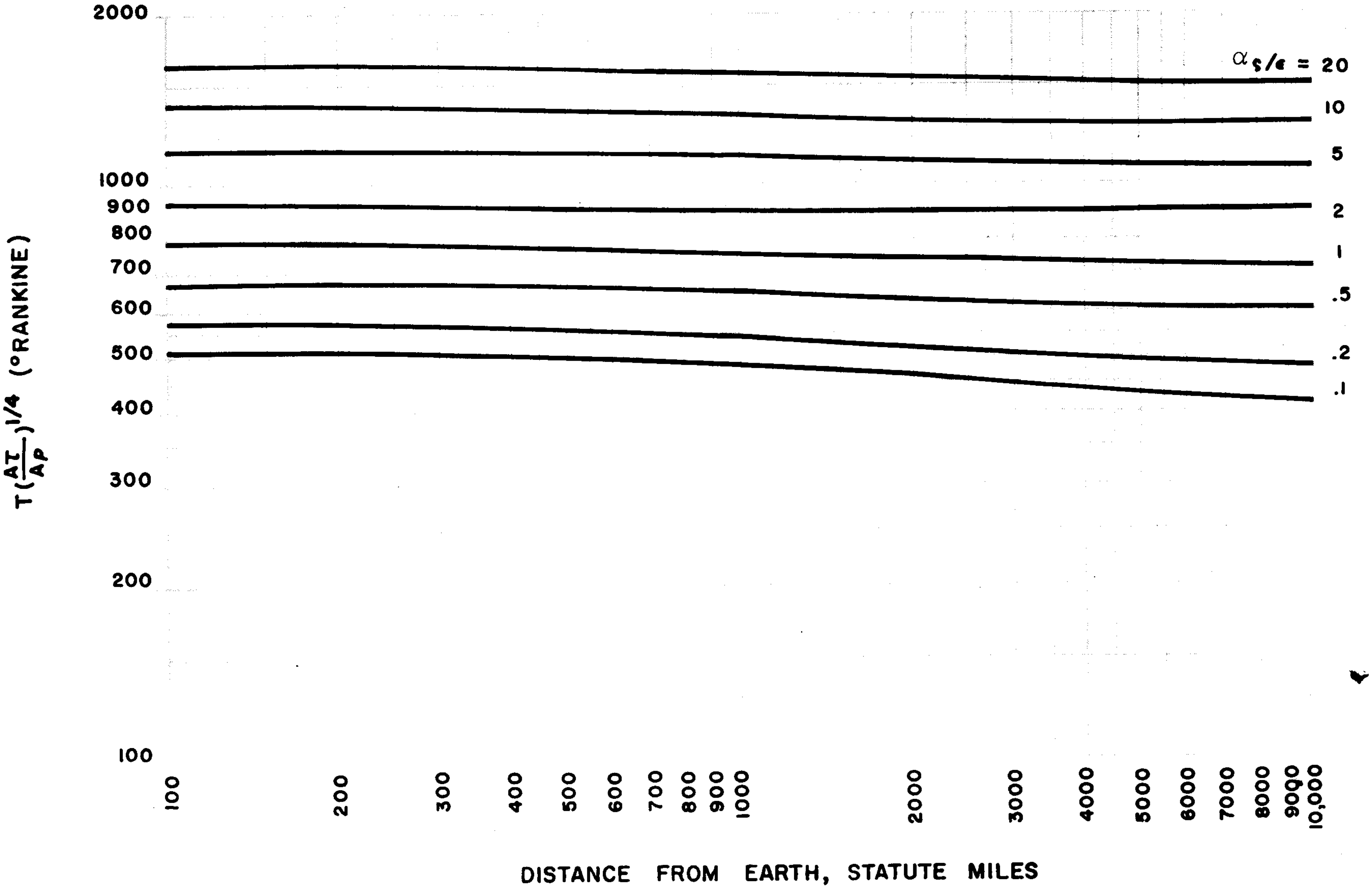


Figure 3-17 GENERALIZED BODY TEMPERATURE, NEAR MOON

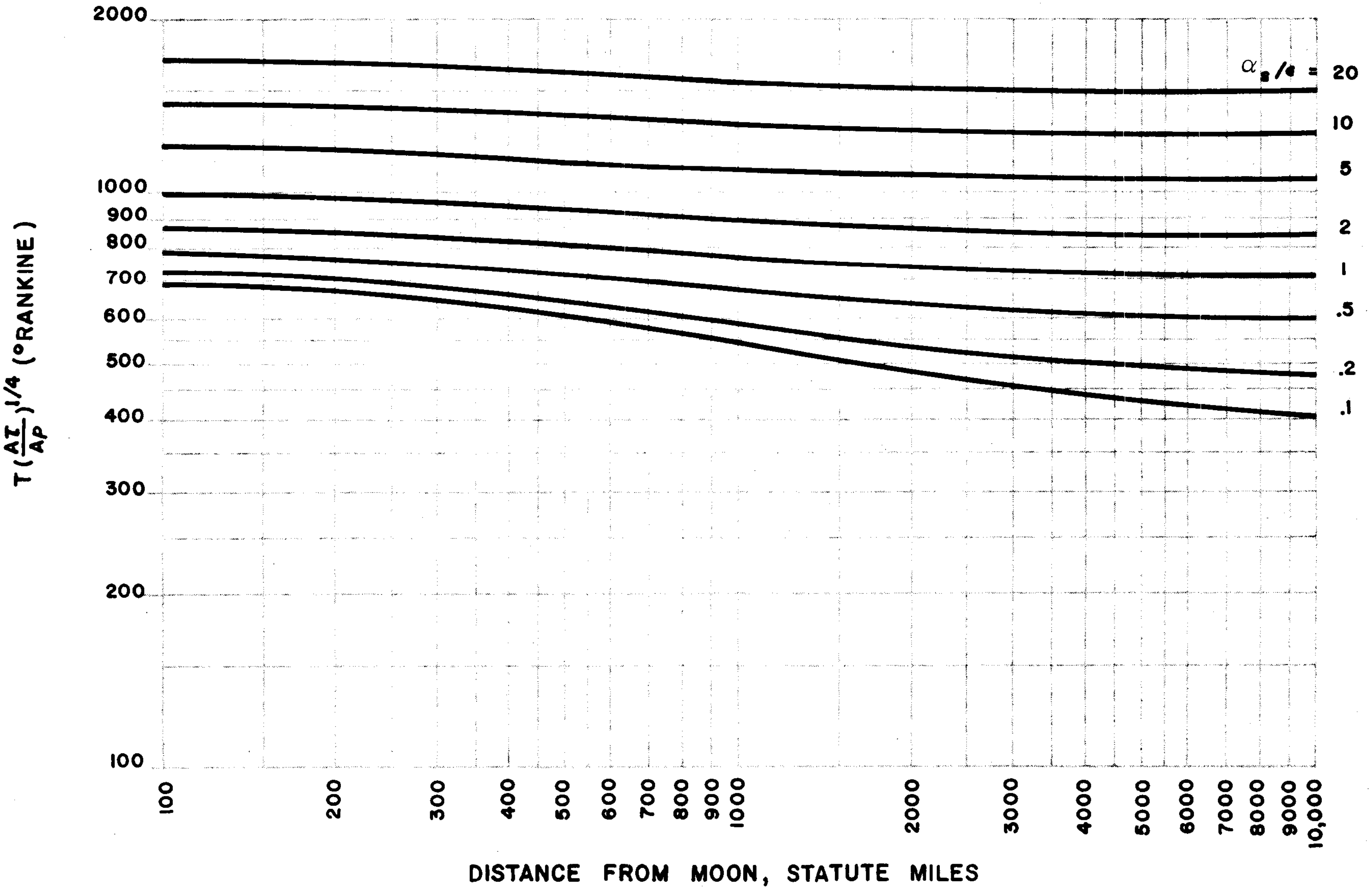


Figure 3-18 GENERALIZED BODY TEMPERATURE, NEAR MARS

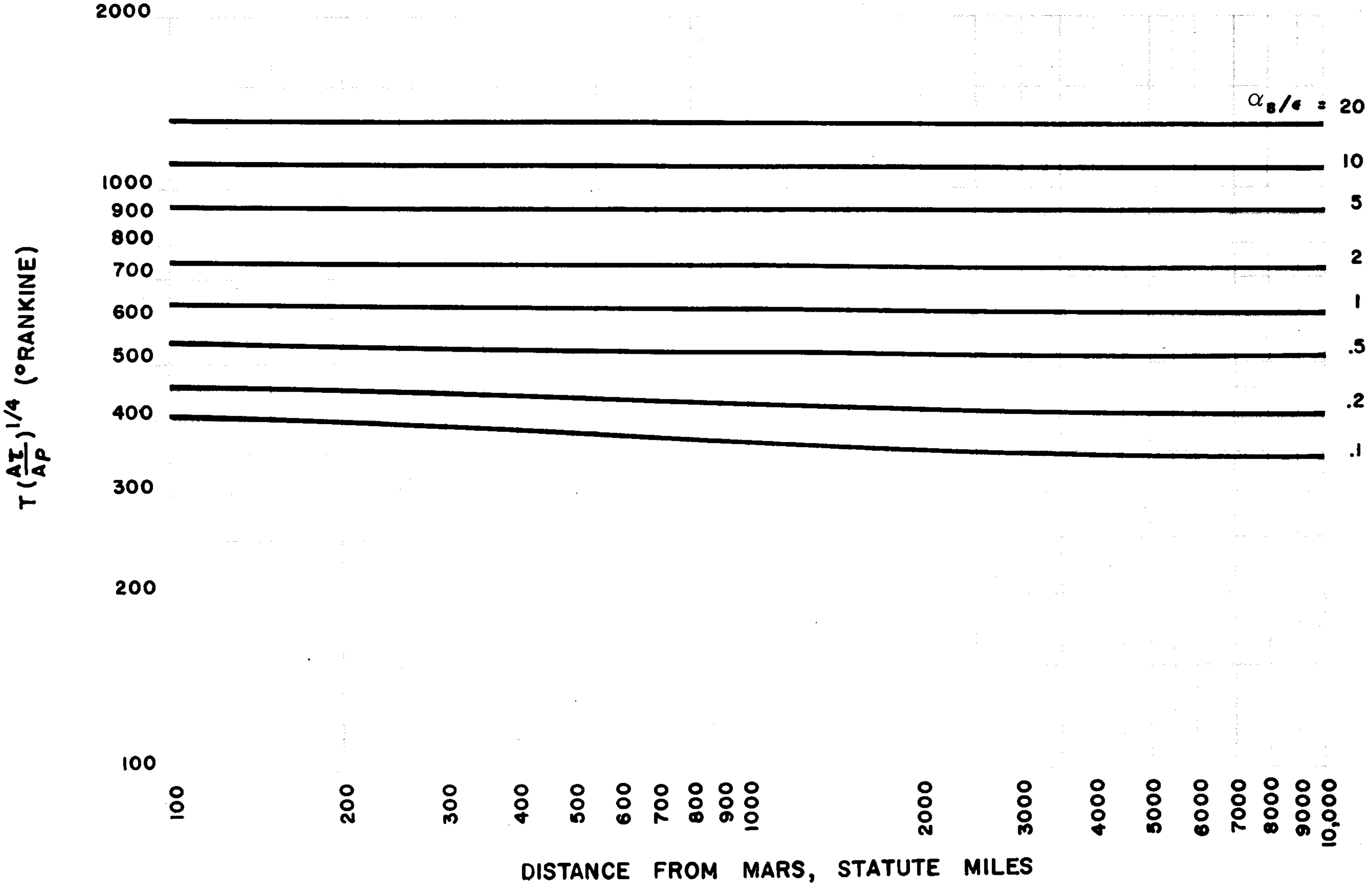


Figure 3-19 BODY TEMPERATURE VS DISTANCE FROM THE SUN

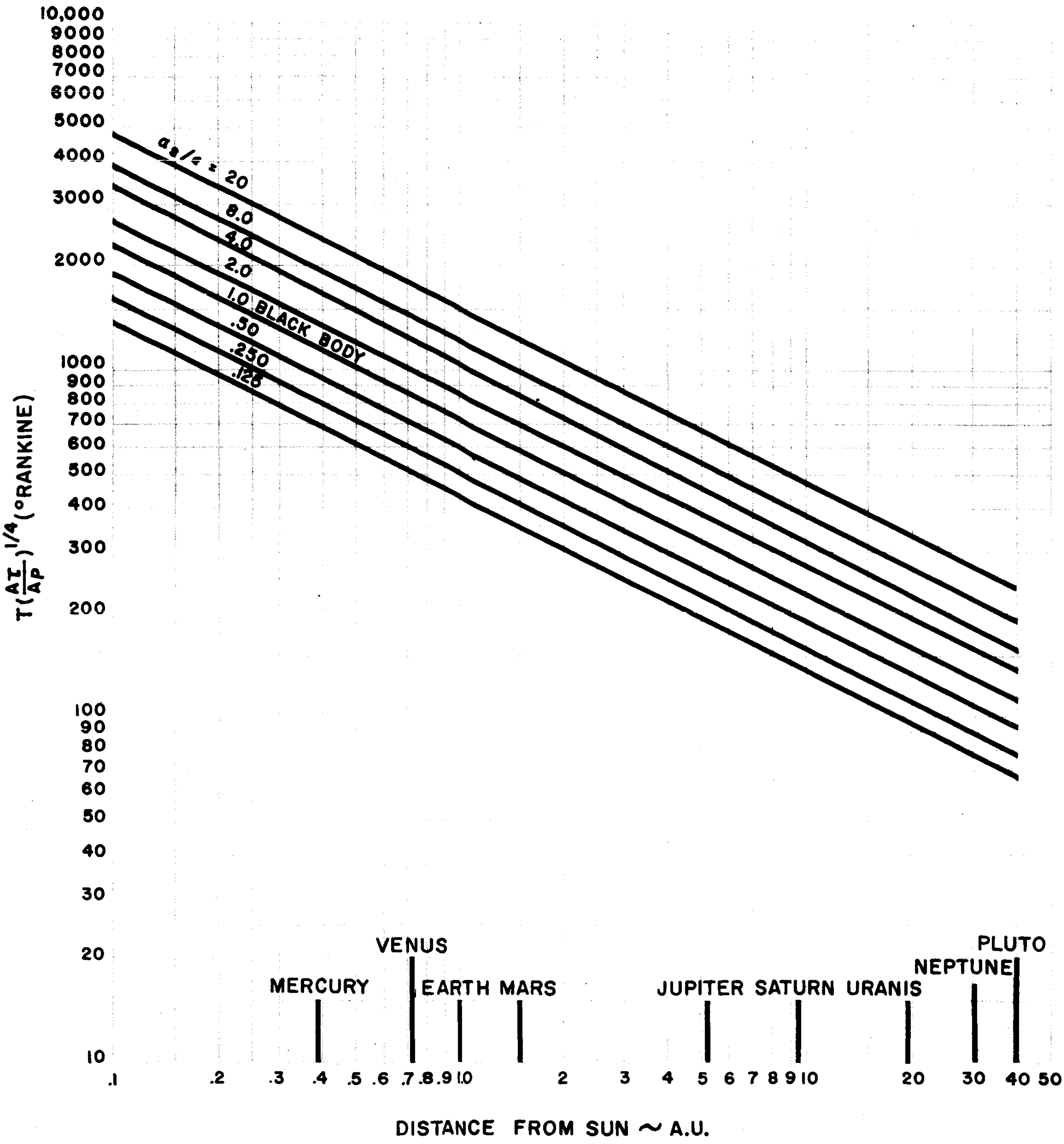
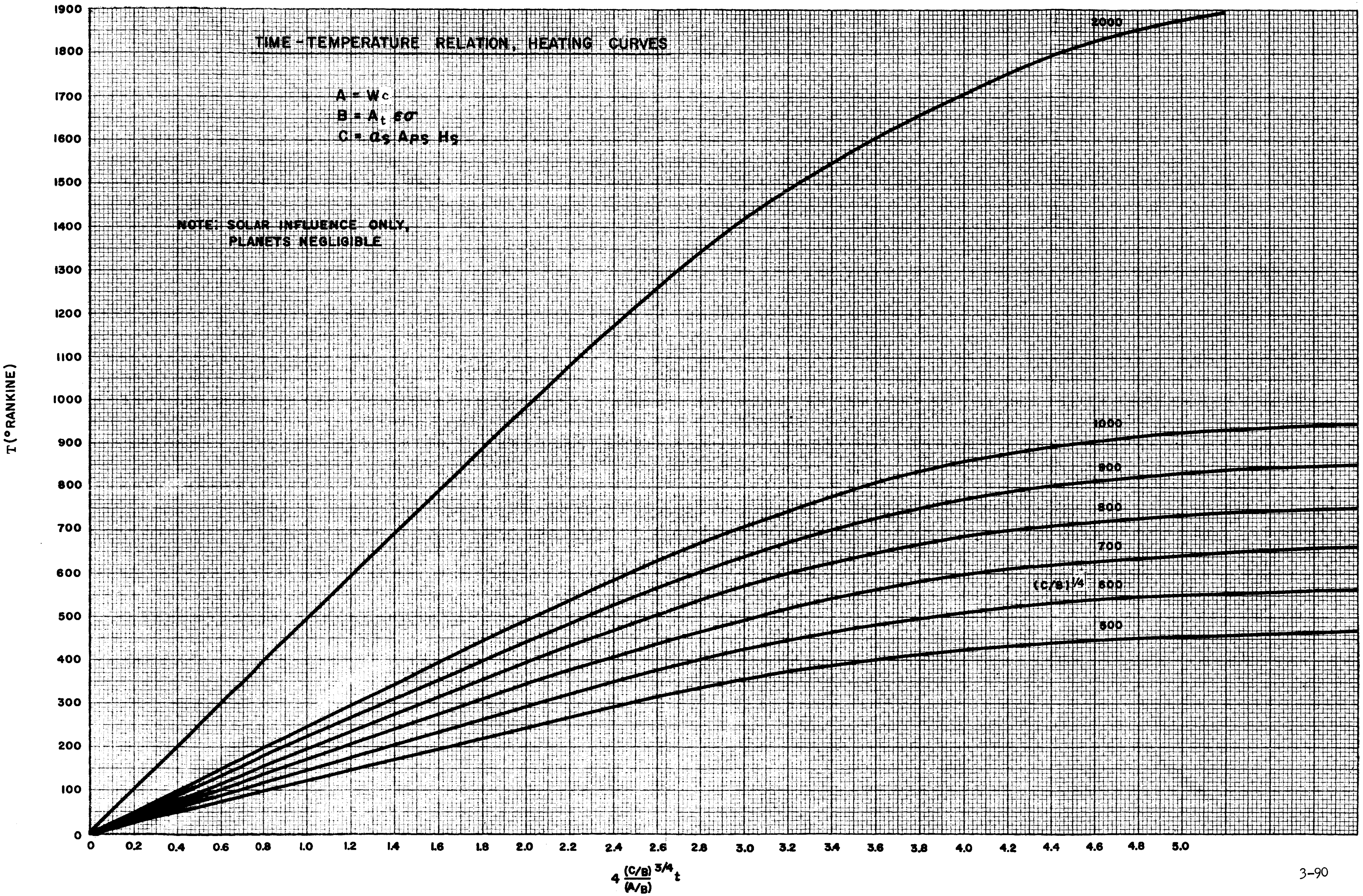


FIGURE 3-20


TIME - TEMPERATURE RELATION, HEATING CURVES
A = Wc
B = A_t εσ
C = a_s A_{PS} H_S
NOTE: SOLAR INFLUENCE ONLY, PLANETS NEGLIGIBLE
2000
1000
900
800
700
$(C/B)^{1/4}$ 600
500
T(°RANKINE)
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
$4\frac{(C/B)^{3/4}}{(A/B)}t$

METEOROIDS

Introduction

Increased sophistication of present and future space vehicle demands optimum design and increasing reliability. For man's interplanetary travel as well as unmanned deep space probes, vehicles must be designed to circumvent the hazards found in and beyond the earth's atmosphere while still maintaining a high degree of reliability at a minimum cost in weight to the vehicle. One hazard of space about which there is much theoretical and actual test data is the meteoroidal penetration of materials and meteoroidal flux which may be encountered in space travel.

Throughout this report "meteor" and "meteoric" will be used to denote the fiery trails exhibited by particles as they enter our atmosphere at high speed. "Meteoroid" and "meteoroidal" will refer to the space-traveling particles which cause meteors when they enter the earth's atmosphere. "Meteorite" and "meteoritic" will be reserved to designate a stonelike extraterrestrial body found on the earth's surface.

In design of valves for space application it is apparent that much thought should be given to protecting the valves not only from meteoroidal penetration, but from any other ill effects that could result from meteoroids impinging on the valve body; e.g., spalling on inner surface, deformation of cylinder walls, and loss of heat balance of the system.

Origin

It is believed, at the present time, that meteoroids are of two origins, meteoroids from asteroids and meteoroids from comets (Ref. 2)

Meteoroids of asteroidal origin constitute approximately 10 percent of the total influx of particles that enter the earth's atmosphere. Since the particles are of asteroidal origin, their concentration lies in the asteroidal belt located between the orbits of Mars and Jupiter, and the particles enter the earth's atmosphere only when their devious orbits cross the path of earth's orbit and pass sufficiently close to earth to be trapped by its gravitational field. Meteoroids are believed to be the result of continual colliding and grinding of bodies in the asteroidal belt, and for the most part they maintain the same orbit around the sun in or near the ecliptic plane. For this reason, the flux is relatively low at the earth's atmosphere and does not constitute a hazard to spacecraft. However, when interplanetary travel is considered, meteoroids of this extraterrestrial origin may be considered to be hazardous to the spacecraft. Information regarding the flux and concentrations of these particles is too limited to determine analytically what the effects could be. Therefore, information that has been obtained about other particles that frequent the earth's atmosphere must be used as criteria in space vehicle design. These particles, about which there is some valid information, are believed to be of cometary origin.

Most meteoroidal material in the solar system is believed to be associated with existing or extinct comets. Approximately 90 percent of the total influx into the earth's atmosphere is thought to be of cometary origin. It is known that a comet is not a very dense mass, but is, instead, a loose accumulation of particles. A present hypothesis (Ref. 2) is that comets are formed originally at large distances from our sun by a gradual accumulation of atoms and particles which are wandering randomly in space. The distribution of meteoroidal particles is a result of typical comet orbits about the sun; the comets are constantly modified by the effects of sputtering, sublimation from solar radiation, breakage and disruption by mutual collisions among the small particles themselves, planetary perturbations and collisions, solar pressure, and solar radiation drag.

As dissipation of a comet occurs, residue or small particles are released from its medium. Eventually the comet is lost, either in solar capture or collisions with planets. The residue, however, continues in approximately the same orbit as the comet would have pursued had it not been dissipated, allowing, of course, for perturbation forces tending to widen its path. The orbit, being a highly eccentric one, is approximately in the plane of the ecliptic or at some small angle to the plane.

Meteoric flux, as observed in the earth's atmosphere, is the result of meteoroids passing close enough to the earth to be trapped by the earth's gravitational force or by the earth intersecting the elliptical orbits of the meteoroids. In some cases meteoroids are uniformly distributed along the orbit (sporadic distribution), but in other cases meteoroids are concentrated at one point in the orbit. If the earth intersects the orbit at a point of particle concentration, the flux intensity encountered may be as high as 10 times that of the daily frequency of sporadic meteors. This high flux intensity is termed a meteor shower. Fragments recovered in Africa from the booster of the space capsule manned by Colonel Glenn show the results of a high flux intensity meteor shower. (Ref. 3). It was believed at the time that the booster, while still in orbit, disintegrated for reasons unknown. Calculations based upon orbit determination and lapsed time from launch helped to make possible the location and recovery of some of these fragments in Africa. Figure 3-21 (from Ref. 3) shows the location on the booster of the first three fragments recovered. The fourth fragment which was recovered later, was identified as part of the nose section. Upon close investigation of the recovered fragments it was discovered that the surfaces of the fragments had numerous crater-like indentions, and in many cases foreign material resembling slag was deposited in a directional manner. Actual punctures of the material were also apparent in many instances. Distribution of the craters and crater diameters was recorded (Table 3-9 from Ref. 3) revealing a total of 3437 craters in the four fragments with the largest crater diameter recorded being approximately 60 mils. From Table 3-9 (from Ref. 3) it can also be seen that the leading fragments contained the largest number of craters; however, these craters were of the smallest diameter. A typical view of the inside and outside surfaces of one of the fragments is shown in Figure 3-22 and Figure 3-23. (From Ref. 3).

On completion of the extensive investigation of the recovered fragments it was then theorized that disintegration of the booster was probably caused by meteoroid impingement. If this is the case, a flux intensity of this magnitude could only have been the result of a large concentration of particles typifying that of a meteor shower.

Existing information on meteors and meteoroids has been obtained by use of photographic and radar observations, radio measurements, and satellite experiments; e.g., Venus Flytrap (Ref. 4) and Explorer I. A high degree of uncertainty exists as to proper interpretation of this information. In the case of optical and radar observations, the directly measurable quantities are luminous intensity, radio ionization, and number and velocity of particles. Factual data on the mass, size, shape, aerodynamic drag, density, and luminous efficiency of the meteoroidal particles is not known. Thus, the characteristics of the meteor-causing particles are unknown. By assuming a number for the luminous efficiency, theoretical estimates have been made of the mass and density of these particles. Both the photographic and radio-echo measurements agree that the velocity range of meteors is 11 - 72 km/sec with the average velocity relative to the earth at about 30 km/sec (Ref. 5). These observations seem to apply to meteoroids with masses greater than about 10^{-4} gm. At the present time rocket and satellite experiments are limited to measuring the impacts of meteoroids having masses about 10^{-8} gm or less. Present devices carried in a rocket or satellite vehicle can detect only those meteoroids impinging on a small detector with a limited area and limited operating time. Only meteoroids of very small size are in sufficient number to strike these detectors for this limited operating time. For this reason a gap in information exists between meteoroids in the mass range of 10^{-4} to 10^{-7} gm. Only by means of analogy and extrapolation of available information can reasonable estimates be made in this range of masses. It is this range of values, however, that is of importance to the designer of a space vehicle. Any particles smaller than 10^{-6} gm are easily stopped and present no penetration problem. Particles larger than 10^{-3} gm occur too rarely to be considered.

From photographic, radio, and radar observations and recent information obtained from satellite and rocket experiments, the relationship of flux (meteoroids/m^2-sec) to mass (gm) near the earth has been correlated (Figure 3-24, extracted from Ref. 5) to show that as mass decreases, the flux intensity increases.

From Figure 3-24 it can be seen that a wide range of values may be obtained. For calculations of flux intensity versus mass it has been customary to approximate the entire spectrum, including the satellite data, by one straight line (Whipple, Ref. 6). Since new data have been obtained from more recent satellites, the problem of joining this curve to the photographic and radar data curve has become more difficult to solve. For this reason, a new straight line approximation, $\phi = 10^{-17}\ m^{-1.70}$, with increased slope is shown for a range of particles of mass less than 10^{-6}g (Ref. 5). For masses greater than 10^{-3}g, the straight line approximation $\phi = 10^{-12}\ m^{-10/9}$ with decreased slope falls close to the curve obtained by Whipple (Ref. 7). The flux intensity in the range of masses important to penetration calculations must at present be extrapolated from the data obtained from satellites as well as from radar and photographic data. The curve assigned to this range of 10^{-3} to 10^{-6}g (Ref. 5) has been approximated to be $\phi = 1.28 \times 10^{-12}\ m^{-1}$.

Existing data, obtained from measurements in the vicinity of the earth, have been influenced considerably by the earth's shielding atmosphere. It is expected that as travel into space beyond a few earth radii is accomplished, a much greater flux will be encountered. As mentioned previously, an increase in flux will result in a considerable decrease in mass. Using data from Explorer I, Sputnik III, Vanguard III, Explorer II, and Pioneer I, Whipple (Ref. 4) has proven that flux intensities, for a given threshold mass, decrease proportionately to altitude or distance from earth.

METEOROIDAL PENETRATION

One of the main interests of the valve designer in providing protection against meteoroidal impingement on a valve is the penetration capability of a single meteoroid. For unprotected structures or components, Bjork's Penetration Equation on a Semi-infinite Target (Ref. 7) relates meteoroidal penetration to the one-third power of the momentum $(mv)^{1/3}$ of the meteoroid. Bjork's calculations are restricted to a projectile and target of the same material and are based somewhat conservatively on the density of a meteoroid to be 2.7 gm/cc, or that of stone. From observations made in the photographic range, where the mass is larger, there is good indication that the density would be considerably lower, possibly even as low as 0.05 gm/cc.

In recent tests performed by Aerojet General Corporation (Ref 8), velocities of projectiles up to 30,000 ft/sec were achieved. These velocities are still in a range below the estimated average velocity of a meteoroid (30 km/sec, or 10^5 ft/sec). However, this is the most definitive information available at the present. Aluminum projectiles (density approximately that of stone, 2.7 gm/cc) were impinged on different target materials with the results given in Table 3-10 as extracted from the report. From actual test specimens that were used (see Table 3-10) for aluminum projectiles impinging on aluminum targets, estimated penetration depths were calculated using the following common penetration equations:

Bjork:

$$P = 1.09\,(mv)^{1/3} \tag{1}$$

Charters-Summers:

$$P = 2.28\left[\left(\frac{\rho_p}{\rho_T}\right)^{2/3}\left(\frac{V}{C_t}\right)^{2/3}\right] d \tag{2}$$

Herrman-Jones:

$$P = (0.35 \pm 0.07)\left[\left(\frac{\rho_p}{\rho_t}\right)^{2/3}\left(\frac{\rho_t V^2}{H_t}\right)^{1/3}\right] d \tag{3}$$

The resulting predicted penetration depths were plotted along with the actual crater depth observed from the tests (Figure 3-25). By observation it can be seen that a wide variation in values can exist, dependent on the penetration equation chosen. It is then the designer's responsibility to justify usage of a chosen equation and any weight penalty that may result.

It can also be seen in Table 3-10 that the use of high-strength materials such as steel in place of aluminum as a protective material is not warranted. The possible exception to this would be the use of beryllium, with a strength-to-weight ratio greater than that of aluminum.

METEOROID BUMPER AS A METHOD OF SHIELDING

To alleviate the weight penalty involved to prevent meteoroid penetration, Whipple (Ref. 6) suggested the use of a meteoroid bumper. The meteoroid bumper, a thin external shield spaced some distance from the main structure, would intercept and shatter the meteoroid far enough away from the main surface to enable the impact to be spread over a larger area and at a somewhat reduced velocity. For this purpose, the bumper should be as thin as possible, perhaps limited only by fabrication procedures. Experiments show (Ref. 9) that an aluminum projectile will shatter when it is impinged on an aluminum plate 1/10 of its own thickness at velocities of 6-20 km/sec.

The shattering of the particles stopped by a thin shield produces a "spray cone" effect on the target. The cone effect is a result of the dispersion of the shattered fragments leaving the shield. An optimum shield thickness, approximately 0.4 times the projectile length (Ref. 10), would produce a spray cone angle of approximately 55 degrees from the direction of travel of the center particles. At this shield thickness the total penetration (shield plus target) reaches a minimum.

Total penetration is also seen to decrease with an increase in shield spacing until an optimum spacing is obtained where no further reduction in penetration is achieved. Beyond the optimum spacing, each particle in the spray strikes a different portion of the target, while at smaller spacings several spray particles may strike the same location on the target. If the shattered fragments are so spread out that they act independently upon hitting the target, the momentum and energy transmitted to the target at each point of impact are reduced in proportion to the number of fragments. Experiments indicate that approximately 33 percent of the original thickness of the target is required to prevent penetration if an adequate spacing between bumper and target is provided (Ref. 9). Applying this criterion, an elastic analysis (Ref. 9) shows that spacing of a bumper may be determined by the equation:

$$S = 2t_t \sqrt{t_t / t_b \rho_b}$$

where S = Bumper spacing (distance away from target)

t_t = thickness of main target

t_b = thickness of bumper

ρ_b = density of bumper, in gm/cm^3

This indicates that an aluminum bumper 1 percent of the thickness of the target should have a spacing from the target approximately equal to 12 times the target thickness.

Because of clearances and handling conditions, the problem of obtaining optimum spacing between the bumper and a valve body may possibly be lessened by the use of insulation placed between them. Investigations have been made (Table 3-11 from Ref. 8) using such a configuration, and results using NRC-2 insulation proved quite favorable. The use of NRC-2 insulation by itself as a meteoroid bumper may be possible.

PROTECTION OF VALVES AGAINST METEOROIDS

Location of a valve on the space vehicle determines whether or not meteoroidal flux and penetration are inherent problems. For disconnect, vent, and check valves the location is generally on the exterior of the space vehicle, thereby making them vulnerable to any meteoroidal impingement. The basic problem of defining degree of vulnerability to meteoroids and the degree of reliability required of the valve in the system is the concern of the designer. The following examples are based on present quantitative knowledge of meteoroidal flux and the effects of high-speed impact on materials.

Example I:

For a vehicle in near-earth orbit for a period of 2 years, assume a probability of no hits capable of penetration, $P(0) = 0.90$, and a valve body with an exposed area of 12 in.^{2} located on the exterior of the spacecraft body.

Let ϕ = Flux in penetrations/unit area -sec

ϵ = Most probable number of penetrations under which the probability of receiving zero punctures is 0.90

A = Area in in.^{2}

t = Exposed time in seconds

then $\phi = \frac{\epsilon}{At}$ (Ref. 1)

$$\epsilon = -\log_e 0.90 = 0.10536$$

$$At = 12 \times 2 \times 86,400 \times 365 = 75.7 \times 10^7 \text{ in.}^2\text{-sec}$$

$$\phi = \frac{0.10536}{75.7 \times 10^7} \quad 1.375 \times 10^{-10} \text{ meteoroids/in.}^2\text{-sec}$$

for which $\phi = 2.13 \times 10^{-7}$ meteoroids/M^2 -sec; where M is in meters.

From the straight line approximation, $\phi = 1.28 \times 10^{-12}\ m^{-1}$ (Figure 3-24), the mass (m) is found to be 5.95×10^{-6} gm. From Whipple's 1958 summary of meteorite information given in Table 3-12 (Ref. 6), an assumed velocity (V) for a particle of this mass is approximately 18.5 km/sec (60, 700 ft/sec). Using Bjork's equation, $P = 1.09\ (mV)^{1/3}$ (m = mass, V = velocity), penetration depth in aluminum for a particle of this size and velocity would be 0.052 cm or 0.020 inches. A single sheet to prevent penetration of the meteoroid would have to have a thickness $t_t = 1.5\ P$ (Ref. 7). The thickness required to defeat a meteoroid would then be 1.5(020) = 0.030, which is usually less than a design wall thickness of the valve body itself.

Example II:

With all parameters of Example I remaining constant, the probability of no hits capable of penetration, P(0), will be increased to 0.99.

Then $\epsilon = -\ \text{loge}\ 0.99 = 0.01005$

Using $\phi = \frac{\epsilon}{At} = \frac{0.01005}{75.7 \times 10^{7}} = 1.33 \times 10^{-11}$ Meteoroids/in.^{2}-sec

then $\phi = 2.06 \times 10^{-8}$ Meteoroids/M^{2} -sec

Using the approximated straight line curve again,

where $\phi = 1.28 \times 10^{-12} =^{-1}$, m (mass) = 6.21×10^{-5}.

An assumed velocity from Table 3-12 for a particle of this mass would be approximately 21.0 km/sec. Again using Bjork's penetration equation, the penetration depth in aluminum would be

$$P = 1.09\ (6.21 \times 10^{-5} \times 21.0)^{1/3} = 0.118 \text{ cm } (0.047 \text{ in.})$$

Thickness t_t of single sheet protection would be 1.5P or 0.070 in.

Examples I and II clearly show that for any given condition the thickness of the material required to prevent meteoroidal penetration is directly proportional to the reliability that is required of the system.

A more conservative analysis, using Whipple's 1957 estimate of flux and a straight line curve approximating the entire spectrum of flux, along with Charters and Summers' penetration equation, would result in even thicker material being required. If it is required to use the conservative approach, then the use of a meteoroid bumper may be advantageous.

Example III:

This example will be given using all parameters of Examples I and II and using Whipple's 1957 estimate of flux along with Charters and Summers' equation for penetration. Whipple's straight line approximation of the entire spectrum represents a curve of $\log \phi + \log m = -8$ where ϕ = flux intensity in ft^2 -day and m = mass in grams.

Using equation $\theta = \frac{\varepsilon}{At}$

$$\epsilon = 0.01005 \text{ (from Example II)}$$

$$At = \frac{12 \text{ in.}^2}{144} \times 2 \times 365 = 60.9 \text{ ft}^2 \text{ -day}$$

$$\phi = \frac{0.01005}{60.9} = 1.65 \times 10^{-4} \text{ meteoroids/ft}^2 \text{ -day}$$

$$\log (1.65 \times 10^{-4}) + \log m = 8$$

$$\log 1.65 \times 10^{-4} = 0.2175 - 4 = 3.7825$$

$$\log 1.65 \times 10^{-4} = 4.2175 = 0.7825 - 5$$

$$\log m = 4.2175 = 0.7825 - 5$$

$$\text{mass} = 6.06 \times 10^{-5} \text{ grams}$$

Assuming density of meteoroid (P_p) = 2.7 gm/cc, then particle diameter (d) = 0.014 inches.

Density of target material (aluminum) (P_t) = 2.7 gm/cc and speed of sound in the target material (C_T) is equal to 16,750 ft/sec.

From Table 3-12 assume velocity equal to 21.0 km/sec. Summers' penetration equation for semi-infinite targets is:

$$P = 2.28 \left[\left(\frac{P_p}{P_T} \right)^{2/3} \left(\frac{V}{C_T} \right)^{2/3} \right] d$$

From this equation P = 0.084 in., which is the expected crater depth. Thickness of the material required to defeat the meteoroid would then be 1.5 (P) = 0.126 inches.

The result, obtained by using the conservative analysis for determining the protection needed to defeat a meteoroid for a reliability of 0.99, indicates that the use of a meteoroid bumper may provide a weight advantage. Usage of the Whipple meteoroid bumper concept allows the single-sheet thickness required to be reduced by a factor of 3, as previously mentioned. The total thickness required would then be 0.126/3 = 0.043. An optimum bumper thickness to produce a total minimum penetration (shield plus target) would be 0.4 x diameter of particle (Ref. 10). The bumper thickness would then be 0.04 x 0.014 = 0.005 in. with a wall thickness of the valve body equal to 0.038. Bumper spacing, or distance of the shield from the valve, should then be approximately 0.130 inches. From this example it can be seen that the use of an insulation around the valve body would perhaps be sufficient protection against meteoroidal impingement.

In the event that the reliability of the valve must be an order of magnitude higher than the example given, the resultant thickness to prevent penetration would be approximately 0.284 inches. For this thickness requirement, a meteoroid bumper would definitely prove to be a weight advantage.

SPALLING BY METEOROIDS

The effects of spalling and deformation of the inner surface of the valve body when struck by a meteoroid are difficult to predict theoretically, due to the complex wave propagation that occurs on hypervelocity impact. When a meteoroid hits a plate, it not only makes a hemispherical crater on the front surface, but also initiates a strong compressive shock wave which travels through the plate. When this wave reaches the free surface (inner surface) of the target, a reflected plastic wave of tension occurs. Interaction occurs between the reflected tension wave and the remainder of the compression wave propagating in the direction of impact. The result is that at some depth from the free surface of the target, the tensile stress may exceed the fracture stress. If this occurs, a spall is formed on the free (inner) surface and ejected inward at high velocity (Figure 3-26 from Ref. 11). The diameter of the spall is usually several times the plate thickness, varying from 1/10 to 1/2 of the plate thickness. There is a definite tendency for spall thickness to increase with velocity of impact (Ref. 11) and also increase with decreasing plate thickness (Ref. 11).

From investigations on the spalling of materials (Ref. 3) it was noted that the thickness required to avoid spalling varies approximately as the 1/3 power of the impact energy, or the 1/3 power of the number of fragments into which a meteoroid is broken by a bumper. This is the same dependence as that for penetration. Indications are that spacings of bumper and target which spread the impact particles over a larger area and thus decrease penetration of the main target should also separate the pulse waves, which the shattered particles generate in the main target, sufficiently to avoid serious pulse overlap at the inner surface of a valve body.

OTHER EFFECTS OF METEOROIDS ON VALVES

Penetration of meteoroids smaller than 10^{-6} gm is not considered to be a problem, as noted. However, impingement of micrometeoroids on a valve body may remove enough material from an unprotected exterior surface through erosion (removal of material by cratering) to alter the absorptivity (α) and emissivity (ϵ) value of the material enough to create a heat balance problem. Estimates (Ref. 3) show that total volume lost by meteoric erosion is approximately 1 Å/yr in the vicinity of the earth to as much as 200 Å/yr at low satellite altitude. Deposition of meteoroidal dust on the valve body may also produce the same result.

Another possible effect of meteoroidal impacts would be the generation of pressure pulses transmitted to and through the liquid in the valve, causing internal damage.

Propellant containers and lines may also experience extensive damage from pressure pulses transmitted to and through the liquid from meteoroidal impact.

CONCLUSION

It has been shown that meteoroidal hazard to valves in space could exert a definite influence on the design of a valve body, but that protective measures can be taken to prevent damage to the valve without imposing an extremely high weight penalty.

A statistical solution to the problem involves the probability of meteoroidal encounter during the mission and the damage phenomena of a single meteoroidal impact.

The likelihood of encounter of meteoroids depends on:

1) The reliability required of the valve, which may vary with a given mission (e.g., manned or unmanned),
2) The duration and path of the mission,
3) Size of the valve body (exposed area - in^2),
4) The proper choice of flux distribution (Figure 3-24).

Present quantitative knowledge of flux distribution is far from adequate (Ref. 4). In the area of concern to the designer (mass range of 10^{-6} to 10^{-3} gm), extrapolation from recorded data is the only means of estimation of the flux intensity.

Damage phenomena of a meteoroidal impact also warrants more investigation before definite design criteria can be established. At the present time sufficient knowledge relating depth of penetration or fragmentation mechanics of bumpers to material properties is lacking. Similarly, insufficient information is available to correlate depth of penetration with velocity of a particle at impact on metal surfaces. The velocity of impact of meteoroids with space vehicles (in this case, a valve body) is assumed to be approximately 30 km/sec (10^5 ft/sec), a considerably higher velocity than any extensive laboratory data that has been obtained to date on high-velocity impact (Ref. 12). Many theoretical penetration equations for high-velocity impact have been proposed, ranging from very conservative predictions, thereby imposing a weight penalty, to nonconservative predictions requring no protection for a valve. Bjork's penetration equation (Ref. 7) appears to be between the extremes, and predicted results from the equation follow closely to test data obtained to date for target and projectile restricted to the same material (Figure 3-25).

Until more definitive information is obtained concerning flux intensity, fragmentation of particles on impact, and penetration characteristics of hypervelocity particles, the designer must use the information available. Discretion in choice of flux distribution and penetration equation should result in a conservative but reasonable prediction of protection needed to protect a valve from meteoroidal impingement. The use of a meteoroid bumper should definitely be considered as a means of reduction in weight, either for protection against penetration or protection against spalling. If only a minimal amount of shielding is necessary, the proper use of an insulation could be accomplished. The insulation may also be required for thermal properties, thus serving a dual purpose.

REFERENCES - METEOROIDS

1. Davidson, J.R. and Sandorff, P.E., Environmental Problems of Space Flight Structures (Meteoroid Puncture), October 1961, NASA Research Advisory Committee on Missile & Space Vehicle Structures.
2. Herrmann, W. and Jones, A.H., Survey of Hypervelocity Impact Information, September 1961, Aerocastic and Structures Research Laboratory, Massachusetts Institute of Technology.
3. Bjork, R.L., Meteoroids Versus Space Vehicles, ARS Paper No. 1200-60, May 9-12, 1960.
4. Maiden, C.J., Charest, J., and Tardiff, H.P., An Investigation of Spalling and Crater Formation By Hypervelocity Projectiles.
5. Gray, P.D., et al, Rockets in Space Environments - Phase I: Parameter Study, Report No. 2112, 27 October 1961, Aerojet-General Corporation.
6. Whipple, F.C., Dust and Meteorites, ARS Report 2253-61, 9-15 October 1961.
7. Whipple, F.C., The Meteoritic Risk to Space Vehicles, Seventh International Astronautical Congress, Barcelona, Spain, 1957.
8. Summers, J.L., Investigation of High-Speed Impact, NASA TN-94, October 1959.
9. Gray, P.D. et al, Rockets in Space Environments - Phase II Individual Component Investigation, April 1962, Report No. 2263, Aerojet-General Corporation.
10. Sheppard, J. J., et al. Investigation of Recovered Fragments From Atlas 109-D Booster, GD/A/AE 62-0558, 1 July 1962.
11. Jaffe, L.D., Rittenhouse, J.B., Behavior of Materials in Space Environments, JPL TR-32-150, November 1, 1961.

Table 3-9 DISTRIBUTION OF CRATER DIAMETER FOR THE ATLAS 109-D FRAGMENTS

Avg. Dia-Mils	P_1		P_2		P_3		P_4		Total
	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	
5	222	1266	5	845	12	*	7	-	2357
10	90	346	1	366	22	10	11	-	846
15	13	17	2	40	11	9	5	-	97
20	9	9	1	12	7	4	0	-	42
25	3	6	4	8	10	7	2	-	40
30	-	-	2	6	5	1	2	-	16
35	-	1	-	1	4	1	1	-	18
40	-	-	1	2	4	-	-	-	7
45	-	-	-	-	1	-	-	-	1
50	-	-	-	1	7	1	-	-	9
55	-	-	-	-	2	-	-	-	2
60	-	-	-	-	2	-	-	-	2

Only craters > 1-2 Mils were counted.

Table 3-10 HYPERVELOCITY IMPACT IN SEMI-INFINITE METALLIC TARGETS

		Target Data			Particle Data								Crater Data				
Test No.	Data Point	Target Material	Thickness (in.)	Brinell Hardness	Velocity (ft/sec)	Velocity (km/sec)	L/D	Average Dia (in.)	Mass (gm)	Mass (lb x 10^{-4})	Angle of Incidence (1) (deg)	Silhouette Area (2) (in.^{2})	Mean Dia (in.)	Depth (in.)	Depth/Dia Ratio	Volume (in.^{3})	Remarks
	1	Aluminum 2024-T4	1.0	135	32,000	9.75	(3)	.125	.0453	.997	(3)	(3)	.62	.27	.436	.0427	
	2	↓	↓	↓	↓	↓	↓	.0898	.0170	.375	↓	↓	.53	.22	.415	.0244	
	3	↓	↓	↓	↓	↓	↓	.0661	.00669	.147	↓	↓	.35	.144	.411	.0122	
	4	↓	↓	↓	↓	↓	↓	.0337	.000884	.0195	↓	↓	.32	.134	.388	.091	
	5	↓	↓	128	↓	↓	↓	.145	.0740	1.63	↓	↓	.50	.145	.290	-	
	6	↓	↓	128	30,500	9.30	↓	.144	.0637	1.51	↓	↓	.72	.28	.389	.0427	
	7	↓	↓	130	32,000	9.75	↓	.206	.201	4.42	↓	↓	.82	.32	.390	.0548	
	8	↓	4.0	↓	31,600	9.64	↓	.248	.545	12.0	↓	↓	1.35	.57	.416	.555	
	9	↓	↓	↓	31,200	9.51	↓	.239	.311	6.85	↓	↓	1.22	.61	.500	.378	
	10	↓	↓	↓	30,500	9.30	↓	.146	.0714	15.7	↓	↓	.66	.28	.444	.0548	
AC 11	A	Stainless 321	1.0	167	31,800	9.69	5.1	.163	.765	16.83	0	.137	1.05	.350	.333	.163	
	B	↓	↓	↓	30,900	9.43	3.0	.128	.223	4.89	24	.052	.60	.235	.392	.051	
AC 12	A	↓	↓	↓	32,400	9.88	4.9	.148	.543	11.95	36	.090	1.00	.406	.406	.078	(4)
	B	↓	↓	↓	31,800	9.69	2.2	.126	.140	3.07	79	.018	.50	.297	.594	.045	
	C	↓	↓	↓	31,300	9.55	2.5	.144	.269	5.85	6	.052	.58	.204	.352	.035	
AC 13	A	Stainless 347	1.0	195	30,400	9.27	5.8	.151	.702	15.46	30	.117	1.20	.391	.326	.252	(4)
AC 14	A	↓	↓	↓	32,300	9.85	4.0	.147	.432	9.52	14	.085	1.00	.391	.391	.156	(4)
	B	↓	↓	↓	31,600	9.64	1.2	.122	.0754	1.66	59	.019	.53	.266	.502	.038	
	C	↓	↓	↓	31,200	9.52	1.4	.122	.0931	2.05	55	.022	.45	.204	.454	.027	
	D	↓	↓	↓	31,100	9.41	1.4	.119	.0819	1.81	83	.016	.50	.204	.408	.026	
AC 15	A	Aluminum 6061-T4	1.0	95	32,800	10.0	6.0	.139	.249	5.50	62	.044	1.45	.844	.582	.738	(4)
	B	↓	↓	↓	32,400	9.88	3.3	.106	.144	3.13	0	.035	.80	.484	.606	.038	(4)
	C	↓	↓	↓	32,200	9.82	2.9	.077	.0455	.101	17	.014	.40	.235	.587	.017	
	D	↓	↓	↓	31,700	9.67	2.2	.118	.127	2.81	18	.027	.60	.375	.625	.082	
AC 18	E	↓	↓	↓	30,800	9.39	3.2	.0943	.0627	.1383	24	.022	.60	.281	.468	.051	
AC 16	A	Titanium RS55	1.0	135	26,600	8.11	3.1	.168	.519	11.43	4	.087	1.10	.360	.327	.196	(4)
	D	↓	↓	↓	25,900	7.90	1.6	.110	.0738	1.63	11	.012	.63	.297	.472	.041	
	E	↓	↓	↓	25,600	7.80	4.1	.083	.0803	1.77	26	.028	.58	.232	.436	.053	
AC 16B	C	↓	↓	↓	26,800	8.17	2.7	.093	.0749	1.65	0		.58	.188	.324	.024	
	D	↓	↓	↓	26,700	8.14	1.5	.084	.300	6.60	48		.50	.360	.720	.034	
AC 17	A	↓	↓	↓	32,000	9.76	3.7	.151	.443	9.76	27	.083	1.05	.360	.343	.099	(4)
	B	↓	↓	↓	31,700	9.67	2.7	.127	.171	3.78	40	.034	.75	.250	.333	.046	
	C	↓	↓	↓	31,200	9.52	2.2	.110	.100	2.22	27	.027	.50	.187	.374	.015	

Notes:
(1) angle measured between longest axis of particle and plane of target
(2) area of particle as viewed from target
(3) data not available
(4) impact caused slight bulge on back of target

Table 3-11 HYPERVELOCITY IMPACT IN THIN MULTILAYER TARGETS

		Particle Data								Target Data			
Test No.	Data Point	Velocity (ft/sec)	Velocity (km/sec)	L/D	Average Dia (in.)	Mass (gm)	Mass (lb x 10^{-4})	Angle of Incidence (deg)	Silhouette Area (in.^{2})	Material	Thickness (in.)	Separation (in.)	Penetration (in.^{2})
Single-Sheet Target													
AC 7	A	32,800	10.0	4.9	.121	.258	5.67	41	.045	Aluminum 6061-T4 " 2024-T4	.016 1.0	2	.24 (1)
9	C	30,900	9.43	1.7	.110	.0858	1.84	59	.025	Titanium 45A Aluminum 2024-T4	.016 1.0	2	.09 (1)
	D	30,600	9.33	2.8	.092	.0766	1.68	11	.023	Titanium 45A Aluminum 2024-T4	.016 1.0	2	.11 (1)
10C	A	30,100	9.18	2.1	.126	.129	2.86	47	.036	Stainless 321 Aluminum 2024-T4	.016 1.0	2	.07 (1)
	B	30,100	9.18	1.5	.0664	.0153	.337	42	.008	Stainless 321 Aluminum 2024-T4	.016 1.0	2	.03 (1)
	C	30,600	9.33	2.5	.037	.00427	.094	41	.003	Stainless 321 Aluminum 2024-T4	.016 1.0	2	.02 (1)
Double-Sheet Target													
AC 5	C	30,600	9.33	1.9	.106	.0785	1.68	28	.024	Stainless 321 " " Aluminum 2024-T4	.016 .016 1.0	2 2	.08 (1) none
AC 6	A	31,900	9.73	3.0	.204	.870	19.25	6	.126	Titanium 45A " " Aluminum 2024-T4	.016 .016 1.0	2 2	.25 1.33 (1)
Double-Sheet Target with Super-Insulation													
AC 20	A	30,600	9.33	2.1	.105	.0822	1.82	18	.024	Aluminum 6061-T4 Linde SI-44 Aluminum 6061-T6 Aluminum 2024-T4	.016 .250 .125 1.0	0 0 2	.08 4.3 .33 (1)
AC 26	A	31,800	9.69	6.5	.091	.172	3.78	36	.030	Stainless 321 " " " " IRC-2 Stainless 321 Aluminum 2024-T4	.016 .016 .016 .250 .125 1.0	0 0 2	.08 .0031 .0078 5.5 .05 (1)
	B	31,800	9.69	1.5	.037	.00278	.064	90	.003				
	C	31,500	9.61	2.0	.045	.00629	.139	47	.004				
AC 30	A	31,600	9.64	4.0	.085	.0849	1.87	3	.028	Aluminum 6061-T4 Linde SI-44 Aluminum 6061-T6 Aluminum 2024-T4	.016 1.0 .125 .100	0 0 2	.12 4.1 .08 (1)

NOTE: (1) no crater formed; splash or pitting only

Table 3-12 PARAMETERS OF MICROMETEORITES

Visual Magni- tude	Mass (g)	Radius (μ)	Ve- locity (km/sec)	Kinetic Energy (ergs)	No. Striking 3-m Sphere per Day	Flux (particle/ cm^2-sec)
0	25.0	49,200	28	1.0×10^{14}		
1	9.95	36,200	28	3.98×10^{13}		
2	3.96	26,600	28	1.58×10^{13}		
3	1.58	19,600	28	6.31×10^{12}		
4	0.628	14,400	28	2.51×10^{12}		
5	0.250	10,600	28	1.00×10^{12}	2.22×10^{-5}	1.83×10^{-15}
6	9.95×10^{-2}	7,800	28	3.98×10^{11}	6.48×10^{-5}	5.34×10^{-15}
7	3.96×10^{-2}	5,740	28	1.58×10^{11}	1.63×10^{-4}	1.34×10^{-14}
8	1.58×10^{-2}	4,220	27	5.87×10^{10}	4.09×10^{-4}	3.36×10^{-14}
9	6.28×10^{-3}	3,110	26	2.17×10^{10}	1.03×10^{-3}	8.49×10^{-14}
10	2.50×10^{-3}	2,290	25	7.97×10^{9}	2.58×10^{-3}	2.12×10^{-13}
11	9.95×10^{-4}	1,680	24	2.93×10^{9}	6.48×10^{-3}	5.34×10^{-13}
12	3.96×10^{-4}	1,240	23	1.07×10^{9}	1.63×10^{-2}	1.34×10^{-12}
13	1.58×10^{-4}	910	22	3.89×10^{8}	4.09×10^{-2}	3.36×10^{-12}
14	6.28×10^{-5}	669	21	1.41×10^{8}	1.03×10^{-1}	8.49×15^{-12}
15	2.50×10^{-5}	492	20	5.10×10^{7}	2.58×10^{-1}	2.12×10^{-11}
16	9.95×10^{-6}	362	19	1.83×10^{7}	6.48×10^{-1}	5.34×10^{-11}
17	3.96×10^{-6}	266	18	6.55×10^{6}	1.63	1.34×10^{-10}
18	1.58×10^{-6}	196	17	2.33×10^{6}	4.09	3.36×10^{-10}
19	6.28×10^{-7}	144	16	8.20×10^{5}	1.03×10	8.49×10^{-10}
20	2.50×10^{-7}	106	15	2.87×10^{5}	2.58×10	2.12×10^{-9}
21	9.95×10^{-8}	78.0	15	1.14×10^{5}	6.48×10	5.34×10^{-9}
22	3.96×10^{-8}	57.4	15	4.55×10^{4}	1.63×10^{2}	1.34×10^{-8}
23	1.58×10^{-8}	39.8[a]	15	1.81×10^{4}	4.09×10^{2}	3.36×10^{-8}
24	6.28×10^{-9}	25.1[a]	15	7.21×10^{3}	1.03×10^{3}	8.49×10^{-8}
25	2.50×10^{-9}	15.8[a]	15	2.87×10^{3}	2.58×10^{3}	2.12×10^{-7}
26	9.95×10^{-10}	10.0[a]	15	1.14×10^{3}	6.48×10^{3}	5.34×10^{-7}
27	3.96×10^{-10}	6.30[a]	15	4.55×10^{2}	1.63×10^{4}	1.34×10^{-6}
28	1.58×10^{-10}	3.98[a]	15	1.81×10^{2}	4.09×10^{4}	3.35×10^{-6}
29	6.28×10^{-11}	2.51[a]	15	7.21×10	1.03×10^{5}	8.49×10^{-6}
30	2.50×10^{-11}	1.58[a]	15	2.87×10	2.58×10^{5}	2.12×10^{-5}
31	9.95×10^{-12}	1.00[a]	15	1.14×10	6.48×10^{5}	5.34×10^{-5}

[a] Maximum radius permitted by solar light pressure.

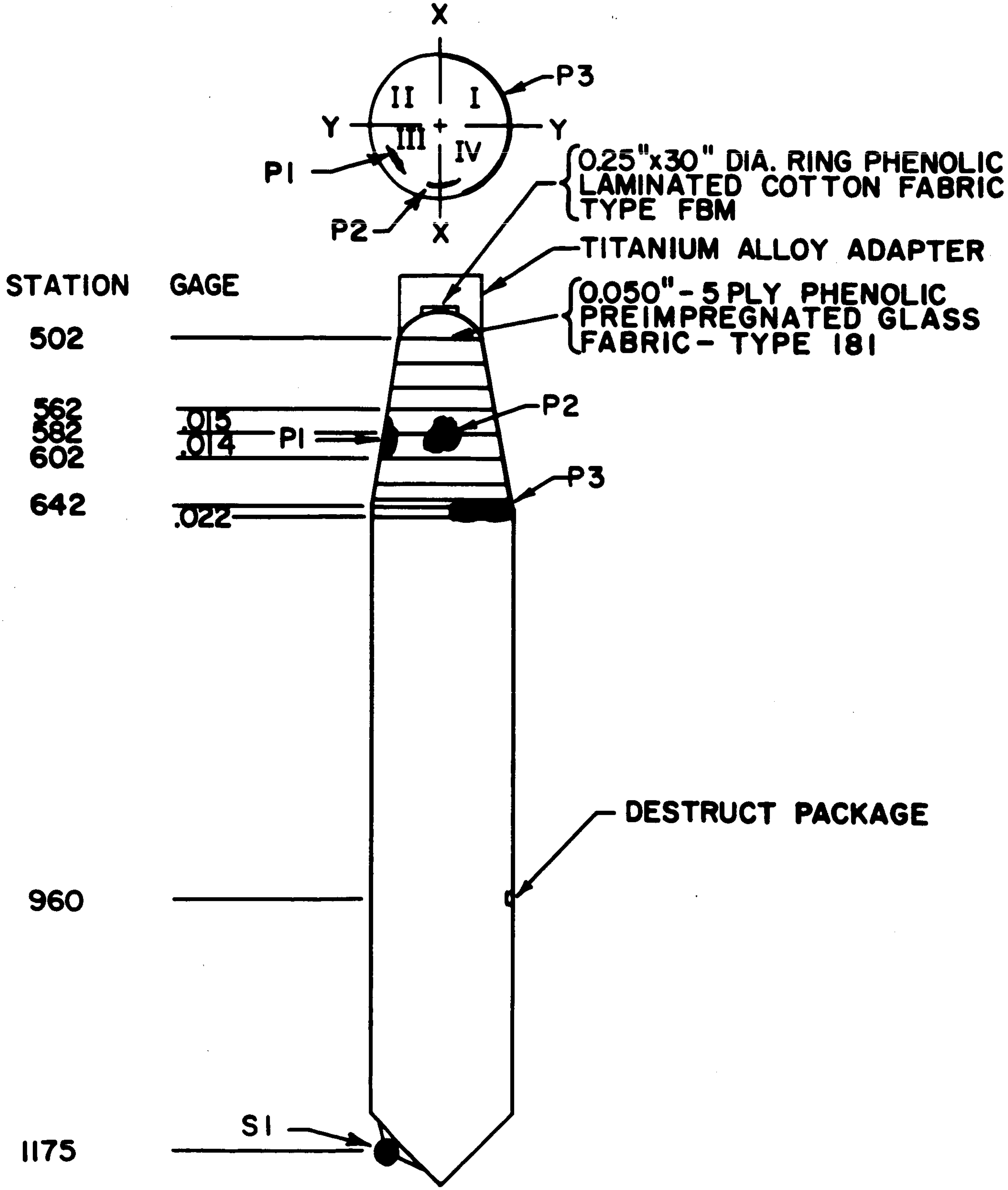


Figure 3-21

LOCATION OF RECOVERED FRAGMENTS (SHADED) ON MA-6
BOOSTER ATLAS 109-D

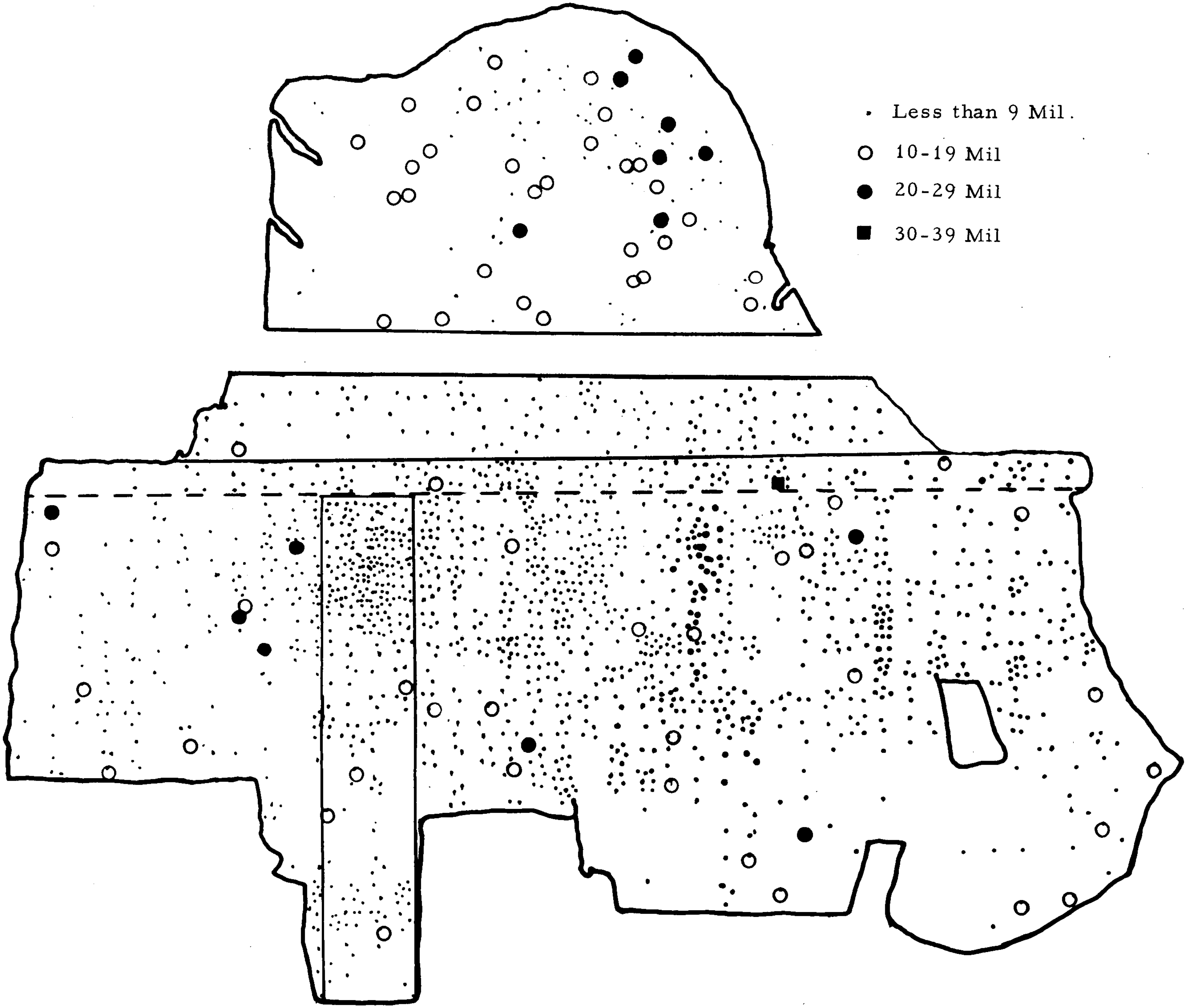


Figure 3-22 Inside view of P-1 showing crater locations.

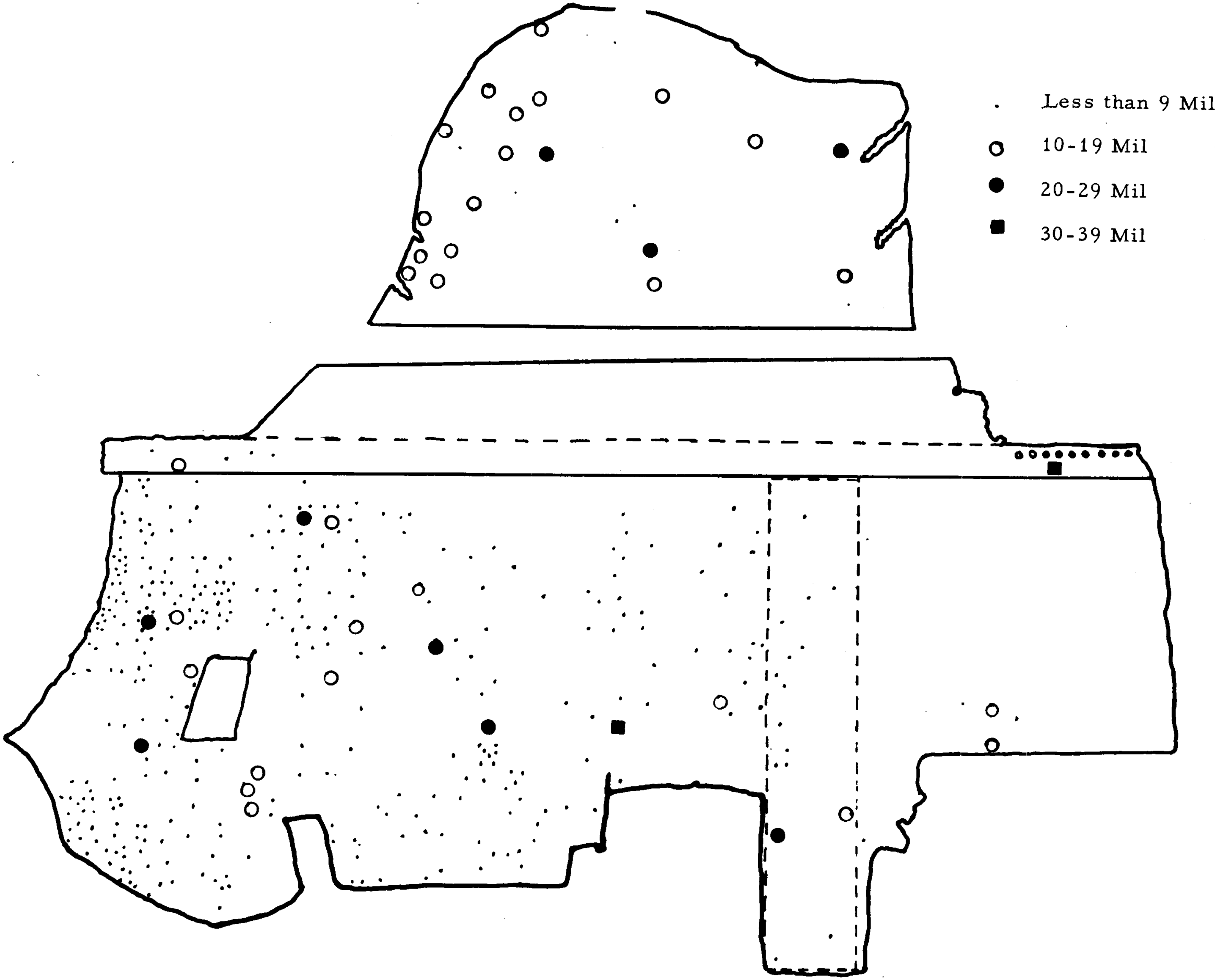


Figure 3-23 Outside view of P-1 showing crater locations.

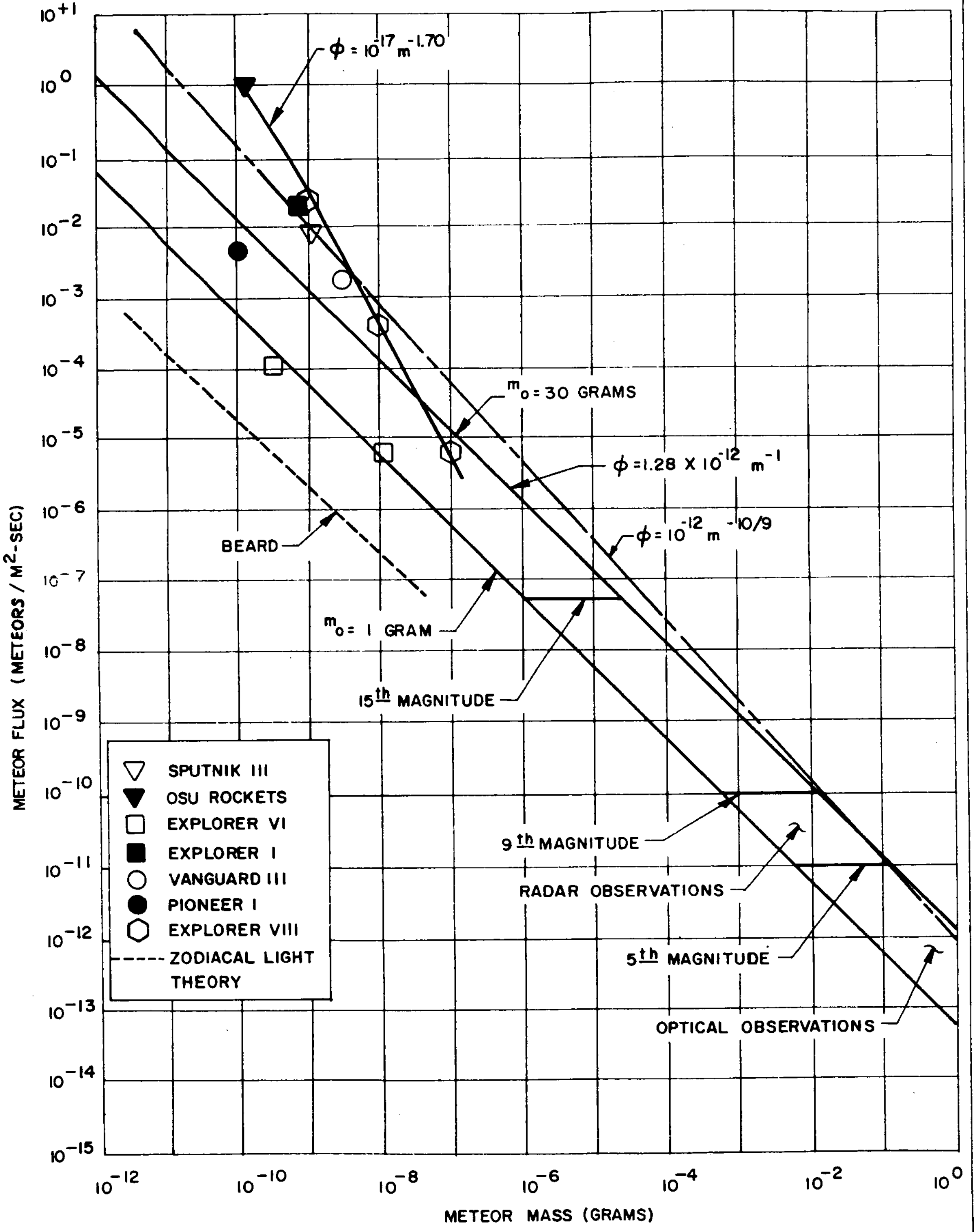


Figure 3-24

FREQUENCY OF OCCURRENCE OF METEORS IN THE VICINITY OF EARTH

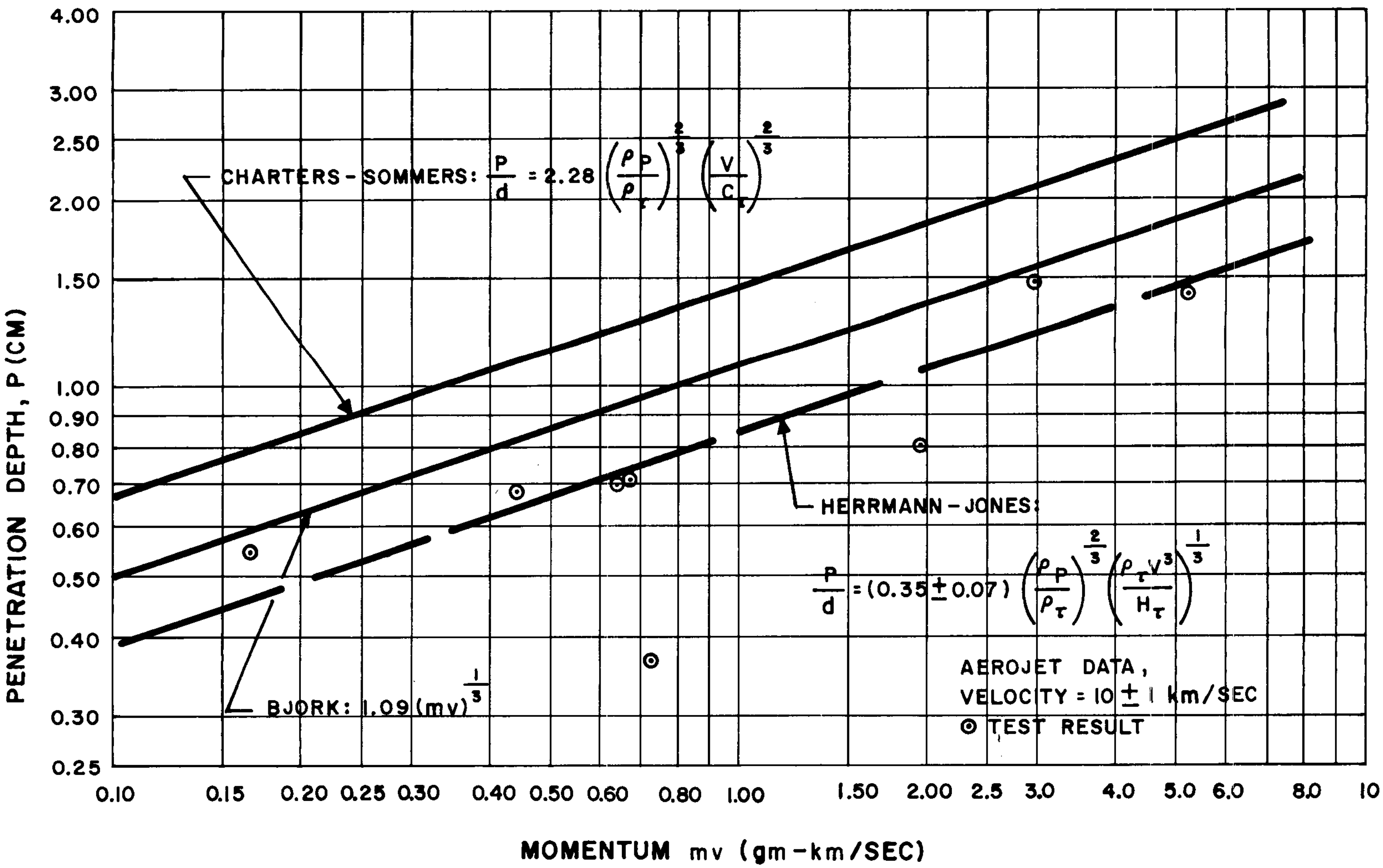
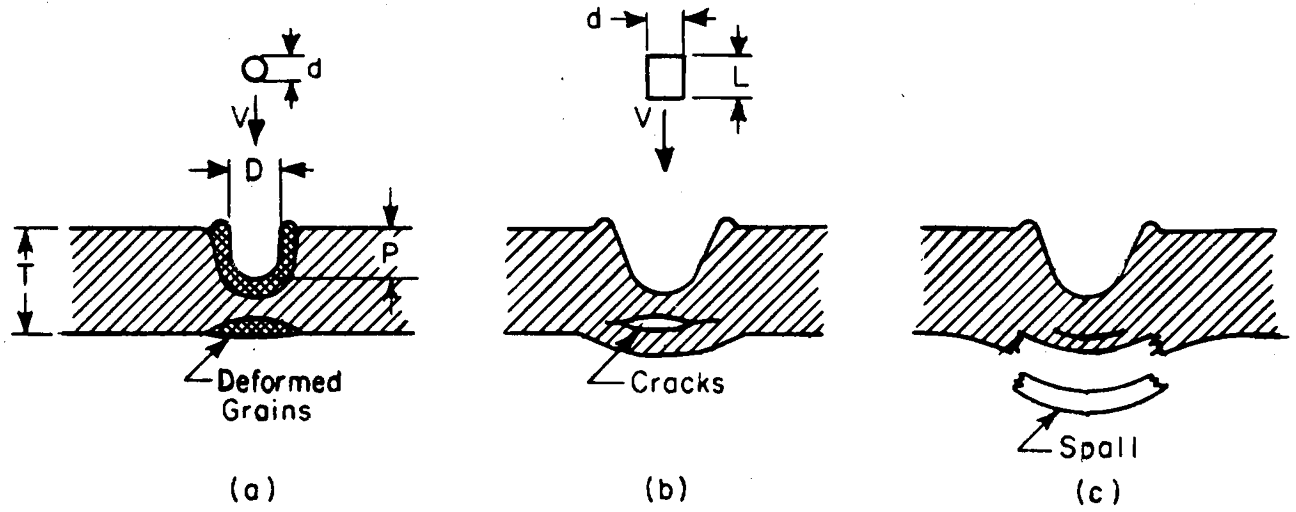


Figure 3-25 HIGH-VELOCITY PENETRATION IN ALUMINUM



Rear Surface Damage in Relatively Thick Targets

Figure 3-26

Products of Combustion

For some space flight maneuvers such as "turn around" and "rendezvous" the products of combustion may be of concern. The effects of these products on the spacecraft may include corrosion, abrasion and condensation, and coating onto components.

Any study directed toward the effects of the products of combustion on the valves would depend on many parameters, such as the mixture ratio of the propellants, the rocket nozzle design, and the distance of the component from the nozzle or the time lag which would affect the concentration. The principal products of combustion at high expansion are given in Table 3-13

Table 3-13 Principal Products of Combustion for Typical Oxidizer - Fuel Ratios

Propellant Mixture	Principal Products of Combustion at High Expansion
$\frac{N_2O_4}{N_2H_4}$	N_2, H_2, H_2O
$\frac{N_2O_4}{C_2H_8N_2}$	N_2, H_2, H_2O, CO, CO_2
$\frac{LOX}{LH_2}$	H_2, H_2O
$\frac{LF_2}{LH_2}$	H_2, HF
$\frac{B_5H_9}{N_2H_4}$	N_2, H_2, BN (Solid)
$\frac{N_2O_4}{B_5H_9}$	N_2, H_2, H_2O, B_2O_3(Solid)
$\frac{Cl\ F_3}{N_2H_4}$	N_2, H_2, HCl, HF, Cl_2
$\frac{LOX}{LiBH_4}$	H_2O, H_2, B_2O_3(Solid), Li_2O(Solid), LiOH(Solid)

PLANETARY ENVIRONMENTS

MOON

The moon is the celestial body nearest earth. It has a mass 0.0123 that of the earth, and a mean surface gravity of 0.165 of the earth's surface gravity. The temperature extremes are approximately from -243° to +260°F. The escape velocity is 1.39 miles/sec, and its mean distance from the earth is 238, 857 miles. There is essentially no atmosphere on the moon.

The surface of the moon is characterized by craters and the great plains called maria. The craters are believed to have been formed by impact from meteoroids, with some exceptions such as the smaller craters near the great crater Copernicus, which may have been formed by volcanic activity. The maria are believed to consist of deep layers of dust produced by ultraviolet rays, solar rays, corpus-cular radiation, and by heating and cooling of the moon's surface. Vast amounts of dust could also be produced by volcanos. Radio measurements have indicated that there is a dust layer of at least a millimeter in depth covering a large portion of the moon's surface. Detailed information about the moon's surface is lacking.

Quick settling of the lunar dust after being disturbed by impact is expected because of the absence of a lunar atmosphere; however, due to the lighter gravitational field, the rise or spread of the dust particles would be greater on the lunar surface than on the earth's surface for the same impact conditions. Because of the position of the valving on the rocket engine, it is conceivable that this dust will contaminate the exposed area of the valves, actuators, and the closure seat of the shutoff valve.

It is assumed for the purpose of this report that a vertical approach to the lunar surface is necessary and that the maria are the more advantageous landing areas. It is also assumed that the surface layers of the moon are from 1 to 10 cm in depth, that the layers consist of loose particles ranging in size from rock flour to approximately 0.3 mm in diameter, and that the particles are composed of material with a high silica content.

MARS

Mars comes closer to earth than any other planet except Venus. Its mass is 0.108 that of the earth, and its mean surface gravity is 0.40 times the earth's surface gravity. The escape velocity of Mars is 3.9 miles/sec and its distance from the earth varies from 34.5 million to 141 million miles. The atmosphere of Mars is estimated to be 95 percent nitrogen and 5 percent carbon dioxide with a surface atmospheric pressure of about 0.1 earth atmospheres.

There is still a great deal to be learned about the Martian atmosphere. Three types of clouds have been observed on Mars, white, yellow, and blue. The white clouds are believed to be composed of small ice crystals at altitudes of approximately 12 to 16 miles. Except in the polar regions of Mars the white clouds seldom persist until noon.

The yellow clouds are believed to be dust clouds at altitudes of up to 3 miles. The yellow clouds are seen more frequently when Mars is near perihelion, and it is believed this is due to the higher surface temperatures, which stimulate convection currents.

Less is known about the blue clouds, but the transmission properties of this layer indicate particles of 0.1 to 1.0 microns in size, and speculation suggests these particles range from meteoric dust to solid CO_2 or water at an altitude of from 18 to 22 miles.

The temperature of Mars at the subsolar point varies from about 90°F when Mars is at perihelion to approximately 30°F when Mars is at aphelion. At night temperatures may fail as low as -180°F, but because of the difficulty in measuring night temperatures, this value may be inaccurate.

Although Mars has an atmosphere, the surface can be seen. The polar caps are believed to be areas of frost which extend in the winter and sublimate or melt back in the summer. The bright areas of the Martian surface are orange in color and are believed to be sandy deserts. The existence of sandy deserts is also consistent with the interpretation of the yellow clouds mentioned earlier. Observations of the Martian surface show that there are no mountains, or at least no very large mountains. The dark areas of Mars are thought to be vegetation of some kind, but at present no explanations are given which are generally accepted.

Mars has two satellites which may be used as space stations and, therefore, are important to any environmental study. Phobos is 5820 miles from the center of Mars and is about 10 miles in diameter. The other satellite, Deimos, is 14,600 miles from the center of Mars and is about 5 miles in diameter.

VENUS

Venus can approach nearer to the earth than any other planet. Its mass is 0.82 that of the earth, and its gravity is 0.9 of the earth's gravity. The escape velocity from the Venus surface is approximately 6.45 miles/sec. Its distance from the earth varies from 26 million to 160 million miles. Venus has an extremely opaque cloud coverage which completely hides its surface; thus, nothing is known about its geographic makeup. The atmosphere is considered to be composed of 95 percent nitrogen and

5 percent carbon dioxide at 16 atmospheres. Its surface temperature is assumed to be from 620° to 1150°F.

JUPITER

Jupiter is the largest planet in the solar system. Its mass is nearly 317 times that of the earth, and its gravity is 2.6 of the earth's gravity. The escape velocity from the planet's surface is about 38 miles/sec. Jupiter's distance from the earth varies from 390 million to 577 million miles. Jupiter has a dense cloud coverage which hides the surface from observation. The atmosphere is believed to consist largely of ammonia and methane. The temperature of the surface, based on the distance of the planet from the sun and its reflecting power, is estimated at -220°F.

The existence of a Van Allen radiation belt on the planet Jupiter has been fairly well determined by the radio astronomers of the California Institute of Technology. The belt is about 200,000 miles above the surface of the planet and is considered to be a much more serious hazard to space travel than that of the earth.

IV. FURTHER STUDIES FOR DESIGN CONSIDERATIONS

This section includes studies on materials and selected problems that may be associated with leakage in metal-to-metal valve seats. The materials were studied to determine the extent of the compatibility problems encountered with valves that will be expected to operate with present and future propellants used in space propulsion systems. Additional studies included the effects of the space environments such as vacuum and radiation on valve materials. Preliminary tests were conducted on machining in a high vacuum on various materials to determine possible problems associated with space maintenance. The effects of wear particles and temperature gradients on the valve seats were also investigated to determine their effects on leakage.

MATERIALS COMPATIBILITY - PROPELLANTS

INTRODUCTION

Many liquid propellants are highly reactive with the engineering materials used in valve construction, the results of the reaction being evidenced by severe corrosion and, under certain conditions, by fire or detonation. Conversely, some metals cause a degradation of the propellants by effecting a decomposition of the fluid. Cryogenic fluids can adversely affect the strength of structural materials and care must be taken to base design calculations on the allowable stress at the operating temperatures.

In considering the compatibility of materials with propellants, only those propellants of current interest for space application were taken into account. Consideration was then given only to the materials that would be subjected to the propellant environment for long-term duration, or as would be experienced by the valves operating on a space vehicle in an extended orbit of approximately two years. In general, materials that are considered acceptable are rated according to corrosion and impact tests that have been performed. These materials exhibit a very small corrosion rate (approximately 1 mil per year or less), do not promote decomposition of the propellant, and are free from impact sensitivity. In the case of cryogenic application such as would be experienced with liquid hydrogen, materials were selected that maintained structural strength at the temperature of LH_2.

The materials selected as compatible with a given propellant and presented in this report are intended to be used as a guide to the valve designer. Disagreement in ratings of some materials by different sources of information may have resulted from inadequate test procedures, isolated adverse effects due to improper cleaning, etc. In many cases temperatures given are only test temperatures and are not necessarily limit temperatures needed to maintain an acceptable rating.

Omission of some design materials often used in valve construction, e.g., tungsten carbide, is due to lack of sufficient test data and does not necessarily mean such materials are incompatible with the propellants.

NITROGEN TETROXIDE (N_2O_4)

Nitrogen tetroxide is a highly reactive, toxic oxidizer, insensitive to all types of mechanical shock and impact. Although it is nonflammable itself, it will support combustion and upon contact with certain high-energy fuels such as the hydrazines will react hypergolically.

Dry nitrogen tetroxide is compatible with many materials and alloys used in space vehicle constructions. However, water contamination present in the nitrogen tetroxide causes the formation of nitric acid which is corrosive to many metals.

In general, aluminum alloys and stainless steels are most suitable for use as materials in contact with nitrogen tetroxide. The resistance to corrosion exhibited by the various aluminum alloys is a function of water content in the nitrogen tetroxide and the aluminum content of the alloy in question. As the water content in the nitrogen tetroxide exceeds 0.3 percent, the highly alloyed materials (e.g., 7075 Aluminum Alloy) show a sharp increase in corrosion rates as contrasted by the purer aluminum alloys (e.g. 1100 Al. Alloy), whose increase in corrosion rate is much less pronounced. For stainless steel, however, the corrosion rate in nitrogen tetroxide varies directly with water content.

The use of titanium alloys with nitrogen tetroxide has been questioned due to its known impact sensitivity with strong oxidizers. However, majority of data indicates that titanium alloys exhibit satisfactory resistance to nitric acid and are suitable for use except under extreme impact conditions.

Copper, magnesium and nickel alloys are not recommended for use because of their poor corrosive resistance to nitric acid.

Most nonmetallic materials show poor resistance to nitrogen tetroxide and are considered unsatisfactory for use. Reaction of nitrogen tetroxide with non-metals can result in decomposition of the materials causing degradation or complete destruction, or it can alter the physical properties such as volume and/or hardness of the material. The propellant may also be affected in its physical characteristics. Of all the plastics available for use, Teflon and Teflon products exhibit the best resistance to nitrogen tetroxide, however, nitrogen tetroxide permeates and is absorbed by Teflon. Results from permeability tests conducted show that the permeability rate for Teflon TFE7 is three times greater than Teflon FEP.

Most lubricants in contact with nitrogen tetroxide are either dissolved and washed off or undergo a substantial change in hardness. Dry lubricants Molykote Z, Drilube 703 and Electrofilm 66-C have been rated as compatible with nitrogen tetroxide. At the present, Microseal 100-1 is rated as compatible with nitrogen tetroxide and does not undergo any physical changes.

Table 4-1 lists those materials which are considered to be compatible with nitrogen tetroxide for long-term application. It should be noted that temperatures, temperature ranges and per cent of water contamination are parameters of conducted tests and are not necessarily temperature limits or moisture content limits.

TABLE 4-1

MATERIALS COMPATIBLE WITH NITROGEN TETROXIDE (N_2O_4) FOR LONG TERM APPLICATION

Material	Remarks		
	Per Cent of H_2O Less Than	Test Temp (^oF)	Other
<u>Aluminum Alloys</u>			
1060	0.1	80	
1100	0.3	55-60	
2014-T6	0.2	55-60	
2024-0	0.2	100	
2219-T81	0.2	55-60	
3003-H14	0.6	150	
5052-0	0.3	100	
5086-H34	0.5	115	
5086-H36		63-67	
5254-F		63-67	
5456-H24	0.2	55-60	
5456-H321	0.2	55-60	
4043	0.1		
6061-T6	0.5	130	
6066			
7075-0	0.2	100	
7075-T6	0.6	55-60	
356-T6	0.2	55-60	
Tens 50			
<u>Stainless Steel</u>			
301			
302		100	
303		100	
304		55-65	
304 L (Incl. Welded)	3.2	63-67	
316		63-67	
321 (Incl. Welded)	3.0	55-60	
347 (Incl. Welded)	10.0	100	

TABLE 4-1 (cont'd) Materials Compatible with Nitrogen Tetroxide (N_2O_4) For Long Term Application

Material	Remarks: Per Cent of H_2O Less Than	Remarks: Test Temp (°F)	Remarks: Other
Stainless Steel (Cont.)			
17-4 PH (Cond A)		63-67	
17-4 PH (H 1100)	0.3	100	
17-7 PH	3.0	55-65	
17-7 PH (TH 950)	0.3	100	
PH 15-7 Mo (Cond A)	3.2	63-67	
AM 355 (Cond H)		63-67	
AM 350 Ann.	10.0	100	
A 286 Ann.	0.5	55-60	
*410 H & T		63-67	
*410 (RC41)	1.0	100	
416		55-60	
440 C		63-67	
440 C Ann.	0.6	100	
8630		140	
Other Metals			
ASTM A-285 (Grade C) Steel	0.8	165	
1020 Steel	0.2	55-60	
Cast Iron	0.1	80	
Inconel		55-65	
Inconel X			
*Ti Alloy - B-120 VCA		55-60	
*Ti Alloy - C-120 AV	0.2 3.2	55-60 70-165	
*Ti Alloy - 75 A	3.2	70-165	
*Ti Alloy - 65A	25.0	100	
*Ti Alloy - A-110 AT		55-65	

*Disagreement exists between authorities as to acceptability.

TABLE 4-1 (Continued) Materials Compatible with Nitrogen Tetroxide (N_2O_4) for Long Term Application

Material	Remarks	
	Test Temp (^oF)	Other
<u>Other Metals</u> (Cont.)		
Cobalt Alloy - Stellite	55-67	
Non-porous Chromium Plating		0.0005-0.003 In. Thickness
Gold Plating	55-60	0.0001-0.001 In. Thickness
Tin Plating	55-60	0.001-0.003 In. Thickness
Tantalum	55-65	
<u>Plastics and Elastomers</u>		
Teflon (TFE)	63-67	N_2O_4 Permeated and was absorbed
Teflon filled with Asbestos	55-60	
Teflon filled with Glass	70-80	
Teflon filled with Calcium Fluoride	70-80	
Fluorobestos filled with Asbestos	55-60	
Fluorogleen filled with Ceramic	55-60	
Teflon (FEP)	70-80	Less Permeable by N_2O_4 than TFE
Kynar	63-67	
<u>Lubricants</u>		
Microseal 100-1	63-67	
Molycote Z (Binderless)	55-60	
Drilube 703	55-60	
Electrofilm 66-C	55-60	
Graphite (Dry)	63-67	

CHLORINE TRIFLUORIDE (ClF_3)

Chlorine Trifluoride, like Fluorine, is among the most active chemicals known. Being a very strong oxidizing agent it reacts vigorously with most oxidizable substances at room temperature and with most common metals at elevated temperatures. Under ordinary conditions, chlorine trifluoride reacts violently with water. It is, however, insensitive to mechanical shock, nonflammable in air, and shows good thermal stability at ambient temperature.

The corrosion resistance of all materials of construction used with chlorine trifluoride depends on the formation of a passive metal-fluoride film which protects the metal from further attack. The ability of some compact metals such as Monel, copper, nickel, stainless steel, etc., to form a passive metal-fluoride film makes them resistant to attack by chlorine trifluoride. Among the metals mentioned, Monel and nickel are preferred because of their resistance to hydrazine fluoride and hydrazine chloride, which are formed by the reaction of chlorine trifluoride with water.

There are at the present no nonmetallic materials or lubricants that are completely compatible with chlorine trifluoride. Teflon has been found to be compatible with chlorine trifluoride under static propellant (non flow) conditions if it has been properly cleaned.

Table 4-2 lists those materials which are considered to be compatible with chlorine trifluoride under most conditions for long-term application. However, materials that are listed in the table must be thoroughly cleaned and passivated (in the case of metal) to insure contamination free surface. All chlorine trifluoride systems must also be dry and leakproof.

TABLE 4-2

MATERIALS COMPATIBLE WITH CHLORINE TRIFLUORIDE (ClF_3) UNDER MOST CONDITIONS FOR LONG-TERM APPLICATION

MATERIAL

Aluminum Alloys

- 1100
- 1160
- 2024
- 3003
- 5052
- 6061
- 6066
- 356
- Tens 50

Stainless Steels

- 301
- 302
- 303
- 304
- 316
- 321
- 347

MATERIAL

Other Metals

- Nickel
- Monel
- K. Monel
- Inconel
- Rene Nickel 41
- Nitralloy
- Copper
- Tin
- Indium
- Tin Indium Alloy
- Lead Indium Alloy
- Bronze
- Magnesium
- Magnesium Alloys

Non-Metals

- Teflon (Under Static Cond. Only)
- Kel-F (Under Static Cond. Only)

Note: Metals must be properly cleaned and passivated prior to use.

AEROZINE-50 (50% HYDRAZINE/50% UDMH)

The storable fuel blend of a nominal 50 per cent by weight of hydrazine and 50 per cent by weight of unsymmetrical dimethylhydrazine is a hygroscopic (capable of absorbing moisture readily) liquid which is insensitive to mechanical shock but flammable in both liquid and vapor states. When combined there is a definite tendency for each to dissolve in the other. However, because of their different densities they are easily stratified with UDMH being above the N_2H_4. Since the vapor above the fuel blend at 72°F is predominately UDMH, the flammability hazards of the mixture are the same as for UDMH. Explosion hazards can be minimized, however, by maintaining the fuel in closed systems.

Most common metals, with the exception of the magnesium and copper alloys which might be used for valve construction, are compatible with the 50/50 fuel blend providing they are clean. Care should be exercised when using ferrous alloys because of the possible catalytic decomposition of the fuel blend due to rust. Under certain conditions (eg. high temperature) rust may be a decomposition catalyst to N_2H_4 and ignition may result.

Although there has been some skepticism on the use of molybdenum-bearing stainless steels because of catalytic decomposition of N_2H_4 by the molybdenum, many tests have shown that up to 160°F alloys of this type have shown no adverse effects.

Most plastics, elastomers, lubricants and coatings are either dissolved, their physical properties altered, or completely destroyed by the 50/50 fuel blend. Of the plastics, Teflon and Teflon products are chemically resistant to the 50/50 fuel blend. Other plastics may be suitable if a change in physical properties, e.g., swelling and brittleness, can be tolerated. Of the elastomers, most butyl rubbers show good resistance to the 50/50 blend. Most lubricants dissolve or wash out when exposed to the 50/50 blend with the exception of the dry lubricants such as Microseal.

Table 4-3 lists those materials which are considered to be compatible with the 50/50 fuel blend for long term application.

TABLE 4-3

MATERIALS COMPATIBLE WITH AEROZINE-50 (50% Hydrazine/50% UDMH) FOR LONG TERM APPLICATION

Material	Test Temp (°F)
Aluminum Alloys	
1100	55-60
2014-T4	55-60
*2014-T6	160
*2024-T6	160
2219-T81	55-60
3003-H14	150
5086-H36	160
5254-F	160
5456-H24	55-60
5456-H321	160
6061-T6	160
6066	160
*7075-T6	160
356	160
Tens 50	160
Stainless Steels	
303	160
304L	
*316	160
321	160
347	160
PH15-7Mo (Cond. A)	160
*17-4PH	160
17-4PH (Cond. A)	160
*AM355 (Cond. H)	160
*AM 350 SCT	160
*410 H & T	160
440C	160

TABLE 4-3 MATERIALS COMPATIBLE WITH AEROZINE-50 (Continued)

Material	Test Temp (°F)
Other Metals	
*1020 Steel (rust free)	55-60
4130 Steel (rust free)	55-60
A286 Steel (rust free)	55-60
Monel	80
*Nickel	160
Ti Alloy B/20VCA	55-60
Ti Alloy A110-AT	160
Ti Alloy C/20 AV	160
Stellite 25	160
Stellite 6K	160
*Stellite 21	160
Berylco 25	160
Non-porous Chromium Plating	55-60
Non-porous Electrolytic Nicket Plating	55-60
Electroless Nickel Plating	160
Silver	55-60
Tin	55-60
Anodize Coatings on Aluminum	160
Titanium Carbide (Ni Binder)	160
Silver Solder	55-60
Plastics and Elastomers	
Teflon (TFE)	70-80
Teflon filled with Graphite	55-60
Teflon filled with Molydisulfide	55-60
Teflon filled with Asbestos	55-60
Fluorobestos filled with Asbestos	55-60
Fluorogreen	55-60
Teflon (FEP)	70-80
Low-density Polyethylene	55-60
Zytel 31 Nylon	70-80
Hadbar XB800-71 Rubber	160
Parker B496-7 Rubber	160

TABLE 4-3 MATERIALS COMPATIBLE WITH AEROZINE -50 (Continued)

Material	Test Temp (^{o}F)
Lubricants and Graphite	
Microseal 100-1 (dry lube)	70-80
Graphitar 39	70-80
Graphitar 84	70-80
Graphitar 86	160
National Carbon CCP-72	160
Purebon P3N	160
Ceramics	
Temporall 1500	55-60
Sauereisen 31	55-60

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* Disagreement exists between authorities as to acceptability

Unsymmetrical Dimethylhydrazine (UDMH)

UDMH (unsymmetrical dimethylhydrazine) is a moderately toxic, shock insensitive, high energy storable liquid propellant. It exhibits excellent thermal stability and resistance to catalytic breakdown. UDMH has been rapidly accepted as a high energy storable propellant due to its compatibility with almost all metals under normal environmental conditions and also for its ability to be stored for extended periods of time.

Due to an extremely wide flammable range in air and the possibility that explosive vapor-air mixtures may be found above the liquid, UDMH should not be exposed to open air. Instead, it should be stored in a closed container under a nitrogen blanket.

At the present time test results imply that lubricants which are compatible for use with UDMH are still in the development stage. Lubricants such as Parkerlube 6PB, Molykote and Peraline 12-4 may cause decomposition, while petroleum and silicone greases are dissolved by the UDMH.

Table 4-4 lists those materials which are considered to be compatible with UDMH for long-term application.

TABLE 4-4

MATERIALS COMPATIBLE WITH UNSYMMETRICAL DIMETHYLHYDRAZINE (UDMH) FOR LONG-TERM APPLICATION

MATERIALS	REMARKS
Aluminum Alloys	
1100	Temp < 75°F
1260 - H14	
2014	Temp < 75°F
2017	Temp < 75°F
2024	Temp < 75°F
3003	Temp < 75°F
3004 - H34	
5052	Temp < 75°F
5086 - H34	
5154 - H34	
6061	Temp < 75°F
6063 - T6	
7075	Temp < 160°F
43	
356	Temp < 75°F
Stainless Steel	
302	
303	Temp < 140°F
303 (Passivated)	Temp < 160°F
304	Temp < 140°F
316	
321	Temp < 140°F
347	Temp < 160°F
410	Temp < 160°F
416	Temp < 160°F
422	
17-7 PH	Temp < 160°F
Carpenter 20	Temp < 140°F
Haynes Alloy 25	

Table 4-4 (Continued) Materials compatible with Unsymmetrical Dimethylhydrazine (UDMH) for Long Term Application

MATERIALS	REMARKS
Stainless Steel (Cont'd)	
A286	
AM350	
AM355	
17-4 PH Cond. H925	
17-4 PH Cond. H1150	
Misc. Metals	
Mild Steel	
4130 Steel	Temp $< 75^{\circ}$F
Hastelloy (B, C, X, F)	
Inconel	
Monel	
Magnesium Alloy AZ-92-F	
Magnesium Alloy AZ-31B-0	
Titanium A-55 (Commercially Pure)	
Titanium Alloy B-120VCA	
Titanium Alloy C-120AV	Temp $< 160^{\circ}$F
* Copper	Temp $< 75^{\circ}$F
* Brass	Temp $< 75^{\circ}$F
Plastics and Elastomers	
Teflon	Temp $< 160^{\circ}$F
Teflon (FEP)	
Polyethylene	Temp $< 80^{\circ}$F
Nylon	Temp $< 130^{\circ}$F
Kel-F (Unplasticized)	Temp $< 140^{\circ}$F
Misc. Materials	
Delanium	Temp $< 75^{\circ}$F
Glass Pyrex	Temp $< 160^{\circ}$F
Graphite	Temp $< 75^{\circ}$F

* Disagreement exists between authorities as to acceptability.

HYDRAZINE (N_2H_4)

Hydrazine is a high-energy propellant that is insensitive to mechanical shock or friction and exhibits excellent thermal stability at ambient temperatures. It is considered a hazardous propellant, however, due to its toxicity, reactivity and flammability. Being a strong reducing agent, hydrazine when decomposed under elevated temperatures and catalyzed by a metal oxide such as an iron oxide or copper oxide, releases considerable energy resulting in a possible explosion or fire. In addition, liquid hydrazine exerts sufficient vapor pressure above $100^{\circ}F$ to form flammable air mixtures.

In assessing the compatibility of a material with hydrazine, the specific application for its use must be considered.

Metals satisfactorily used with hydrazine where air oxidation of the surface can be prevented, may not be satisfactory for service where prolonged exposure to air cannot be avoided. Factors to consider when selecting materials to use with hydrazine for any given exposure condition are: 1) corrosiveness of the material in contact with hydrazine and 2) the effect of the material and/or its corrosion products formed on the rate of decomposition of hydrazine.

These factors to be considered are particularly true for carbon steel, low-alloy steels, copper alloys and molybdenum. From the corrosion standpoint, these metals are satisfactory for use in hydrazine, however, these metals and/or their oxides may catalyze hydrazine decomposition at elevated temperatures and explosions may result.

Table 4-5 lists those materials considered to be compatible with hydrazine for long-term application.

TABLE 4-5

MATERIALS COMPATIBLE WITH HYDRAZINE (N_2H_4) FOR LONG-TERM APPLICATION

MATERIAL	REMARKS
Aluminum Alloys	
1100	Temp $< 77^{\circ}$F
2014	
2024	Temp $< 68^{\circ}$F
3003	Temp $< 80^{\circ}$F
4043	Temp $< 75^{\circ}$F
5052	
6061	
6066	
** 7075	
356	
Tens 50	
Stainless Steel	
304	Temp $< 80^{\circ} - 160^{\circ}$F
304L	Temp $< 80^{\circ} - 160^{\circ}$F
347	
AM350	Temp $< 100^{\circ}$F
AM355	Temp $< 100^{\circ}$F
A286	Temp $< 100^{\circ}$F
Misc. Metals	
Inconel	Temp $< 80^{\circ}$F
Inconel X	Temp $< 73^{\circ}$F
** Nickel	Temp $< 80^{\circ}$F
** Monel	Temp $< 80^{\circ}$F
Ti Alloy 6AL-4V	Temp $< 160^{\circ}$F
Tantalum	

** Disagreement exists between authorities as to acceptability.

Table 4-5 MATERIALS COMPATIBLE WITH HYDRAZINE (N_2H_4) (Continued)

MATERIAL	REMARKS
Plastics and Elastomers	
Teflon	Temp $\leq$ 140°F
Kel-F	Temp $\leq$ 80°F
Polyethylene	Temp $\leq$ 80°F
Teflon 100-X	
Nylon	Temp $\leq$ 80°F
Misc. Materials	
Asbestos	Temp $\leq$ 80°F
Chromium Plating	
Glass	
Graphite	Temp $\leq$ 80°F

** Disagreement exists between authorities as to acceptability.

PENTABORANE (B_5H_9)

Pentaborane is an extremely hazardous, high-energy rocket fuel, insensitive to mechanical shock and in an inert atmosphere exhibits satisfactory thermal stability. It is considered a hazardous propellant due to its toxicity, high reactivity and erratic hypergolic characteristics. Pure pentaborane will usually ignite spontaneously upon contact with air and at atmospheric pressure. It is also hypergolic with high-energy oxidizers such as chlorine trifluoride at atmospheric pressures. In oxidation-reduction reactions, pentaborane behaves as a very strong reducing agent.

Any substance which will function as a potential oxidizer will react with pentaborane. Materials such as water, air, metal oxides and reducible organic compounds are in this category. For this reason, considerable care should be exercised in the selection of materials to be used with pentaborane, so as to avoid use of any organic compounds containing a reducible functional group.

Organic materials such as gaskets, lubricants, and seals must be chemically inert to pentaborane if they are to be used. High-porosity castings and gaskets should be avoided. To date, no metals are known to be incompatible with pentaborane at ordinary room temperatures and atmospheric pressure.

Table 4-6 lists these materials which are considered to be compatible with pentaborane for long-term application.

TABLE 4-6

MATERIALS COMPATIBLE WITH PENTABORANE FOR LONG-TERM APPLICATIONS

MATERIAL

Aluminum Alloys

- 2024-T3
- 3003-H14
- 5052-S
- 6061-T6
- 7075-T6
- 356-T6
- Chromated Aluminum
- Cadmium Coated Aluminum

Stainless Steel

- 302
- 304
- 321
- 347

Other Metals

- Cadmium Plated Steel
- Brass
- Copper
- Hastelloy No. X-1258
- Titanium Alloy C-110M
- Titanium Alloy C-130AM
- Magnesium Alloy, AZ318
- Magnesium Alloy, AZ63A
- Monel, Soft, M-8330-B
- Nichrome "V"
- Iron
- K-Monel

MATERIAL

Non-Metals

- Fluoroflex T
- Fluorosilicon Rubber
- Glass
- Kel-F
- Kel-F No. 5500
- Kel-F and Glass Yarn
- Viton
- Viton A
- Graphite Impregnated Asbestos
- Teflon
- Graph Tar No. 39
- Molybdenum Disulfide
- Rockwell Nordstrom Lube No. 921
- Polyethylene
- Polypropylene
- Velumoid
- Barlack 230

LIQUID OXYGEN (LOX)

Liquid oxygen is a non-toxic, nonflammable, and non-explosive oxidizing agent having a reactivity much lower than gaseous oxygen. Mixing of liquid oxygen with a fuel will cause the latter to solidify, the resulting mixture being extremely shock sensitive.

Most metals are not corroded by liquid oxygen, however, the low temperature of liquid oxygen (-300°F) does cause embrittlement of some metals, especially the body-centered ferrous alloys. As a result, the alloys most commonly used in liquid oxygen handling equipment are nickel, Monel, copper, aluminum, the 300-series of stainless steels, brass, and silver solder. Several instances have been reported of violent reactions of titanium and liquid oxygen, presumably due to impact. On the other hand, titanium alloys have been successfully used for helium pressure bottles in contact with liquid oxygen in the Titan missile, and for the liquid oxygen pressure bottles used in the X-15 rocket planes. It has been postulated that a gas phase is needed to initiate the reaction, but this is still under investigation. Apparently, the surface conditions of cleanliness and smoothness are of major importance in reducing the danger of detonation. Thus, the use of titanium in contact with liquid oxygen must be carefully investigated with respect to the specific conditions present. Impact studies have also shown some reactivity of liquid oxygen with zirconium and aluminum.

The use of organic materials in a liquid oxygen system should be avoided wherever possible because of possibilities of explosions. Many plastics, elastomers and even certain oils and greases do not spontaneously react with liquid oxygen. However, if energy is introduced into a system of an organic material and liquid oxygen, explosions or at least ignition may occur. Energy introduced into the system need not be from just impact alone. Sources of energy may also be from operation of mechanical parts such as: 1) heat produced by friction of metal surfaces, 2) heat from shearing of liquids, 3) shock waves, 4) heat generated by the catalytic breakdown of an organic material in contact with the metal surface, etc.

The most reliable organic materials for liquid oxygen applications are the fluorinated organic compounds (the more highly fluorinated the compound, the more stable* to attack by liquid oxygen.) In special applications many other organic compounds probably can be used. However, investigations with satisfactory testing procedures are needed before organic materials can be used with liquid oxygen with any great assurance of success.

Currently, there is no single test or group of tests which gives a reliable compatibility rating for materials suitable for use with liquid oxygen because of difficulty in determining impact sensitivity. Much of the data which is available was based on a 70 ft-lb acceptance level for impact sensitivity. Apparently, this was an arbitrary requirement based on the impact threshold level of a particular lubricant which, at the time, was considered to be the only safe available lubricant. Because of the lack of a technical basis for the establishment of the 70 ft-lb as an acceptance test parameter, and because the size and shape of the sample and the design of the testing machine affect the detonation results, little value can be assigned to published compatibility tables. For this reason, none is included in this report.

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*The word stable here is more applicable than resistant because it deals with impact sensitivity and not resistance to corrosion.

LIQUID HYDROGEN (H_2)

Liquid hydrogen is a transparent, odorless liquid that normally does not present an explosive hazard when it evaporates and mixes with air in an unconfined space. However, an unconfined mixture of hydrogen gas and air will burn if exposed to a limited ignition source such as a spark. Liquid hydrogen is not in itself explosive but reacts violently with strong oxidizers. If it is contaminated with oxygen it becomes unstable and an explosion is likely to occur. Reaction with fluorine and chlorine trifluoride is spontaneous.

At the low temperature (-423°F) at which hydrogen is a liquid, corrosive attack on materials is not considered to be an important factor in selecting materials to be used. A more important factor in selecting the materials for use with liquid hydrogen is the embrittlement of the materials by the low temperature of the liquid. Embrittlement of some materials by the low temperature of the liquid requires selection of materials on the basis of their structural properties, i.e., yield strength, tensile strength, ductility, impact strength, and notch sensitivity. The materials must also be metallurgically stable, so that phase changes in the crystalline structure will not occur either with time or temperature cycling. It is known that body-centered metals (such as low-alloy steels) undergo a transition from a ductile to brittle behavior at low temperatures, therefore, are generally not suitable for structural applications at cryogenic temperatures. Face-centered metals, such as the austenitic stainless steels, normally do not show a transition from a ductile to brittle behavior at low temperatures. For this reason these types of materials are desirable for use in cryogenic applications. However, care should be exercised in selection of face-centered metals. Low temperature toughness is not a characteristic of all face-centered metals, nor is it a characteristic of all conditions of a specific metal. For example, severely cold-worked or sensitized (carbide precipitation at grain boundaries) austenitic stainless steels can become embrittled at low temperatures.

The use of organic materials is limited because of the embrittling effect of the low temperatures on their physical properties. However, by maintaining the sealing or bearing material at a higher temperature than that of liquid hydrogen, so that only the hydrogen gas contacts the joint, materials such as Teflon, Mylar, Kel-F, Nylon and Micarta have found uses.

Table 4-7 lists those materials which are considered to be compatible with liquid hydrogen for long-term application.

TABLE 4-7

MATERIALS COMPATIBLE WITH LIQUID HYDROGEN (H_2) FOR LONG-TERM APPLICATION

Aluminum Alloys

- 1100
- 1100T
- 2024T
- 4043
- 5052

Stainless Steel

- 301
- 302
- 303
- 304
- 304L
- 316
- 321
- 347
- 410
- Haynes 21

Other Metals

- Molybdenum
- Nickel
- Monel
- Inconel
- Low Carbon Steel
- High Nickel Steel
- Titanium

Non-Metals

- Nitryl Rubber
- Silicone Rubber
- Teflon
- Garlock Packing
- Bakelite
- Micarta
- Lucite
- Graphite

Note: The above listed materials were rated compatible primarily for their embrittlement properties at cryogenic temperatures. Non-metals shown as being compatible should be restricted for "warm" joint application or equivalent.

LIQUID FLUORINE (LF_2)

Fluorine is the most powerful chemical oxidizing agent known. It reacts with practically all organic and inorganic substances, with a few exceptions being the inert gases, some metal fluorides and a few uncontaminated fluorinated organic compounds. It exhibits excellent thermal stability and resistance to catalytic breakdown, thereby presenting little or no problem in these areas. Compatibility ratings are, therefore, based primarily on the reaction of the fluorine with the various materials used.

Although fluorine is the most chemically active of all elements, many of the common metals can be considered for use in liquid fluorine systems.

Fluorine is a liquid at atmospheric pressure only in the short temperature range of $-306^{\circ}F$ to $-363^{\circ}F$. At these low temperatures, chemical reactions in general tend to take place rather slowly, thus corrosive attack by the liquid fluorine is generated at a slower rate. Another factor responsible for low rate of attack by liquid fluorine on the common metals is that protective films of fluoride compounds tend to form on metal surfaces and act as a barrier to further reaction.

The effectiveness of the protective film formed on the metals by the liquid fluorine is based on the solubility of the various metal fluorides that form in the film in fluorine. It is believed that, as a protective film builds up and the rate of reaction slows down, an equilibrium between reactive rate and solubility of the film will be reached and a relatively steady corrosion rate will result. Lack of solubility data for fluorine compounds and corrosion rates for long periods of exposure can only be supplemented by actual service data and extrapolation of existing data. Service data indicate that the fluorides of nickel, copper, chromium and iron are relatively insoluble in liquid fluorine. Also, metals such as Monel, nickel and stainless steels exhibit satisfactory performance in liquid fluorine and indications are that much lower rates of corrosion can be expected for long term exposure where equilibrium rates are reached, than for short term laboratory exposure.

Several light-weight metals such as the alloys of aluminum, titanium and magnesium are also known to produce protective films in liquid fluorine. Of these, titanium probably exhibits the lowest rate of corrosion; however, tests have shown it to be impact sensitive in fluorine.

Other factors to consider in selecting materials for use in a liquid fluorine system are: 1) flow rates, 2) water contamination in the system, and 3) mechanical properties of the material at the low temperatures experienced with liquid fluorine. The rate of flow of the liquid fluorine in a valve and through an orifice is considered to be an important factor in maintaining the protective film on the materials being attacked. Fluoride coatings on some metals that are less resistant to fluorine, such as low-alloy steels, are sometimes very brittle or porous and powdery. High flow rates tend to remove these coatings and thus increase corrosive action. In restricted flow applications, "flaking"of the coating may result in contamination of the propellant and thus create leakage problems at the valve seat.

Of the non-metals, Teflon has withstood exposure to liquid fluorine in a static condition. However, Teflon tends to react with fluorine to break down the polymers and form unsaturated low molecular weight fluorocarbons. These fluorocarbons do not adhere to the surface. Any flow of the propellant or movement of material over the surface of Teflon will remove these fluorocarbons, thus leaving them valueless as a protective film.

Fluorine will react with any water present in the system to form hydrofluoric acid. This acid tends to attack some materials that are normally resistant to uncontaminated fluorine. Of all the metals showing resistivity to fluorine attack, Monel is generally preferred for use because of its inherent resistivity to the hydrofluoric acid.

In selecting materials for use in fluorine systems, consideration should also be given to the effects of low temperature environment on the mechanical properties of the materials. Some metals such as the martensitic stainless steels become brittle at these low temperatures.

To date there are no polymers that are known to be entirely resistant to reaction with liquid fluorine. Almost all organic materials react spontaneously and violently with liquid fluorine, with the exception of the halogen-carbon compounds. Although organic gaskets should be avoided where possible, Teflon and Kel-F can be used, both of which exhibit cold-flow characteristics. Of the inorganic nonmetallics, alumina is resistant to fluorine, glass is suitable if no water is present to form hydrofluoric acid, and asbestos, although difficult to clean, may be used.

Table 4-8 lists those materials which are considered to be compatible for service with liquid fluorine. However, as previously stated, insufficient information on prolonged usage of these materials in liquid fluorine restricts any rating for long-term application. Also, before using any material with fluorine, extreme care should be exercised in cleaning the material thoroughly to remove all possible contamination that may be present. Pretreatment or conditioning treatment is also recommended. After thoroughly cleaning the material, a conditioning treatment exposes the material at room temperature to a mixture of fluorine diluted with an inert gas. This initiates the formation of a relatively inert fluoride film. With the use of a diluted gas, the reaction that may take place with any traces of contamination remaining after cleaning would be less violent in nature. This treatment will then permit the material to withstand attack by full strength fluorine with much less reaction.

TABLE 4-8

MATERIALS COMPATIBLE WITH LIQUID FLUORINE (LF_2)

Aluminum Alloys

- 1100
- 2017
- 2024
- 5052
- 6061
- 7079

Stainless Steels

- 304
- 304L
- 316
- 347
- 410
- 420
- PH 15-7 Mo
- AM 350

Other Metals

- Brass (excluding castings)
- Bronze
- Copper
- Cupro-Nickel
- Everdur 1010
- Inconel
- Magnesium Alloy HK31
- Magnesium Alloy A31
- Monel
- Nickel
- Tantalum
- Zircaloy-2

Note: Materials listed above are rated compatible based on corrosion resistance and shock sensitivity; they do not include effects of cryogenic temperatures on the materials' mechanical properties.

REFERENCES AND BIBLIOGRAPHY - MATERIALS COMPATIBILITY, PROPELLANTS

1. Bell Aerosystems Company. "Titan II Storable Propellant Handbook" March 1962, Bell Report No. 8182-933004, for AFBSD, Contract No. AF04(694)-72

2. Battelle Memorial Institute, Defense Metals Information Center, "Compatibility of Rocket Propellants with Materials of Construction" DMIC Memorandum 65, 15 Sept 1960

3. Rocketdyne. "Hydrazine Handling Manual" AF/SSD-TR-61-7, R-3134, Sept 1961

4. Rocketdyne. "Nitrogen Tetroxide Handling Manual" AF/SSD-TR-61-8, R-3135 October, 1961

5. Rocketdyne. "Chlorine Trifluoride Handling Manual" AF/SSD-TR-61-9, R-3136, October 1961

6. Rocketdyne. "Pentaborane Handling Manual" AF/SSD-TR-61-10, R-3137, October 1961

7. Arthur D. Little, Inc. "Hydrogen Handbook" AF33(616)-6710, AFFTC TR-60-19, April 1960

8. Liquid Propulsion Information Agency, Maryland. "Liquid Propulsion Manual I", March 1961

9. Rocketdyne. "Mechanical System Design Criteria Manual for Nitrogen Tetroxide" AF/SSD-TR-61-5 R-3131, September 1961
   Rocketdyne. "Mechanical System Design Criteria Manual for Pentaborane"
   Rocketdyne. "Mechanical System Design Criteria Manual for Hydrazine"
   Rocketdyne. "Mechanical System Design Criteria Manual for Chlorine Trifluoride"

10. F. W. Fink and E. L. White. Corrosion Effects of Liquid Fluorine and Liquid Oxygen on Materials of Construction, NACE Paper submitted at the 16th Annual Conference, 22 March 1960

11. The Martin Company. "Compatibility of Materials with Liquid Oxygen" November 1958, Report No. M-M-MI-58-66

Vacuum Effects on Organic Materials

Table 4-9 and Figures 4-1 through 4-6 list some materials studied and present the experimental data obtained by Space Technology Laboratories in sublimation studies for OGO. Table 4-9 presents the initial specimen weight, the total exposed surface area of each specimen, the total time of each test, and the total weight loss of each specimen. Figures 4-1 through 4-6 graphically display typical experimental results in plots giving the rate of weight loss in grams per square centimeter per exposed surface area per hour as a function of time of exposure to the test environment. Table 4-10 presents the specific formulation and curing schedule of the materials. Table 4-11 lists the sources of the materials.

The majority of the specimens were prepared by cutting rectangular sections approximately 1 inch square from a prepared sheet of material. Thickness of the specimens varied from 0.003 to 0.005 inch for films and coatings to 0.030 to 0.035 inch for laminates and cast materials. In certain specific cases, materials were received in conditions other than those described. These specimens were cut so as to yield the maximum exposed surface area. After cutting to size, the specimens were wiped with solvent, dried, and stored in a desiccator until tested.

Film and laminate materials were obtained in the fabricated form from qualified vendors. Potting compounds, encapsulants, adhesives, coatings, and similar materials were received in the uncured state and mixed, cast, and cured in the laboratory.

Based on the assumption that the weight-loss exhibited by the various materials tested in this program was the result of evaporation of low vapor pressure constituents, the loss is highly dependent upon the surface area of the specimen and the diffusion rates of the constituents to the surface. The reader is therefore cautioned that the total loss of the materials reported in Table 4-9 must be interpreted with this in mind and should not be directly compared unless the specimen configurations are identical, or nearly so.

It is evident from the experimental results that the rate of weight-loss of the tested materials is, for some initial period, relatively high.

It is assumed that the products of this initial loss are in general surface contaminants such as moisture, absorbed gases, low molecular weight products of the formulation, and similar materials. Following this initial rapid rate of loss, the plastic begins to indicate its true character. It is then that the weight-loss rate begins to follow a definite path for the material, suggestive of its general character, formulation, and cure. In some instances, such as for unmodified epoxies, the rate of weight-loss becomes exceedingly small and may even be undetectable. Materials formulated with completely unreactive additives, with additives which do not completely cross-link, or those materials polymerized by catalysts exhibit varying rates of weight-loss. It is doubtful whether any of the materials tested in this program exhibited actual depolymerization or chemical breakdown of the polymers during these experiments because of the relatively moderate test temperature of 200°F. Exceptions to this statement may possibly be the polysulfide, Pro-Seal 727, and the polysulfide-polyamide adhesive, Pro-Seal 501. These materials, because of their poor elevated temperature stability, may have suffered some chemical decomposition during the test. Since the chemical composition of the vaporized products formed in these experiments was not determined, this has not been established definitely.

Conclusions

1. High molecular weight polymers apparently do not evaporate or sublime in vacuum.

2. The thermal stability of these polymers should be at least as good in vacuum as in air.

3. The weight-loss exhibited by engineering plastics in vacuum is the result of the evaporation of relatively lower molecular weight fractions, unreacted additives, contaminants, etc.

4. Weight-loss rate and amount of weight-loss are greatest early in the test period when the materials at or near the surface evaporate; these loss factors decrease subsequently to a rate determined principally by diffusion rates through the polymer to the surface.

Recommendations

1. Rigid plastics are, in general, preferred over flexible, elastomeric materials.

2. Materials with minimum number and quantity of additives and modifiers are preferred.

3. Complete cure of the plastics must be obtained by extended time and/or elevated-temperature post-curing to ensure the elimination of unreacted, low molecular fractions in the product.

4. Those materials exhibiting high loss rates but considered necessary for use on space vehicles because of special desirable properties should be preconditioned in vacuum at elevated temperature to reduce, as much as possible, the potential loss of the material to space.

Table 4-9 Specimen Data and Total Weight Loss at 200°F and 10^{-7} mm Hg

Material	Exposed Surface Area (cm^2)	Initial Specimen Weight (grams)	Total Weight Loss (%)	Total Time of Test (hr: min)
Lockheed 10801C	9.7	0.43	1.1	63:45
PR 5-1, Type I (modified)	21.9	0.87	1.1	95:50
Cat-a-lac 443-1	20.0	0.29	1.7	188.20
Cat-a-lac 463-1-8	17.0	0.12	0.7	76:45
Kemacryl M49WC17	20.7	0.14	5.0	94:30
PT-207	17.5	0.09	7.9	166:05
Pro-Seal 727 (Room Temp)	1.7	0.19	3.9	119:00
Pro-Seal 501 (Room Temp)	3.6	0.32	0.6	72:00
Pro-Seal 501	17.9	0.96	25.8	66:15
RTV-11	14.9	0.75	1.7	96:30
RTV-60	12.2	0.99	0.9	142:20
Sylgard 182	20.6	0.78	1.6	162:00
Adiprene L-100	22.2	0.84	0.5	81:35
Scotchcast 8 and 10, Cure A	13.5	0.83	7.8	142:35

Table 4-9 Specimen Data and Total Weight Loss at 200°F and 10^{-7} mm Hg (Continued)

Material	Exposed Surface Area (cm^2)	Initial Specimen Weight (grams)	Total Weight Loss (%)	Total Time of Test (hr: min)
Scotchcast 8 and 10, Cure B	17.9	0.57	4.9	138:10
Scotchcast 235	17.4	0.90	3.4	194:20
Hysol 2039	18.6	0.87	4.7	74:15
EC 1469	17.6	0.84	0.2	76:00
H-33-E	10.3	0.57	1.9	142:20
H-42-6	13.8	0.62	2.8	142:30
Epon 826-TETA	17.8	0.72	0.2	93:15
Epon 826-140	21.3	0.80	0.6	74:55
Epon VIII	17.0	0.77	0.2	76:00
Epon 911 M	13.2	0.95	1.6	94:20
EPD X-74 (Mod II)	20.4	0.94	2.0	91:25
Mereco X-305	7.2	0.60	1.8	74:40
Irradiated Polyolefin (Coax)	7.4	0.96*	0.2	146:35

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*Total weight of insulated wire.

Table 4-9 Specimen Data and Total Weight Loss at 200°F and 10^{-7} mm Hg (Continued)

Material	Exposed Surface Area (cm^2)	Initial Specimen Weight (grams)	Total Weight Loss (%)	Total Time of Test (hr: min)
Irradiated Polyolefin (Hook-up) (Commercial)	6.8	0.95*	0.1	142:10
Irradiated Polyolefin (w/o additives)				
Run Number 1	9.3	0.95*	0.2	24:45
Run Number 2	6.7	0.96*	0.1	140:05
Geon 8800	25.5	0.46	4.2	46:00
Scotch 850 Tape: Run Number 1	16.1	0.57	0.6	91:35
Run Number 2	17.7	0.11	0.7	69:30
Zytel 101, 0.020 inch thick	20.0	0.57	0.2	166:30
Zytel 101, 0.030 inch thick	19.9	0.88	0.2	141:50
Alkyd 446	14.9	0.87	0.3	140:00
Alkyd 541	13.5	0.99	~ 0.3	76:05
FF-95	11.6	0.82	1.7	74:45
FF-95 (Al coated)	11.9	0.84	0.2	70:55
Epon 828-CL	13.7	0.77	0.2	98:05
Epon 828-CL	13.7	0.80	2.0	28:10
H-2497	14.5	0.96	0.2	71:25
GEC 111	13.5	0.88	0.3	69:45

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*Total weight of insulated wire

Table 4-10 Specimen Formulation and Curve Schedule

Material	Mixing Proportions		Cure
Lockheed 10801C	As Received		1 hr at 210°F after each coat, plus 1 hr at 400°F after final coat
PR5-1 Type I (Modified)	Epon 815 Beetle 216-8 TETA	100 pbw 2 pbw 10 pbw	15 hr at room temperature, plus 4 hr at 200°F
Cat-a-lac 443-1	443-1 Curing Agent	100 pbw 2.5 pbw	1 hr at 120°F after each coat, plus 4 hr at 120°F after final coat, plus 16 hr at 200°F, plus 4 hr at 250°F
Cat-a-lac 463-1-8	463-1-8 Curing Agent	100 pbw 2.5 pbw	1 hr at 120°F after each coat, plus 4 hr at 120°F after final coat, plus 16 hr at 200°F, plus 4 hr at 250°F
Kemacryl M49WC 17	One Component		Air Dry
PT-207	One Component		45 min at 150°F after each coat, plus 16 hr at 150°F after final coat
Pro-Seal 727	727 Curing Agent	100 pbw 12 pbw	Room Temperature
Pro-Seal 501	501 501A	100 pbw 30 pbw	24 hr at room temperature, plus 4 hr at 200°F
RTV 11	RTV 11 Thermolite 12	100 pbw 0.2 pbw	18 hr at room temperature, plus 8 hr at 200°F
RTV-60	RTV-60 Thermolite 12	100 pbw 0.2 pbw	18 hr at room temperature, plus 8 hr at 200°F
Sylgard 182	Sylgard 182 Curing Agent	10 pbw 1 pbw	4 hr at 150°F
Adiprene L-100	L-100 MOCA	100 pbw 11 pbw	20 hr at 200°F
Scotchcast 8 & 10	Compound No. 8A Compound No. 8B Compound No.10A Compound No.10B	1 pbw 1 pbw 1 pbw 1 pbw	Cure A: 3 hr at 150°F Cure B: 2 hr at 150°F, plus 18 hr at 200°F

Table 4-10 Specimen Formulation and Curve Schedule (Continued)

Material	Mixing Proportions		Cure
Scotchcast 235	One Component		21 hr at 200°F
Hysol 2039-3482	Hysol 2039 Hysol 3482	1 pbw 2 pbw	18 hr at 215°F
EC 1469	EC 1469 EC 1470	100 pbw 4 pbw	4 hr at 200°F
H-33-E	Part A Part B	2 pbw 1 pbw	16 hr at 200°F
H-42-6	Part A Part B Part C	60 pbw 6 pbw 1 pbw	Room Temperature
Epon 826-TETA	Epon 826 TETA	100 pbw 10 pbw	4 hr at room temperature, plus 4 hr at 200°F
Epon 826-140	Epon 826 Versamid 140	100 pbw 100 pbw	20 hr at room temperature, plus 4 hr at 200°F
Epon VIII	Epon VIII Curing Agent "A"	100 pbw 6 pbw	3 hr at 200°F
Epon 911 M	Part A Part B	10 pbw 7 pbw	Room Temperature
EPD X-74	Part A Part B	6 pbw 1 pbw	3 hr at 200°F
Mereco X-305	Part A Part B	2 pbw 1 pbw	24 hr at room temperature
Irradiated Polyolefin	As Received		
Geon 8800	As Received		
Scotch 850	As Received		
Zytel 101	As Received		
Alkyd 446	As Received		
Alkyd 541	As Received		
FF-95	As Received		

Table 4-10 Specimen Formulation and Curve Schedule (Continued)

Material	Mixing Proportions		Cure
828-CL	Epon 828	100 pbw	1 hr at 210°F, plus
	Metaphenylenediamine	14 pbw	1 hr at 350°F
	Volan A-120 Glass Cloth		
H-2497	As Received		
GEC 111	As Received		

Table 4-11. Material Source

Vendor	Material
Allied Chemical Corporation, New York, N. Y.	Alkyd 446 Alkyd 541
American Cyanamid Co., Wallingford, Conn.	Beetle 216-8 FF-95 Versamid 140
B. F. Goodrich, Akron, Ohio	Geon 8800
Coast Pro-Seal and Mfg. Co., Los Angeles, Calif.	Pro-Seal 501 Pro-Seal 727
Dow-Corning Corp., Midland, Mich.	Sylgard 182
E. I. du Pont de Nemours, Wilmington, Del.	Adiprene L-100 Zytel 101
Electronic Production and Development, Hawthorne, Calif.	EPD X-74
E. V. Roberts, Los Angeles, Calif.	Metaphenylenediamine (CL) Triethylenetetramine (TETA)
Finch Paint & Chemical Co., Torrance, Calif.	Cat-a-lac 443-1 Cat-a-lac 468-1-8
General Electric Co., Waterford, N. Y.	RTV-11 RTV-60
Hoffman Electronics Corp., Los Angeles, Calif.	H-33-E H-42-6
Lockheed Missiles & Space Co., Sunnyvale, Calif.	Lockheed 10801C
Metachem Resins, Cranston, R. I.	Mereco X-305
Metal and Thermit Corp., Rahway, N. J.	Thermolite 12

Table 4-11. Material Source (Continued)

Vendor	Material
Minnesota Mining and Manufacturing Co., St. Paul, Minn.	EC 1469 EC 1470 Scotch 850 tape Scotchcast 8 Scotchcast 10 Scotchcast 235
Products Techniques, Inc., Los Angeles, Calif.	PT-207
Radiation Materials, Inc., Long Island City, N. Y.	Irradiated Polyolefin
Shell Chemical Corp., New York, N. Y.	Epon VIII Epon 815 Epon 826 Epon 828 Epon 911 M
Sherwin-Williams Co., Los Angeles, Calif.	Kemacryl M49WC17
Taylor Fibre Co., Morristown, Pa.	GEC 111
Westinghouse Electric Corp., Hampton, S. C.	H-2497
Hysol Corp., Olean, N. Y.	Hysol 2039 Hysol 3482

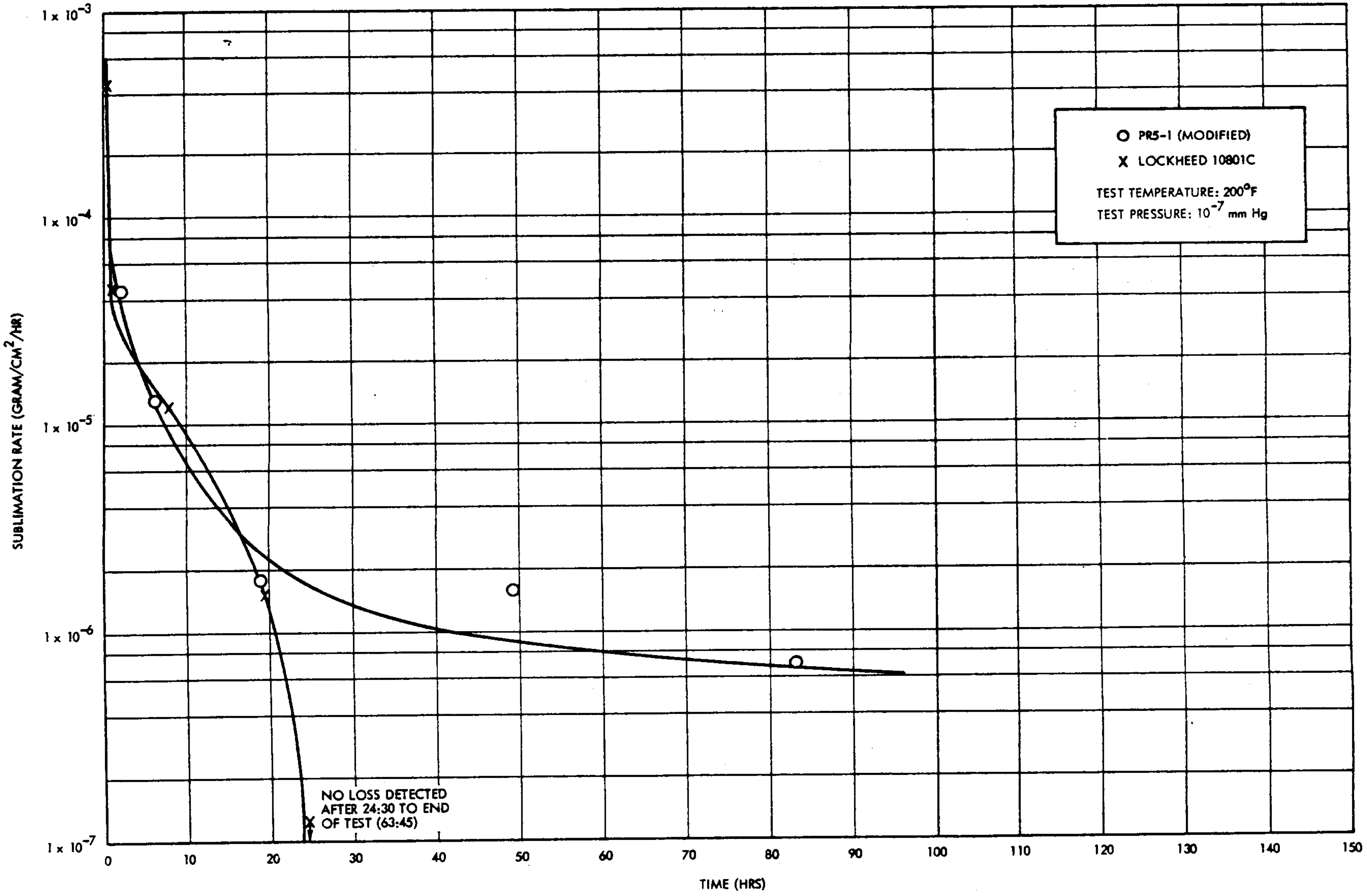


Figure 4-1

Sublimation Rate as a Function of Time in Test Environment

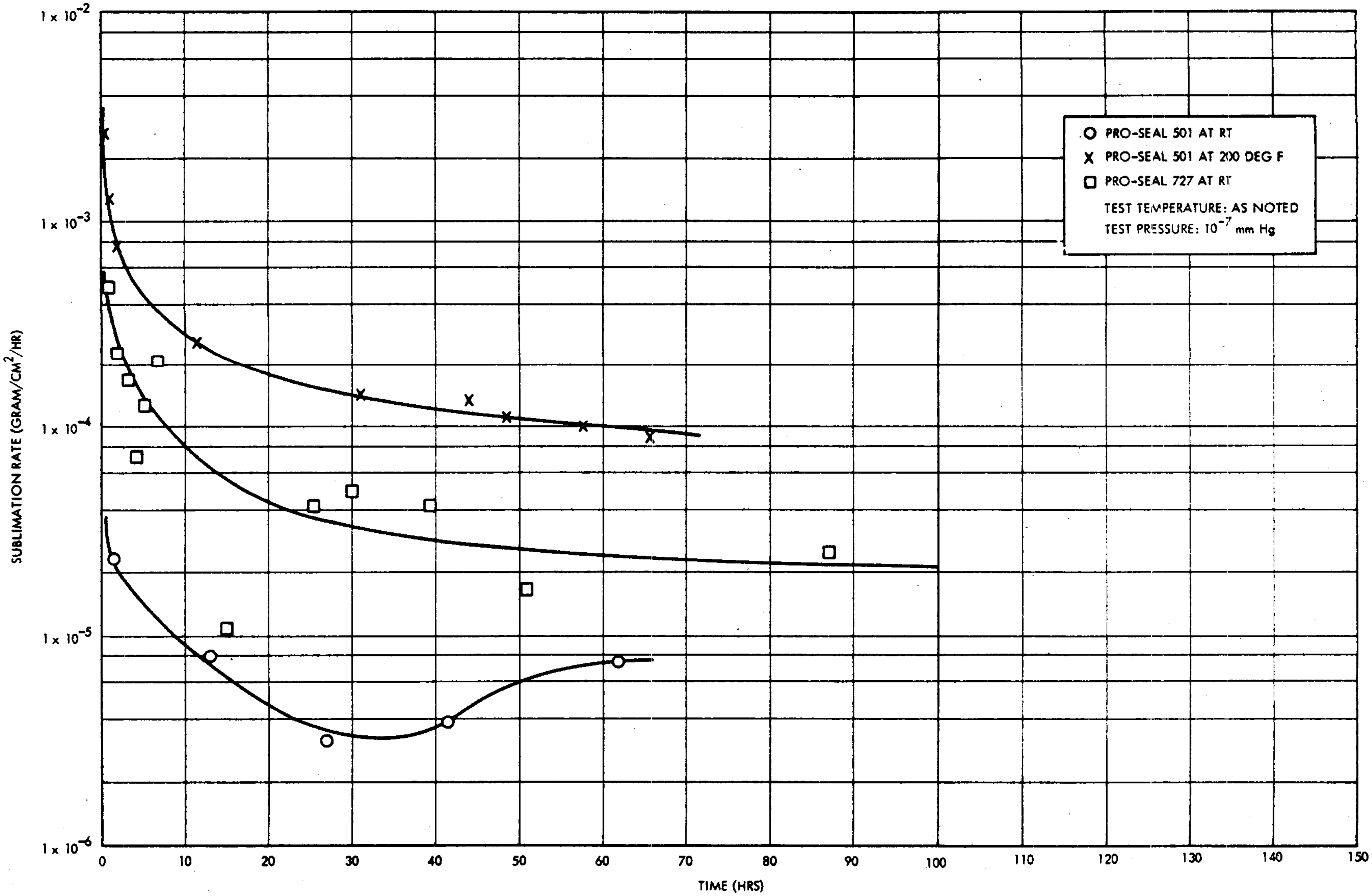


Figure 4-2

Sublimation Rate as a Function of Time in Test Environment

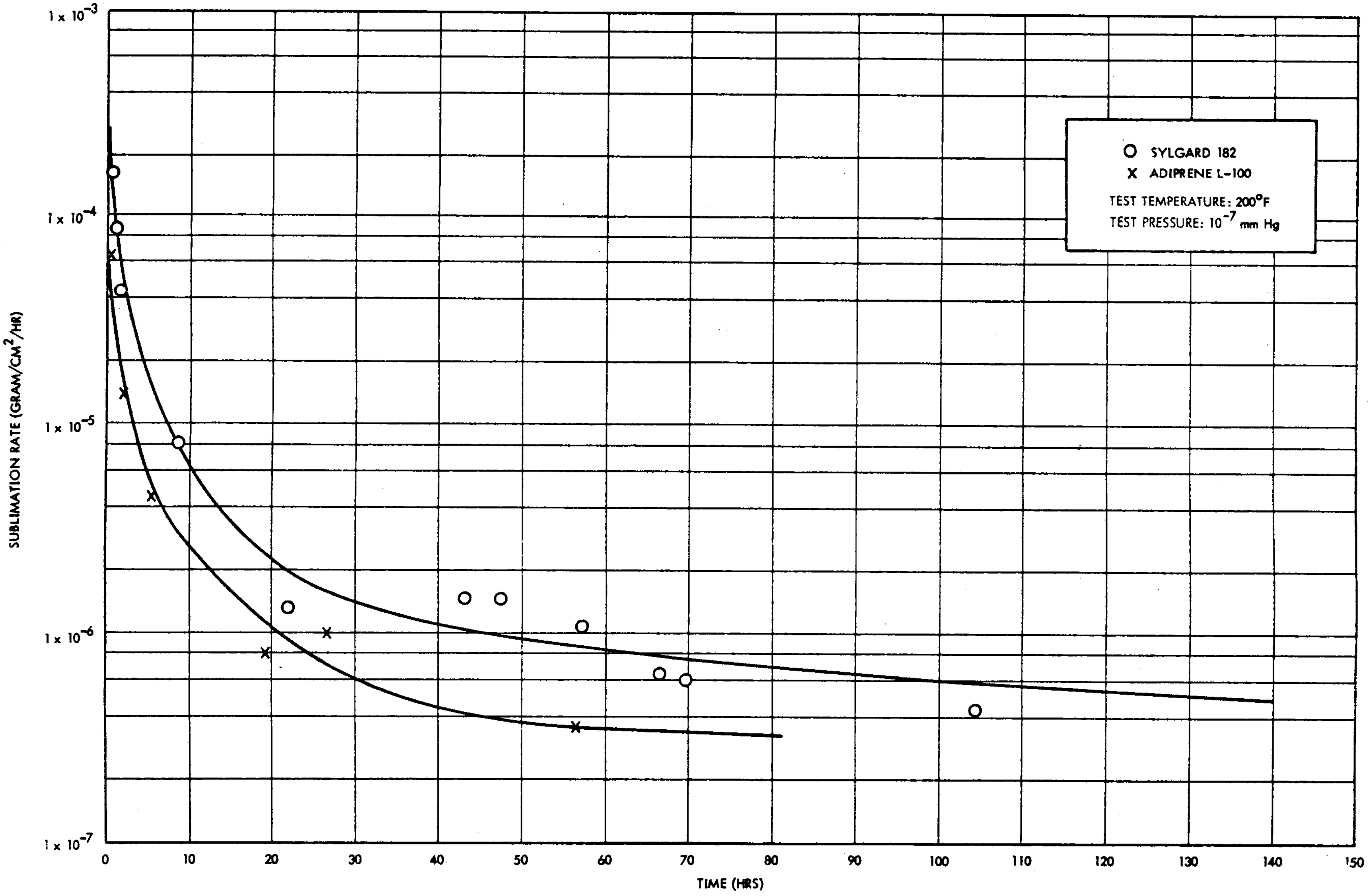


Figure 4-3

Sublimation Rate as a Function of Time in
Test Environment

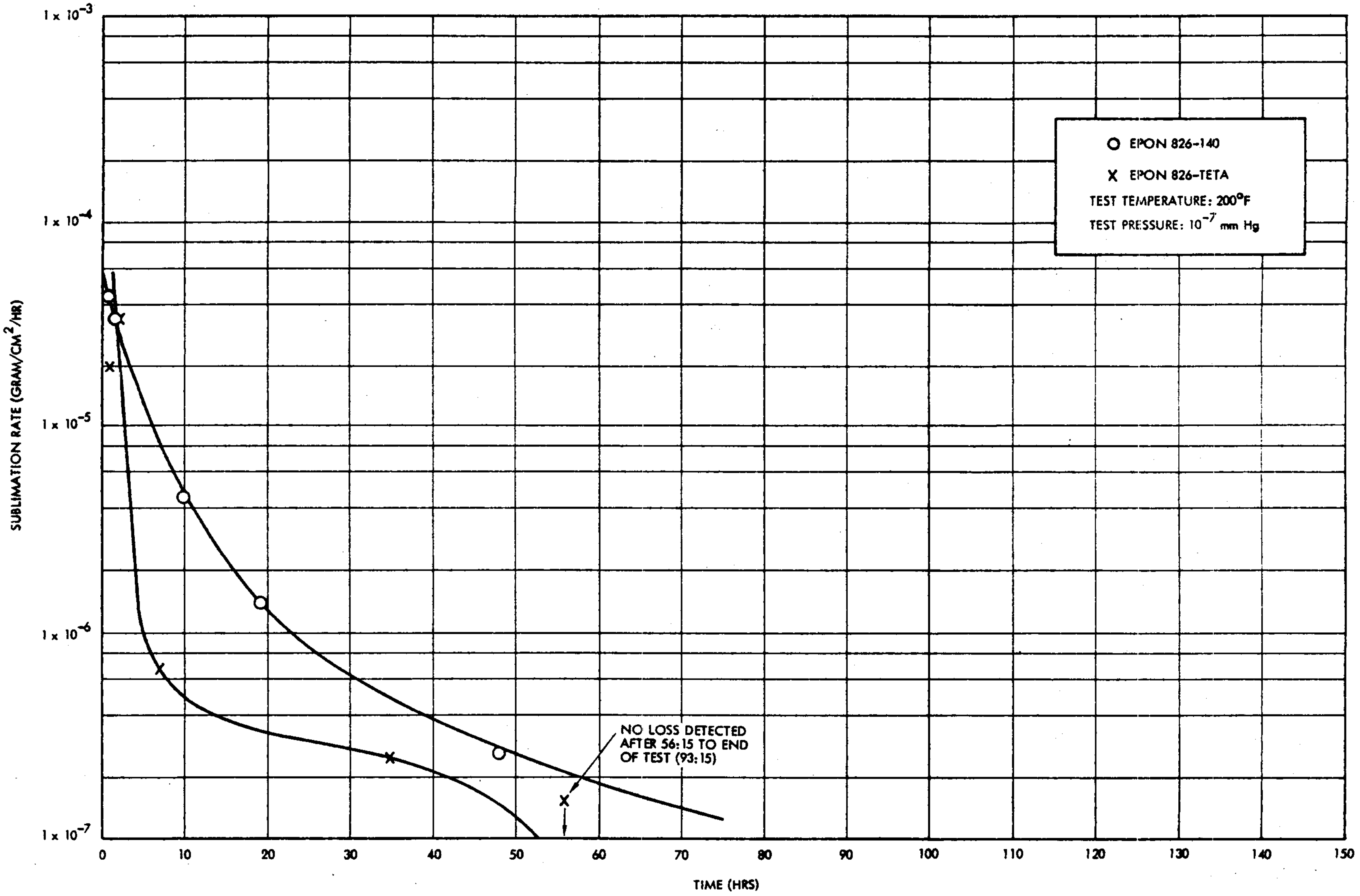


Figure 4-4

Sublimation Rate as a Function of Time in Test Environment

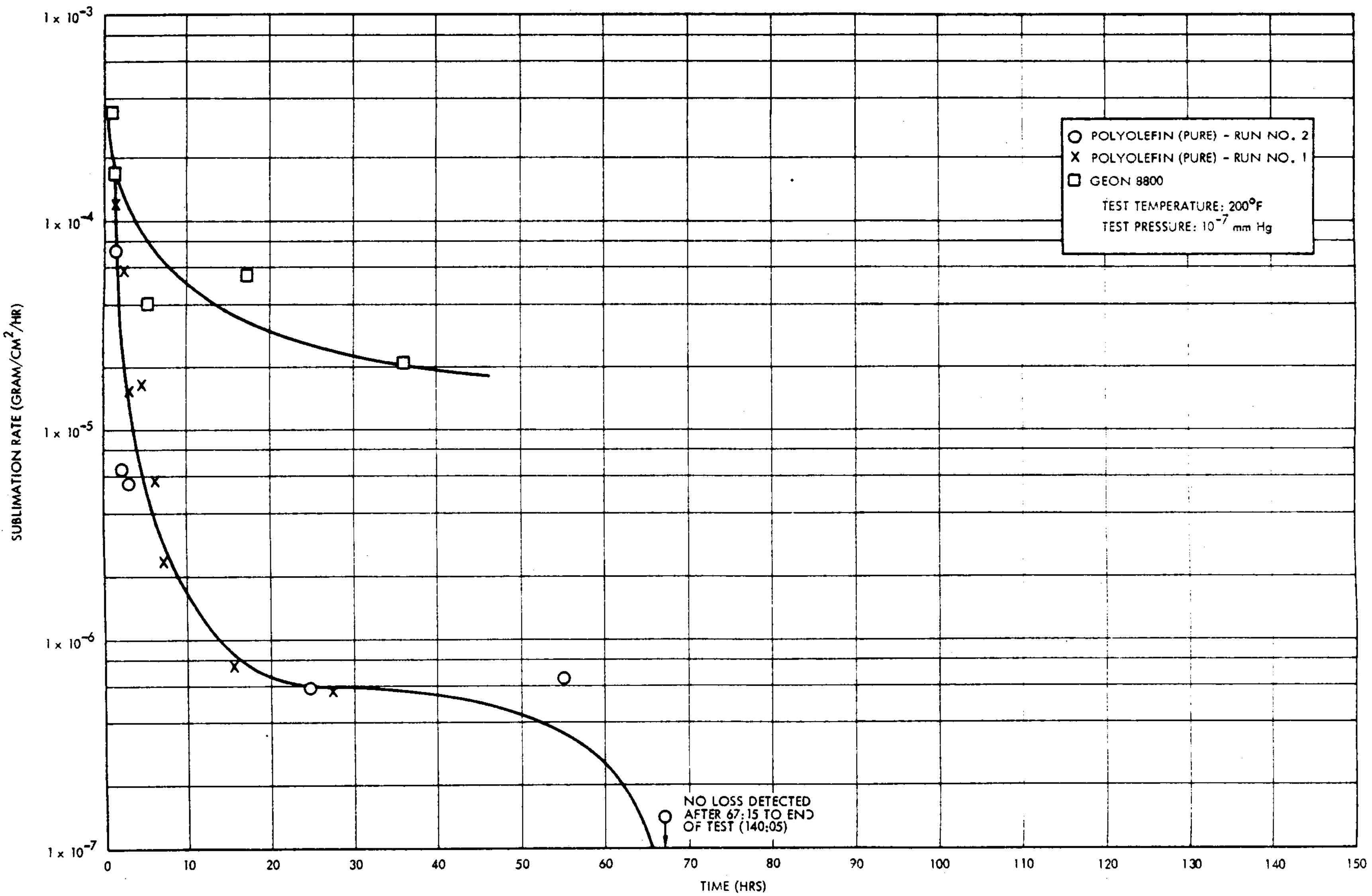


Figure 4-5

Sublimation Rate as a Function of Time in Test Environment

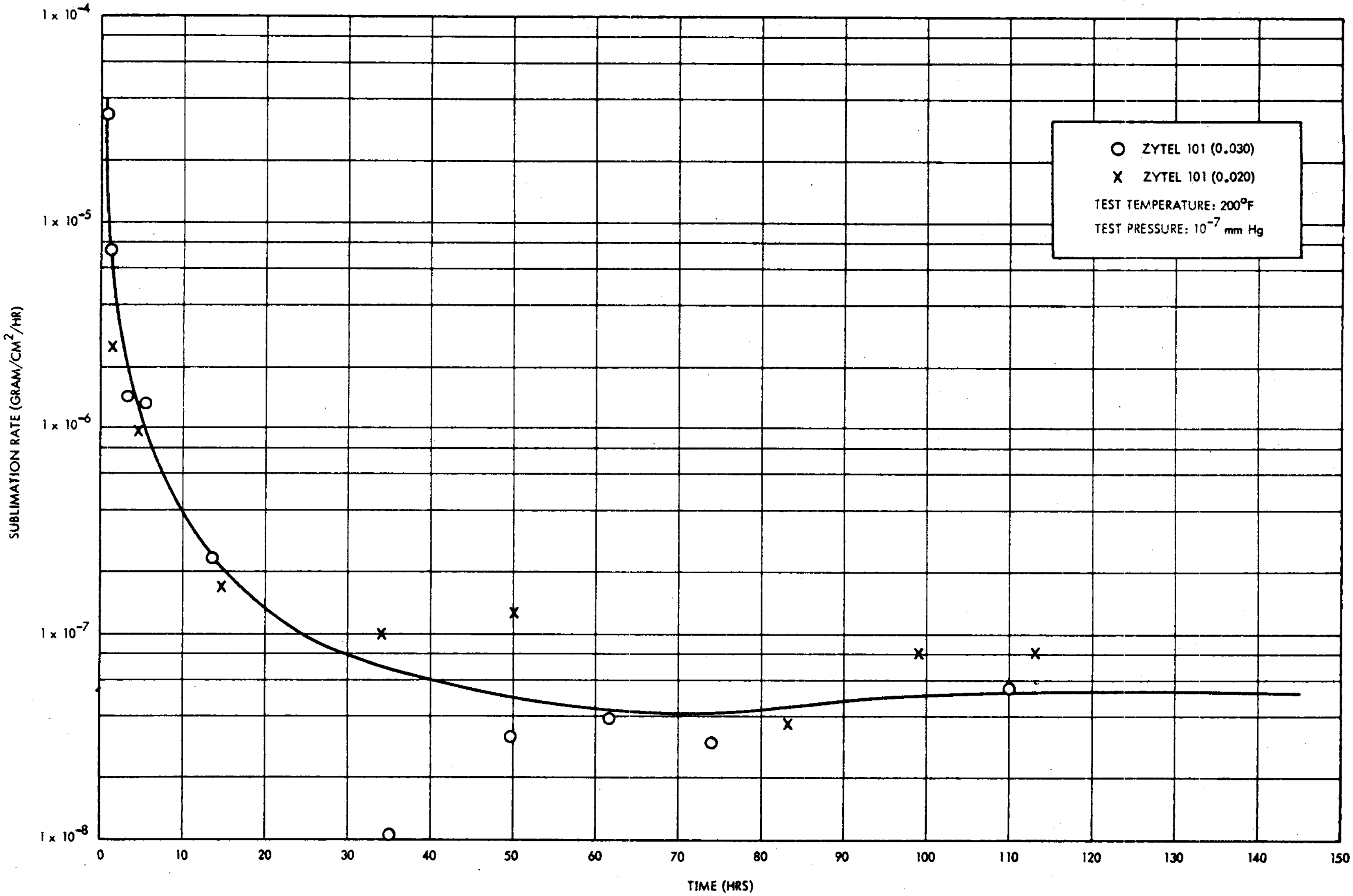


Figure 4-6

Sublimation Rate as a Function of Time in Test Environment

EFFECTS OF SPACE RADIATION ENVIRONMENT ON VALVE MATERIALS

Introduction

The requirements of space vehicle system materials to withstand and perform in the presence of space environments constitutes one of the major design problems in spacecraft systems. Typical examples of these space environments are high vacuum, ultraviolet radiation, zero g conditions, and penetrating charged-particle radiation. Since these environments are not found naturally at the earth's surface and are difficult to simulate in the laboratory, a large amount of uncertainty exists concerning the performance of materials in these environments. To this end a large amount of experimental and theoretical work has been performed in an effort to determine the effects of these environments and their subsequent interactions on materials of the type commonly used in spacecraft systems.

The space environment of charged-particle radiation is one of the most difficult environments to simulate in the laboratory for several reasons. First, the actual charged-particle radiation environment in space is not accurately known nor easily measurable in all its forms in contrast to some of the other space environments, such as high vacuum. Second, the complete spectrum of charged particle radiations in space is very complex, consisting of electrons ranging in energies from a few kilovolts to approximately 10 Mev or higher, and protons ranging from a few kilovolts to energies in excess of 1 Bev. In addition to these naturally occurring charged-particle radiation environments in space, recent experiments have shown that artificial energetic electron belts of radiation can be produced in space through nuclear detonations. It is, therefore, an extremely difficult, if not impossible, task to simulate accurately in the laboratory this exact radiation environment due to the complexity of equipment required to produce these spectra of energetic charged particles. The purpose of the following study will be to present a summary of the "state-of-the-art" of the effects of the space environment on spacecraft materials. The particular materials chosen for study are materials of the type commonly found in propellant valves of the type used in propulsion systems.

Radiation Damage in Materials

Nuclear radiations are known to alter the properties of solid materials, often to such an extent that the changes in material properties are of important engineering significance. The manners in which energy radiation reacts with material are many and varied. Typical of these interactions are the production of vacancies and interstitial atoms, thermal spikes, impurity atoms, ionization effects, displacement spikes, and replacement collisions. Any or several of these interactions may control the material response depending upon the type of material involved. Metals and semiconductors are most sensitive to disturbances such as vacancies, interstitial atoms, thermal spikes, etc, while organic materials are normally most affected by ionization effects. Since no semiconducting materials are normally used in valves and, further, since metallic materials exhibit extremely high resistance to radiation damage, the problem can be readily reduced to the ionization effects produced by the incident radiation on the organic materials commonly used in valves. Typical usage of organic materials in valves are as seals, sleeves, etc.

The passage of charged particles through an organic solid may cause extensive ionization and electronic excitation which, in turn, lead to bond rupture, free radicals, coloration, luminescence, etc. Since the majority of the energy absorbed in material in the process of attenuating charged-particle radiation consists of energy lost through ionization, it is convenient to assume that the energy lost through other previously mentioned mechanisms is negligible. Further, it can be stated that as a general rule, the amount of radiation damage produced in an organic material is proportional to the amount of energy absorbed by the material. This statement, however, must be used with great caution as it applies only to a limited class of materials; for example, semiconducting materials are most sensitive to displaced atoms, the production of which involves only approximately 1 per cent of the total energy absorbed in the material. For these reasons radiation tolerances in organic materials are commonly expressed in units of energy absorbed such as ergs/gm. It is also common when expressing radiation tolerances of organic materials to specify not the amount of energy absorbed, but the radiation environment the material was subjected to in units of r (Roentgens). The relationship between r and ergs/gm is approximately 1 r = 87 ergs/gm in air. Due to the composition of most hydrocarbon organic materials, a close approximation to a conversion between r of radiation environment and ergs/gm of energy absorbed in organic materials is that 100 ergs/gm of energy will be absorbed by the organic material when placed in an atmosphere of 1 r of ionizing radiation. Clearly, this is not an exact relationship but when considered in the light of the inaccuracies involved in measuring radiation environments and specifying changes in physical properties of materials, this generalization is more than adequate. For these reasons the data which will be presented on the effects of ionizing radiation on typical valve materials will be given in units of r for convenience in relating the damage thresholds to the space radiation environment.

One of the primary difficulties in attempting to predict theoretically the operation of a valve containing organic materials when exposed to ionizing radiation is the engineering correlation between a given amount of change in the physical property of the material and the corresponding effect of this change on the mechanical operation of the valve. Common failure modes of materials are changes in only a few of the more sensitive material properties at rather low radiation levels. Clearly, if a device is constructed which depends strongly upon a material characteristic which is most sensitive to radiation, an early failure will occur while, of course, the converse is also true. For example, the tensile strength and elongation properties of Teflon are drastically affected at rather low radiation levels, yet Teflon insulated wire, which does not depend strongly on the mechanical properties of Teflon, would remain useful long after the tensile strength properties of the insulation have been adversely affected. For these reasons one of the most difficult problems that must be faced here is the determination of what degree of change can be accepted in only those material properties of importance in the particular engineering application to which a material is applied.

Experimental Data

A large amount of effort has been extended in recent years in the study of the response of organic materials to ionizing radiation. Due to the normal differences in test equipment and procedures utilized by different experimental groups, a corresponding deviation in reported data can be expected. In addition, some of the materials tested are extremely sensitive in their response to ionizing radiation to limited amounts of trace impurities and to intricate details of the materials forming processes. In addition, the reaction of some materials to ionizing radiation is dependent upon the environment in which they are subjected. Typical environments of importance here are temperature and atmospheric content. For these reasons it is clearly not possible to assign accurate damage thresholds for most materials when placed in a radiation environment. Errors and discrepancies of an order of magnitude in radiation tolerances are common in the analysis of a large amount of experimental data. For this reason radiation tolerances have to be accepted with accuracies ranging from a factor of 2 to a factor of 10. These inaccuracies, however, are not large when compared with the extremely wide range of response of various materials to ionizing radiation.

A summary of the radiation tolerances of contemporary organic valve materials is presented in Table 4-12 . This table obviously does not represent all of the experimental data available but merely presents a summary of available data on the materials listed. There are also many cases in which data on a particular material are not readily available or do not exist. In addition, very little experimental work has been done on the effects of ionizing radiation on these materials in the presence of the propellant environments in which they will be found under normal operation as valves in missile propulsion systems. It can be anticipated that these surrounding environments will in many cases drastically change the response of the material considered to ionizing radiation.

Some work has been done in evaluation of propellants - both polymeric and double base - after exposure to radiographic inspection (x-ray - cobalt). The solid propellants tested showed signs of degradation at levels of 10^6 r. One would expect typical carbon-carbon polymer degradation of the urethane based propellants at these levels based on knowledge of similar polymeric systems. The effect on double base materials, comprising an explosive gel of nitrated organic materials, could be the same mechanism or of nitrate decomposition. In any case this would appear to be the limiting factor for solid propellants in a charged particle radiation environment. Available unclassified information on inorganic (perchlorate, etc.) explosives is extremely limited.

Using the radiation tolerance data listed in Table 4-12 in addition to other specific radiation damage information that may be required on materials not listed in Table 4-12, an estimate of the useful life of a particular subsystem, in this case typical propulsion system valves, can be calculated. The first step in this exercise is to determine meaningful physical properties of the materials and the appropriate limits to which these properties can be changed. Following this, a series of calculations can be performed on the materials which appear to be desirable for use from an engineering standpoint. These calculations can become extremely complex if a high degree of accuracy is required. To illustrate the type of calculations, a simplified example will be performed here. This sample calculation will be performed on Teflon, inasmuch as this material is one of the most sensitive materials in the class of concern.

Referring to the Radiation Environments study in Section III, it can be seen from Table 3-7 that the maximum intensity of electrons and protons occurs in the inner zone for an equatorial orbit of 1.5 Re (Earth Radii). These intensities are as follows:

$$\text{Electrons}/_{\text{cm}^2\text{day}} - 8.6 \times 10^{13}$$

$$\text{Protons}/_{\text{cm}^2\text{day}} - 8.6 \times 10^{9}$$

Assuming .06" thick aluminum shielding
The dosage contributions are:

Bremsstrahlung $R\ 3.3 \times 10^{-13} \times 8.6 \times 10^{13} < 835$ rad/day

Electrons $R = 1.8 \times 10^{-8} \times 8.6 \times 10^{13} = 1.55 \times 10^{6}$ rad/day

Protons $R = 4.6 \times 10^{-7} \times 8.6 \times 10^{9} = .396 \times 10^{4}$ rad/day

Total dosage $= 1.55 \times 10^{6}$ rad/day

The use of .06" AL shielding yields a large error for the Bremsstrahlund dosage but the estimate is maximum, assuming all electrons were stopped by the aluminum. It can be seen that this dosage is significantly small compared to that of the electrons and would not have an appreciable effect on the total dosage. Teflon (TFE) is not appreciably affected for dosages less than 10^4 rads (in air), and from Table 4-12:

$$\text{Life (Teflon TFE)} = \frac{10^4}{1.55 \times 10^6} = .645 \times 10^2 \text{ Days}$$

or 9.24 minutes.

A 25% decrease in tensile strength and a 60% decrease in elongation of Teflon TFE (air) has been reported (Ref. 11) at 10^5 rads.

$$\text{Life (Teflon TFE)} = \frac{10^5}{1.55 \times 10^6} = 1 \text{ Hr. } 32 \text{ Min.}$$

For .06" thick aluminum shielding the electron dosage predominates. It would be instructive to determine the electron dosage for thicker material.

Integrating the dose rate equation given in Section III for electrons:

$$R = 3.2 \times 10^{-8} k_\beta \int_0^\infty e^{-\alpha(E + 13.3t)} \, dE \text{ rad/day}$$

then:

$$R = 3.79 \times 10^{-8} ke^{-12.4t} \text{ rads/day (inner zone)}$$

Solving for various thicknesses of aluminum shielding as before, the life of Teflon TFE (in air) in the maximum intensity belt is as follows:

Aluminum Thickness t inches	Life No Damage	Life -25% Tensile -60% Elongation
.06	9.24 min.	1 hr-32 min
.125	20.9 min	3 hrs-28 min
.250	1 hr-38 min	16 hrs-27 min

The reason air was selected as the atmospheric environment is apparent when it is considered that a propellant such as N_2O_4 may dissociate into $N_2 + 2\,O_2$ when permeating the Teflon seal. These are the same elements that make up the air environment. Although the density of the dissociated gas is not known, the air environment assumption should yield a more realistic value for design purposes, when Teflon is sealing N_2O_4.

It should be emphasized that the life durations indicated offer too small a safety factor to allow for a conclusion because of the amount of uncertainty in both the radiation environment calculations and the test results reported. However, the results of these calculations, in addition to illustrating the techniques involved, do offer a designer a means for guidance in selecting organic materials and shielding thicknesses.

REFERENCES

1. Broadway, N. J. and Palinchak, S., "The Effect of Nuclear Radiation on Fluoropolymers," REIC Memo 17, June 30, 1959.
2. Collins, C. G. and Calkins, V. P., "Radiation Damage to Elastomers, Plastics, and Organic Liquids," General Electric Co., Atomic Products Division, September 1956.
3. Broadway, N. J.; Youtz, M. A.; Zaring, M. L.; and Palinchak, S., "The Effect of Nuclear Radiation on Elastomeric and Plastic Materials," REIC Report No. 3, May 31, 1958.
4. Broadway, N. J. and Palinchak, S., "The Effect of Nuclear Radiation on Elastomeric and Plastic Materials (First Addendum)," REIC Report No. 3 (Addendum), May 31, 1959.
5. Burkhard, et al, "Radiation Damage Literature Survey" Vol I, Convair Report REM - 580, 14 March 1958.
6. Johnson, P. M.; Weller, G. S.; Peach, T. E.; "Radiation Damage Literature Survey" Vol. III, Convari Report REM - 580, 14 March 1958.
7. "Third Semi-Annual Radiation Effects Symposium," Vol. 5, Lockheed Nuclear Products, October 28, 29, 30, 1958.
8. Schmidt, D. L., "Effects of Gamma Radiation on Aircraft Transparent Materials," Materials Laboratory, WADC, May 1958.
9. Leininger, R. I., "Memorandum on the Effects of Nuclear Radiation on Fluorinated Polymers in Different Environments," REIC, October 31, 1957.
10. Colner, W. H., "Space - A New Environment for Materials," Materials Research and Standards, August 1962.

Table 4-12

RADIATION TOLERANCES OF TYPICAL VALVE MATERIALS

Material	Radiation	Environment	Temp	Damage	Remarks			Ref
	r							
Teflon	3.4×10^4	Air	Room	25%				1,9
	4.3×10^7	Oil	Room	Tolerance				1,9
	$< 4.4 \times 10^5$	Air	400°F	Tolerance				1,9
	10^6	Mil-L-7808 oil	400°F	Tolerance				1,9
	8.7×10^3	Air	Room	Threshold				1,6,9
	2.5×10^8	Air	Room	Loses All Strength				1,6,9
	2.0×10^4	Air	75-105°F	Threshold				2,5,6,9
	4.5×10^4	Air	75-105°F	25%				2,5,6,9
	1.7×10^4	Air	Ambient	Threshold				3,9
	3.4×10^4	Air	Ambient	25%				3,4,9
	10^6	Vacuum	Ambient	25%				10
Teflon (100x)	10^7	Air	Ambient	Loses All Strength				7
Kel - F	1.8×10^7	Air	Room	25%				1
Kel - F Elastomer (5500)	4.5×10^6	Air	Room	Tolerance				1
					Hardness	Elongation	Tensile Strength	
	10^6	Air	Ambient		0.0%	9.1%	44.2%	3,7
	5.0×10^6	Air	Ambient		0.0	-8.2	19.6	3,7
	2.2×10^7	Air	Ambient		3.2	-41.8	-28.8	3,7
	5.5×10^7	Air	Ambient		16.1	-73.6	-24.9	3,7
	10^8	Air	Ambient		25.8	-80.0	-13.9	3,7
Viton A-7	10^8	Air	Ambient		12.5%	-94.0%	6.8%	3,9

Table 4-12 (Cont'd)

Material	Radiation	Environment	Temp	Damage	Remarks			Ref
	r				Hardness	Elongation	Tensile Strength	
Viton A-8	10^8	Air	Ambient		22.8	-88.9	-1.0	3,9
A-9	10^8	Air	Ambient		24.4	-84.7	46.3	3,9
A-10	10^8	Air	Ambient		23.4	-85.7	12.4	3,9
A-11	10^8	Air	Ambient		24.1	-80.3	27.9	3,9
A	$>2.0 \times 10^7$	Oronite 800 Fluid	Room	Tolerance				
	8.4×10^7	Diester Oil	400°F	Tolerance				
	6.0×10^7	Air	Room	Tolerance				
Lucite	8.9×10^5	Air	75-105°F	Threshold				2,4,8
	1.2×10^7	Air	75-105°F	25%				2,4,8
Polyethylene	2.0×10^7	Air	75-105°F	Threshold				2,3,5,6
	9.6×10^7	Air	75-105°F	25%				2,3,5,6
Bakelite								
Asbestos Fabric Laminate Filler	2.0×10^7	Air	75-105°F	Threshold				2,5
	8.6×10^8	Air	75-105°F	25%				2,5
Asbestos Fiber Filler	8.7×10^7	Air	75-105°F	Threshold				2,5
	1.0×10^9	Air	75-105°F	25%				2,5
Linen Fabric Laminate Filler	3.8×10^5	Air	75-105°F	Threshold				2,5
	3.1×10^6	Air	75-105°F	25%				2,5
Paper Filler	4.2×10^5	Air	75-105°F	Threshold				2,5
	2.9×10^7	Air	75-105°F	25%				2,5
Micarta								
Paper Laminate Filler	3.8×10^5	Air	75-105°F	Threshold				2
	9.1×10^6	Air	75-105°F	25%				2

Table 4-12 (Cont'd)

Material	Radiation	Environment	Temp	Damage	Remarks	Ref
	r					
Nylon						
FM10001, FM-1	9.2×10^5	Air	75-105°F	Threshold		2,3
	5.0×10^6	Air	75-105°F	25%		2,3
FM3003	9.2×10^5	Air	75-105°F	Threshold		2,3
	5.0×10^6	Air	75-105°F	25%		2,3
Acrylonitrile	2.0×10^6	Air	Ambient	Threshold		3,4
Rubber	7.0×10^6	Air	Ambient	25%		3,4
Butyl Rubber	2.0×10^6	Air	Ambient	Threshold		2,4
	4.0×10^6	Air	Ambient	25%		2
Buna S Rubber	2.1×10^6	Air	70°F	Threshold		2
	1.1×10^7	Air	70°F	25%		2
Buna 406 Rubber	10^8	Air	Ambient	No Change		5
Buna N Rubber	9.9×10^7	Air	Room	No Change		5
Goodyear BTC-6	9.9×10^7	JP-4	140°F	No Change		5
Silicone Rubber						
Silastic LS-53	$< 5.0 \times 10^6$	Air	Room	Tolerance		1
Silastic 7-170	1.4×10^6	Air	70°F	Threshold		2
	4.6×10^6	Air	70°F	25%		2
SE 371	9.8×10^5	Air	70°F	Threshold		2
	1.3×10^7	Air	70°F	25%		2
SE 450	9.8×10^5	Air	70°F	Threshold		2
	6.0×10^6	Air	70°F	25%		2
SE 550	9.8×10^5	Air	70°F	Threshold		2
	8.2×10^6	Air	70°F	25%		2

Table 4-12 (Cont'd)

Material	Radiation	Environment	Temp	Damage	Remarks			Ref
	r							
SE 551	9.8×10^5	Air	70°F	Threshold				2
	1.1×10^7	Air	70°F	25%				2
SE 750	9.8×10^5	Air	70°F	Threshold				2
	6.8×10^6	Air	70°F	25%				2
				Elongation	Tensile	Tear	Hardness	
Silastic 7-170	10^8	Air	70°F	-45%	+38%	-20%	+38%	3,7
SE 381	10^8	Air	70°F	-20%	0%	-43%	+14%	3,7
Silastic 2048	10^8	Air	70°F	-70%	+47%	-40%	+28%	3,7
Silastic 80	10^8	Air	70°F	-70%	-4%	-75%	+12%	3,7
SE 482	10^8	Air	70°F	-80%	-6%	-66%	+15%	3,7

The Influence of Planetary Atmosphere on Properties of Materials

Little, if any, experimental data is available on the effects that atmospheres of other planets will have on the properties of materials which might be used for valves. The prediction of the influence of such environments is further complicated by the effect which long-time prior exposure to the environments of outer space may have on the material. Abrasion and/or ultrahigh vacuum may produce a chemically clean surface, causing a change in surface energy and resulting in different fracture strength properties. Fatigue properties are generally improved under vacuum conditions, but high temperature stress rupture allowables of some metals are higher in air than in vacuum. Upon re-exposure to a gaseous environment, chemisorption may occur if gas molecules bond to unattached valency bonds of metal, or adsorption by means of Van der Waal forces may result in some cases. In either case the surface energy is reduced and the properties of the material will be affected to some degree. Depending upon the nature of the environment, chemical reactions may also result, which normally would not occur if the metal were covered with an oxide film.

The atmosphere of Mars (assumed to be 95% N_2, 5% CO_2, at 0.1 atm. pressure and -180°F to 90°F) should present no particular materials problems. At these temperature the gases would not be chemically reactive with materials of construction; but on chemically clean surfaces, adsorbed gas layers would form, reducing the surface energy (which would lower the fracture stress), and probably improve frictional characteristics.

The atmosphere of Venus (assumed to be composed of 95% N_2, 5% CO_2, at 16 atm. pressure and 620°F to 1150°F) will cause some serious materials problems, primarily because of the effect of the high temperature. Plastic materials and low melting point metals such as aluminum cannot be used at these temperatures. Exposure of cold-worked metals or heat-treated alloys to temperatures of 1100°F for long periods will result, in most cases, in a lowering of room temperature strength properties. In addition, any metal subjected to stress at such temperatures will be susceptible to creep or stress rupture, as well as reduced short-time strength properties. Microstructural changes, such as carbide precipitation in stainless steels, may also be expected. Nitriding of the surfaces of alloy steels, stainless steels and titanium alloys is also a possibility, although the effect of the CO_2 or any water vapor may inhibit the nitriding reaction. Any nitriding which does occur will harden (and embrittle) the surface, which may be advantageous or detrimental, depending upon the specific application. (Note 1)

Jupiter's atmosphere of ammonia and methane at a temperature of about -220°F should have no unusual effect on materials except, of course, for the influence of the extremely low temperature on mechanical properties of some materials (i.e., embrittlement). The best plastic materials for applications requiring ductility at cryogenic temperatures are the fluorocarbons, such as TFE (Teflon), FEP (Teflon X100), and CFE (Kel-F). It should be noted that the mechanical properties of these materials at cryogenic temperatures depend upon the crystallinity of material which, in turn, is critically dependent on final design shape and processing history. Metals which are most suitable for such low temperature applications include the austenitic stainless steels (300 series), most aluminum alloys, and some of the titanium alloys.

Note 1: At the time of publication, information released by NASA as a result of the Mariner experiments indicated the temperature of Venus to be approximately 800°F.

MACHINING IN A SPACE ENVIRONMENT

Introduction

This study was initiated to determine the effects of vacuum and planetary (nitrogen) environments on the process of metal cutting. A literature search revealed that similar studies had not been conducted by a private company or a government agency. Since the repair, assembly or fabrication of some equipment may be necessary in space environment, an evaluation of the factors involved in metal cutting was in order. Due to the limited time available and to simplify the vacuum chamber equipment, drilling was the method chosen. In addition, drilling would be the metal cutting procedure that would most likely be required. Figure 4-7 is a photograph of the drill fixture.

Discussion

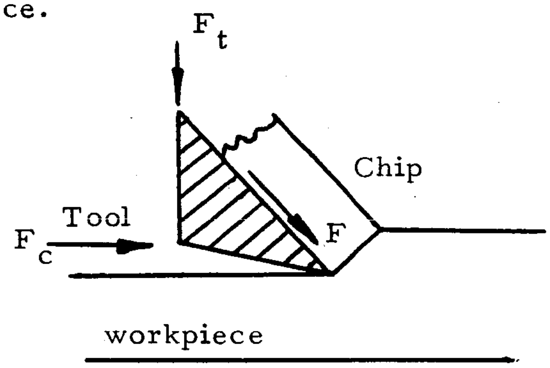
Tests in Vacuum

Tables 4-13 through 4-17 are a summary of the test runs in vacuum and air. There were no appreciable differences in drill time for aluminum especially with the highest feed spring force (Ref. runs 17, 18, 19 and 21). Difficulty was encountered with the 1018 crs specimen at ambient pressure in test runs 26, 28, 33 and 35. Only runs 24 and 30 were successful. The feed spring was not loading the drill properly for this specimen. The condition is analogous to the early test runs in aluminum (test runs 1-16), where the drill time was considerably longer than the later tests. A new spring was installed for run 37 and complete penetration was achieved.

Tests in Nitrogen

A series of drilling tests were conducted in a 100% nitrogen atmosphere. The results are included in Table 4-15 and 4-17. The same drill fixture was used as in the vacuum test. The 100% nitrogen atmosphere was achieved by placing the drill fixture in the vacuum chamber, evacuating the chamber, and bleeding in dry nitrogen gas to 1 atmosphere. Runs 22 and 23 were conducted on aluminum and no appreciable differences for drill time in air and nitrogen were noticed. Runs 39 thru 43 also indicated no unusual drill time differences when drilling 1018 cold rolled steel.

The general accepted theory of metal cutting is best described by an analysis of Merchant (Ref. 1). Observation of the process shows that the deformation of the chip takes place abruptly as shear in a plane extending from the point of the tool to the surface of the metal and inclined at an angle to the horizontal. Essentially, all of the energy involved is expended in two processes; the shear of the metal on the shear plane, and the rubbing of the chip on the tool as it passes up the tool face.



F_c = cutting force on tool
F = friction force on tool face
F_t = thrust force on tool

With all conditions remaining the same for metal cutting in air and vacuum, only the friction forces could be affected. In reviewing the mechanism of dry friction Bowden and Tabor (Ref. 2) suggest the following three factors:

1. Mechanical interlocking of surface asperities.
2. Plowing of asperities of the harder surface through the softer of the two sliding metals.
3. Formation of metallic junctions by welding of asperities.

It would not be difficult to ascertain which of the three factors is most affected by vacuum. The first is dependent on the elastic limit of the material. The second, the plowing effect, is not influenced by the presence or absence of a lubricant film. This has been confirmed by experiments. The third is the condition of "cold welding" which occurs in air and vacuum, but has been proved to occur easily in vacuum in the absence of contaminant films. Any degradation in the metal cutting process can be attributed to the third factor.

Summing the energy expended in metal cutting:

$$E_t = E_1 + E_2$$

E_t = total energy input to cut metal

E_1 = energy required to shear the metal

E_2 = energy required to overcome the friction of the chip on the tool face

but $E_2 = E_{21} + E_{22} + E_{23}$

E_{21}, E_{22}, and E_{23} are the energies attributed to the three factors mentioned above

then $E_t = E_1 + E_{21} + E_{22} + E_{23}$

If we assign arbitrary values (merely to demonstrate the effect of chip friction on the tool face)

	air
E_t =	1.0
E_1 =	0.2
E_{21} =	0.2
E_{22} =	0.2
E_{23} =	0.4

Assume E_{23} to increase by 100% in vacuum (Ref. 3)

$$E_t = 0.2 + 0.2 + 0.2 + 0.8 = 1.4$$

The increase in friction represents a 40% increase in total energy required. Since the total energy is equal to the work done, and power to the drill is the same in air and vacuum, the effect of increased friction is increased drilling time. This estimated 40% increase in the time required for the drilling falls within one to two times the increase required for drilling that was noted in the test program.

Conclusions

It can be reasonably concluded that a vacuum environment will not appreciably affect the process of metal cutting. Utilizing proper speeds and feeds, cutting time may vary from one to two times that required at ambient conditions (excluding lubricants), as demonstrated by test runs 18 and 19 for aluminum and 30 and 37 for 1018 crs. Although the other test runs are not as conclusive, the tests in vacuum required additional drilling time for specimen penetration or for approximately the same drill time achieved less penetration (Ref. test runs 34 and 35).

References

(1) M. E. Merchant "Mechanics of the Metal Cutting Process" Journal of Applied Physics - Vol. 16 - 1945

(2) Bowden and Tabor "The Friction and Lubrication of Solids" Oxford Press

(3) "Research Program on High Vacuum Friction" Litton Systems Inc. Publication No. 1411

TABLE 4-13. DRILLING TESTS

6061-T6 Aluminum - .25 Thick
Spring Force = 5.5 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
1	Ambient	High speed gen'l purpose **1/8" Dia.**	2800 RPM & less	100%	70 sec.	Drilled several holes and partial holes to check calibration of speed control box. Spring force 5.5 lbs.
2	6×10^{-6} mm Hg	same as 1	2800 - 2100	90%	120 sec.	Shutdown due to excessive vibration in test fixture.
3	Ambient	High speed High spiral Drill No. 1 1/8" dia.	2800	100%	90 sec.	
4	Ambient	High speed	2600 - 2100	70%	240 sec.	Shutdown
5	Ambient	High speed High spiral 1/8" dia. Drill No. 2	2800	100%	12 sec.	
6	Ambient	Drill No. 2	2800	100%	12 sec.	
7	5×10^{-5}	Drill No. 2	2800	100%	15 sec.	Exposed to vacuum for two hours. Chamber suspected of being contaminated.
8	2×10^{-9}	High speed High spiral Drill No. 3 1/8" dia.	2800	100%	65 sec.	
9	Ambient	High speed High spiral Drill No. 3 1/8" dia.	2800	100%	30 sec.	

TABLE 4-13. DRILLING TESTS (Cont'd)
6061-T6 Aluminum - .25 Thick
Spring Force = 5.5 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
10	Ambient	High speed High spiral Drill No. 4 1/8" dia.	2800	100%	40 sec.	Replaced bearing in chuck

TABLE 4-14. DRILLING TESTS
2024-T4 Aluminum - .312 Thick
Spring Force = 5.5 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
11	Ambient	High speed High spiral Drill No. 5 1/8" dia.	2800	100%	40 sec.	
12	2×10^{-7} mm Hg	High speed High spiral Drill No. 5 1/8" dia.	2800 - 1600	100%	55 sec.	
13	Ambient	High speed High spiral Drill No.6 1/8" dia.	2800 - 1600	100%	50 sec.	
14	2×10^{-7}	Drill No. 6	2800	20%	95 sec.	Excessive vibration shutdown.
15	Ambient	Drill No. 6	2800	100%	63 sec.	Stopped and started drill motor.
16	3×10^{-7}	Drill No. 6	2800	100%	142 sec.	Last 20 sec. of drilling was accomplished by turning on and off.

TABLE 4-15. DRILLING TESTS
2024-T4 Aluminum - .312 Thick
Spring Force = 10 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
17	Ambient	High speed	2800	100%	13 sec.	
18	4×10^{-6}	High speed	2800 - 2400	100%	23 sec.	
19	Ambient	High speed	2800	100%	14 sec.	
20	Ambient	New 1/8 High speed High spiral	2800	100%	25 sec.	
21	1×10^{-8}	New 1/8 High speed High spiral	2800	100%	15 sec.	
22	Nitrogen	1/8	2200	100%	14 sec.	
23	Ambient	1/8	2100	100%	15 sec.	

TABLE 4-16. DRILLING TESTS
1018 CRS - .25 Thick
Spring Force = 10 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
24	Ambient	High speed	2800	100%	32 sec.	
25	*	High speed	2200	-		*No reading, gauge failed est. 10^{-6} range. Drill failed to penetrate.
26	Ambient	High speed	2200 - 1600	-		Drill failed to penetrate.
27	4×10^{-7} mm Hg	New drill High speed	2800 -0	80%	60 sec.	Drill stalled.
28	Ambient	New drill High speed	2800	80%		
29	Ambient	No. 30 High speed	2800	80%		
30	Ambient	1/8 High Speed	2400 - 1800	100%	3/sec.	
31	5×10^{-6}	New 1/8 High speed	2200	0	120 sec.	
32	5×10^{-6}	New 1/8 High speed	2200	0	120 sec.	
33	Ambient	New 1/8 High speed	2200	75%	240 sec.	Penetrated very slowly.
34	2×10^{-7}	New 1/8 High speed	2200 -0	30%	105 sec.	Drill stalled.
35	Ambient	New 1/8 High Speed	2400	80%	110 sec.	Drill maintained speed, but stopped cutting.
36	5×10^{-7}	New 1/8 High speed	2200		120 sec.	

TABLE 4-17. DRILLING TESTS
1018 CRS - .25 Thick
Spring Force = 14 lbs.

Run	Press	Drill	Speed	Penetration	Time	Remarks
37	2×10^{-6} mm Hg	Used drill for run 28	2800 - 2600	100%	47 sec.	
38	9×10^{-7}	New 1/8 High speed	2800 - 2600	100%	102 sec.	
39	Ambient	New 1/8 High speed	2000	100%	40 sec.	
40	Nitrogen	New 1/8 High speed	1800 - 2200	100%	50 sec.	
41	Nitrogen	New 1/8 High speed	1600 - 2200	100%	1 min-10 sec.	
42	Ambient	1/8	2700	100%	2 min-50 sec.	Dull drill.
43	Nitrogen	1/8	2400 - 2800	75%	3 min.	Dull drill.

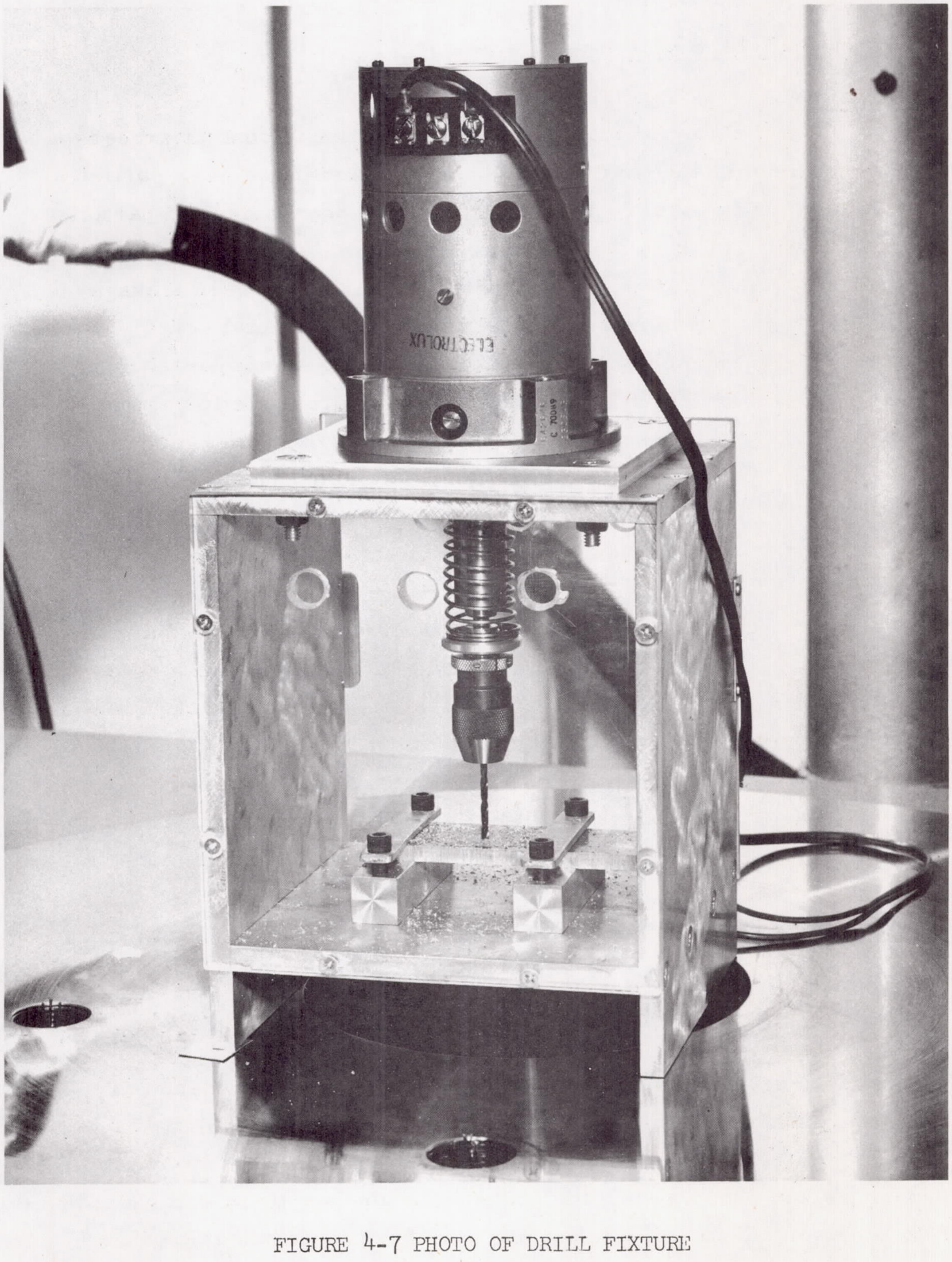


FIGURE 4-7 PHOTO OF DRILL FIXTURE

WEAR PARTICLE STUDY

Introduction

When the normal load between two metals in contact exceeds a certain minimum, adhesive wear takes place and loose wear particles are formed. It is possible that a study of this phenomenon of particle production will result in the following:

a. Determination of a relationship between leakage and materials used in metal-to-metal seats including poppet, ball and spool configurations.

b. Prediction of the optimum filter size for use in valves or in valve-controlled systems.

c. Determination of the minimum clearance between moving parts before seizure can occur, or determination of the optimum materials for close-fitted parts in sliding contact.

d. Determination of the final surface finish that can be expected for sliding surfaces given a long period of time, or determination of the materials that will develop the best finish after wear-in.

e. Determination of the type of motion between sliding materials that will optimize roughness. This may prove useful for ball-type seat configurations.

f. Determination of the minimum normal load materials will sustain before wear takes place or when loose wear particles will not be formed.

Wear

The mechanism of friction is related to the phenomenon of adhesion. When two clean surfaces (surfaces in a vacuum) are brought together, contact is made at the tips of the many microscopic asperities and consequently the pressure at the junctions is high. Adhesions or cold welding takes place at these junctions and, when the surfaces slide relative to each other, these junctions must be sheared. (Ref. 1)

When a junction shears during sliding, and depending on the materials, the shear will take place within one of the surface layers and a wear particle is formed that will adhere to the other surface. Wear particles between surfaces in contact are first developed by adhesive wear, that is, there is adhesion between the asperities. The asperity of the softer material is sheared and retained by the harder material. In the shearing process the particle is deformed and strain energy is stored in the particle. The vertical component of the strain force is relieved but the particle is strained in the horizontal plane and the surface is restrained from contracting at the adhered joint. However, if the strain or surface energy is greater than the adhesive energy of the joint, the joint will fail, creating a loose wear particle.

The theoretical diameter of a particle may set an upper limit on the spacing between the surfaces in contact. It may be an indicator in setting an upper limit on leakage of a valve seat configuration and may predict the screening size of the filters used in the valve or in the plumbing.

A relationship between particle size and adhesive energy has been developed by E. Rabinowicz (Ref. 2) at Massachusetts Institute of Technology, and is given by the equation

$$d = 60\ E\ W_{ab}/\sigma_{yp}{}^2$$

where d = the average diameter of the particle

E = Young's modulus

W_{ab} = the work of adhesion of the contacting materials a and b and is defined as:

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab}$$

where γ_a = surface free energy of material a per unit area

γ_b = surface free energy of material b per unit area

γ_{ab} = interface free energy per unit area

σ_{yp} = yield stress of the material in compression

It is found that σ_{yp} is about one-third the hardness p and that σ_{yp}/E is about 3×10^{3} for many materials.

then, $d = 60,000\ W_{ab}/p$

Experimental results showing a relation between material and an average wear particle diameter, obtained by E. Rabinowicz (Ref. 3), are given in Table 4-18. It can be seen that the average of the W/pd ratio is close to 16×10^{6}, as predicted by the equation $d = 60,000\ W_{ab}/p$. Table 4-18 also shows the relation between some non-metals and their corresponding particle size. Extensive testing of nylon on nylon produced no apparent wear. With Teflon on Teflon the wear fragments were fibrous and had fairly uniform cross-sectional diameters varying from 40μ to 150μ, with the average taken as 90μ.

Table 4-18 also shows that the smaller average wear particle diameters are obtained for the harder materials. It is interesting to note that the harder materials also appear to be more successful in limiting leakage in metal-to-metal seats used in valves. It would appear that one parameter influencing leakage in valve seat closures would be the particle size generated between the seated surfaces.

Wear experiments carried out by Rabinowicz (Ref. 3) show that the size of copper wear particles are essentially independent of surface velocity and that the wear particle size tends to increase with the load. At higher loads a large percent of the particles were greater than 500μ in diameter, and for the lower loaded specimens there were no particles greater than 350μ, with the largest percent of particles being less than 44μ in diameter. Tests made with 1020 steel on 1020 steel showed that at low loads the wear debris was oxides while at higher loads the wear debris was metallic.

Atmosphere composition also has an effect on particle size. Wear experiments on copper conducted by John N. Elliott (Ref. 4) support the theory of E. Rabinowicz that the average particle size should vary inversely as the reactivity of the atmosphere. Table 4-19 gives the results of Elliott's work and includes the effect of some lubricants on copper wear particles.

After the "wear in" period between any two connecting surfaces has been accomplished, the surface finish will reach a value that is characteristic of the wear particle size, which in time is a function of the materials. If the finish is initially very fine but the wear particle size is relatively coarse, the surface finish will degrade to a lower value (higher RMS No.). Conversely, if the initial surfaces have a relatively poor finish, the wear-in process will refine the finish to a lower RMS value.

The tests by E. Rabinowicz and his associates at M.I.T. were conducted in atmosphere. The oxide layers formed in the atmosphere will have an effect on the particle size. In a vacuum the formation of the surface oxides is retarded and the particle size is larger.

A test fixture was designed to determine the effects of wear particle size on leakage in a poppet-type valve closure operating in a vacuum. The essential function of the fixture is to cycle simulated valve poppets in a reciprocating motion under controlled conditions of cycling rate, atmosphere (vacuum), and a bearing load. The fixture provides a means for making leakage tests through the simulated seats before and after the cycling test, and also provides for the collection of loose wear particles that might be generated by the action. As shown in Figure 4-8, the fixture consists essentially of an upper and lower chamber which simulates the upstream and downstream portion of a valve, a spring loading device to permit variable bearing loading on the poppet, and a motor-driven cam to provide the reciprocating motion. Valves for controlling vacuum and inlet pressure complete the assembly.

Combinations of seat materials may be cycled either in vacuum (10-6 to 10-7 Torr) or in gaseous atmospheres that simulate various planetary environments. However, the test work planned with this fixture was not completed to permit inclusion in this report.

Conclusions

The present state of knowledge on friction and wear predicts that the friction force can be reduced for materials in sliding contact in a vacuum by proper selection and combination of materials. The optimum would be a hard material sliding on a softer material plated to a harder material. However, the softer material will produce large wear particles that may influence the leakage.

A parameter to consider in selecting a material for a valve seat is the wear particle size generated by the seat materials. By selecting hard materials which produce the smaller wear particles, leakage should be minimized.

Normally, a valve seat or closure is protected by a filter in the system, usually located as close as possible to the valve, sometimes being integral with the valve. The size of the wear particles generated by the operating action of the valve may dictate the micron size of the filter to be used. For example, if the wear particles generated by the closure were equal to or greater than 10μ, there would be no justification to use a 5μ filter.

A knowledge of the effects that various planetary atmospheres have on wear particle size may be essential to component design. For the atmosphere of the planet Venus, which is estimated to be 90 to 95% nitrogen, the mean particle size would be greater than if it were produced in the earth's atmosphere. The significance of this can be important for many mechanical functions; for instance, in close-fitted moving parts such as a shaft sliding in a bushing, the clearance should be larger than the expected wear particle size. For close-fitted parts seizure may take place in the Venus atmosphere or in the space vacuum, while working perfectly in the earth's atmosphere. A tolerable leak rate for a given valve in an earth atmosphere may increase for the same valve operating in the atmosphere of Venus or Mars due to the larger particle size produced. The surface finish on valve seats is important for leakage control. The initial surface finish should then be comparable or better than the characteristic wear particle size for the softer material.

REFERENCES

(1) F. P. Bowden and D. Tabor. The Friction and Lubrication of Solids, Clarendon Press, Oxford, England (1950).

(2) E. Rabinowicz. "Influence of Surface Energy on Friction and Wear Phenomena", Journal of Applied Physics, vol. 32 No. 8 (August 1961) p. 1440.

(3) E. Rabinowicz and R. G. Foster. "Final Report on the Size Distribution of Wear Fragments", Contract No. DA-19-202-ORD-4705, 10 April 1962, Massachusetts Institute of Technology.

(4) J. N. Elliott. "Some Studies on the Mechanism of Wear", M. S. Dissertation, Massachusetts Institute of Technology, June, 1956.

Table 4-18. Size of Wear Particles and Related Functions under Standardized Conditions of Ambient Atmosphere.

Metal	p	W	W/p	d	W/p/d
Lead	4×10^{8}	440	110×10^{-8}	270×10^{-4}	42×10^{-6}
Tin	6	540	90	120	75
Bismuth	12	375	31	50	62
Woods Alloy	16	400?	25	400	6.2
Cadmium	23	600	26	320	8
Aluminum	30	900	30	140	21
Zinc	30	750	25	440	5.6
Antimony	45	380	85	400	22
Copper	60	1100	18	250	7.3
Brass	120	700?	5.8	100	5.8
Mild Steel	200	1000	5	60	8.3
Iron (oxide)	2000?	600?	.3	1	30
Aluminum (oxide)	2000	900	.45	1	7.5
Teflon	4	15?	3.8	90	42
Nylon	20	30?	1.5	?	?
Babbitt	30	400?	13	350	3.7
Silver	80	920	11.5	330	3.5
Nickel	260	1650	6.3	35	18
Glass	550	200?	.36	1	36

Note: p is the penetration hardness in dynes/cm^2

W is the work of adhesion of the system in ergs/cm^2

d is the diameter of the average wear particle in cms.

Table 4-19. Wear of Copper in Various Environments

Atmosphere	Average Fragment Diameter
Nitrogen	480μ
Helium	380
Carbon Dioxide	300
Dry Air	224
Oxygen	201
Laboratory Air	177
Wet Air	144
Lubricant	
Cetane	12.0
Silicone DC 200	9.5
Ucon LB-70X	9.5
Palmitic Acid in Cetane	8.0

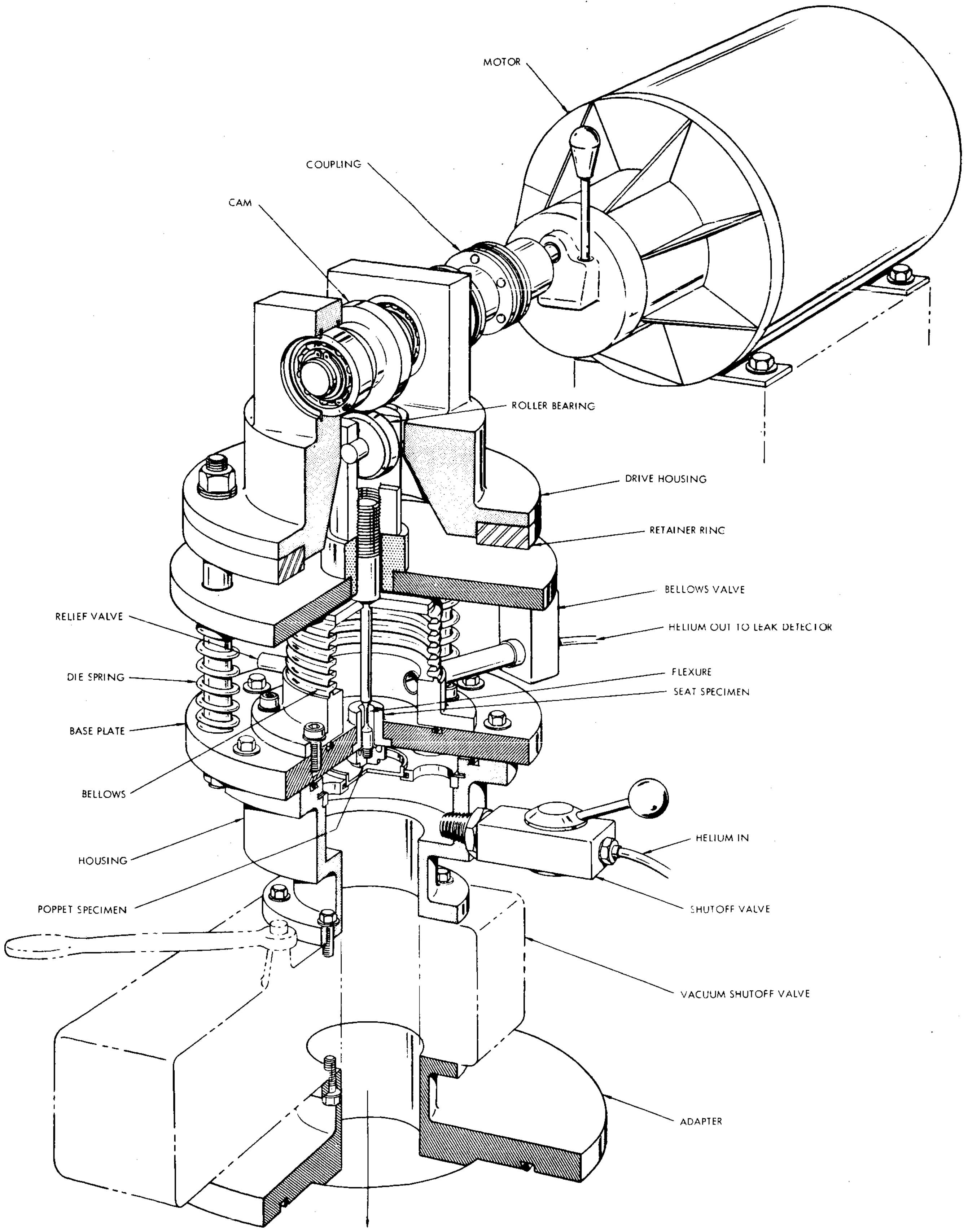


Figure 4-8 TEST FIXTURE, WEAR PARTICLE AND LEAK RATE ASSEMBLY

TEMPERATURE AND STRUCTURAL-MECHANICAL EFFECTS

Introduction

This study presents the results of an evaluation of potential fluid problems due to temperature gradients that may be imposed on the valve closure. The study consisted of a review of the general structural-mechanical-thermal problems of fluid valve designs and a detailed study of the relative importance of thermal distortions of a valve seat due to nominal thermal gradients that would be expected from the radiation space environment.

General Structural-Mechanical-Thermal Valve Problems

Various valve designs of Reference (1) were reviewed for potential structural-mechanical-thermal problems. Design areas which were felt to be possible potential problems and therefore require design attention are discussed below.

Valve Seat Design Problems

Valve seat design problems are centered on maintaining mechanical stability in the anticipated operating environment. In-plane and out-of-plane distortions were considered to be the major design problems. These distortions can be minimized by:

(1) Selecting basically stable valve seat materials;

(2) Reducing thermal gradients by proper structural thermal design (preliminary study results as presented in this study show that these effects are small for nominal gradients);

(3) Allowing controlled material deformations to take place in the valve seat itself; and

(4) Modifying the seat contact line detail to include a slight arc to allow a minute rotational seat misalignment.

Valve Stem Design Problems

Valve stem design problems are similar to the valve seat design problems, i.e., achieving mechanical stability. Mechanical stability can be achieved by:

(1) Selecting basically stable valve stem materials,
(2) Minimizing thermal gradients by proper structural-thermal design,
(3) Permitting controlled material deformations to take place in the valve stem itself,
(4) Designing the valve stem housing so that the stem support redundancy is minimized,
(5) Minimizing the active valve stem length, and
(6) Incorporating the use of a limited "self-centering" stem-seat design arrangement.

Analysis of Thermal Distortions of a Valve Housing

The relative importance of thermal distortions of a valve seat due to nominal thermal gradients was investigated in detail. The idealized solution is summarized below, followed by a numerical example. Results indicate that nominal thermal gradients do not impose any serious distortions of the valve seat.

Analysis

A review of analytical solutions for thermal distortions of a valve housing indicated that a precise three-dimensional solution including edge effects was extremely complicated and unavailable at this time. However, a two-dimensional analysis (based on References 2 and 3) was performed, in which a valve housing was idealized as a thick cylindrical shell subjected to a steady state thermal gradient. It is believed that this idealization is sufficiently accurate for the initial study phase (Figure 4-9).

The two-dimensional analysis assumes, as shown in Reference 3, that in steady state the temperatures on the inner and outer boundaries of the shell can be expanded in a Fourier series of sines and cosines. However, it can be shown that stresses and deformations in the cross section depend only on the terms of the Fourier series involving the first harmonic. Inasmuch as the valve seat temperature due to solar radiation over 180° of its circumference is symmetric about axis A-A, (Fig. 4-9), only cosine terms were considered in the following calculations.

The specialized Fourier series for this problem has the form

$$T(r, \phi) = \sum_{n=1}^{\infty} (a_n r^n + b_n r^{-n}) \cos n\phi + T_{(ref)}$$

and for purposes of the stress and displacement calculations the only term of interest is

$$T(r, \phi) = (a_1 r + \frac{b_1}{r}) \cos \phi$$

The coefficients a_1 and b_1 are obtained from assumed boundary temperature variations. The only significant terms of these variations for purposes of the following illustrative calculation are

$$T_{r=a} = C_1 \cos \phi$$

$$T_{r=b} = C_2 \cos \phi$$

where C_1 and C_2 denote the maximum amplitude of the temperature variation on the two boundaries.

Solving for a_1 and b_1 in terms of C_1 and C_2 one obtains

$$a_1 = \frac{aC_1 - bC_2}{a^2 - b^2}$$

$$b_1 = \frac{ab\,(aC_2 - bC_1)}{a^2 - b^2}$$

It is to be noted that the actual boundary temperature variations may contain terms in the higher harmonics when expanded in Fourier series. However, as indicated above, the in-plane deformations do not depend on the latter and the precise form of the temperature distribution is not required.

With the above boundary equations and constants, the resulting in-plane radial and tangential deflections u and v are respectively,

$$u = \frac{\alpha}{2} \frac{1 + \mu}{1 - \mu} \frac{\cos \phi}{a^2 - b^2} \left\{ \frac{3}{4} r^2 (aC_1 - bC_2) + ab\,(aC_2 - bC_1) \right\}$$

$$v = -\frac{\alpha}{2} \frac{1 + \mu}{1 - \mu} \frac{\sin \phi}{a^2 - b^2} \left\{ \frac{r^2}{4} (aC_1 - bC_2) + ab\,(aC_2 - bC_1) \log r \right\}$$

where r = radius to point in question

ϕ = polar angle

a = inner radius

b = outer radius

α = Thermal coefficient of expansion

μ = Poisson's Ratio

Numerical Example

With the preceding analytical expressions, a numerical example was selected and calculations conducted for a valve housing idealized as in Fig. 4-9 and assuming values for the valve parameters shown below. A temperature gradient of 50°F across the valve was considered.

a) Valve Seat Dimensions and Temperature Coefficients

Inner radius $a = 0.375$ inches

Temperature coefficient at inner radius $C_1 = 12.5^\circ F$

Outer radius $b = 0.75$ inches

Temperature coefficient at outer radius $C_2 = 25^\circ F$

Both outer and inner radii temperature coefficients were estimated based on isolated valve body in space exposed to radiation from the sun.

b) Valve Seat Material

Stainless Steel 440A

Thermal coefficient of expansion $\alpha = 5.8 \times 10^{-6}$ in/in/°F

Poisonn's Ratio $\mu = 0.33$

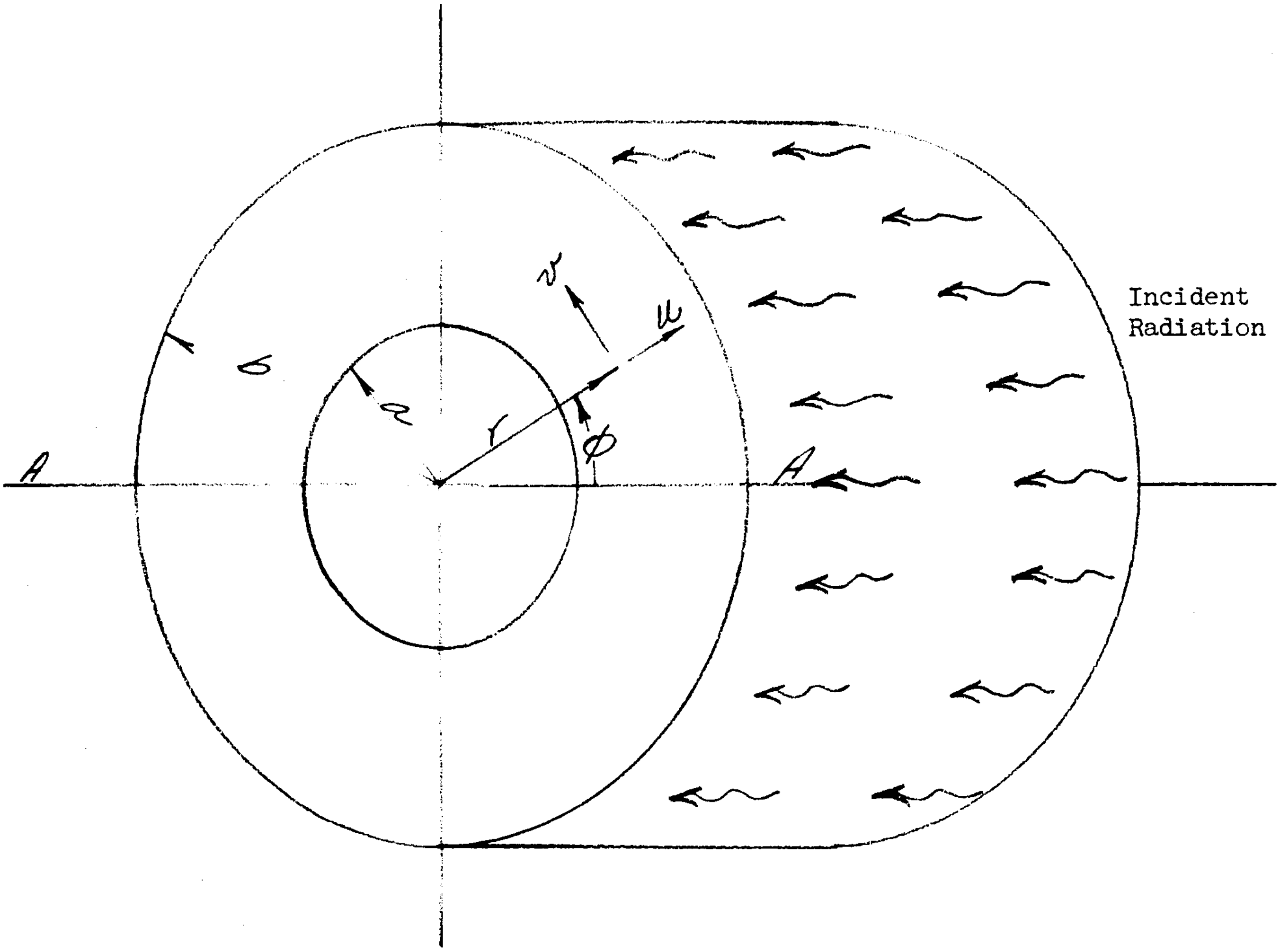
Figure 4-10 shows the computed radial and tangential displacements versus polar angle. With these displacements it may be shown geometrically that the maximum out-of-roundness is less than 2.4×10^{-10} inches, whereas out-of-roundness is defined as the difference between the internal radii at $\phi = 0^\circ$ and $\phi = 90^\circ$. The computed value is extremely small, and neglible from the stress and manufacturing standpoints.

Therefore, it may be concluded that the effects of nominal thermal gradients on the in-plane distortions of valve seats may be considered insignificant.

REFERENCES

TEMPERATURE AND STRUCTURAL-MECHANICAL EFFECTS

1. Rocketdyne Publication Number R-3819-3, "Valve Design, An Industry Survey," by M. D. Ferguson, G. F. Tellier, P. Mannes, dated September 1962.
2. Theory of Thermal Stresses, by B. A. Boley and J. H. Weiner, John Wiley and Sons, Inc., New York 1960.
3. Wärmespannungen, by E. Melan and H. Parkus, Springer-Verlag, Vienna 1953.
4. Unpublished STL Notes by E. Diamant.



r = radius to point in question

ϕ = polar angle

a = inner radius

b = outer radius

u = radial deflection

v = tangential deflection

Figure 4-9 Thick Cylindrical Shell Subjected To A Steady State Thermal Gradient.

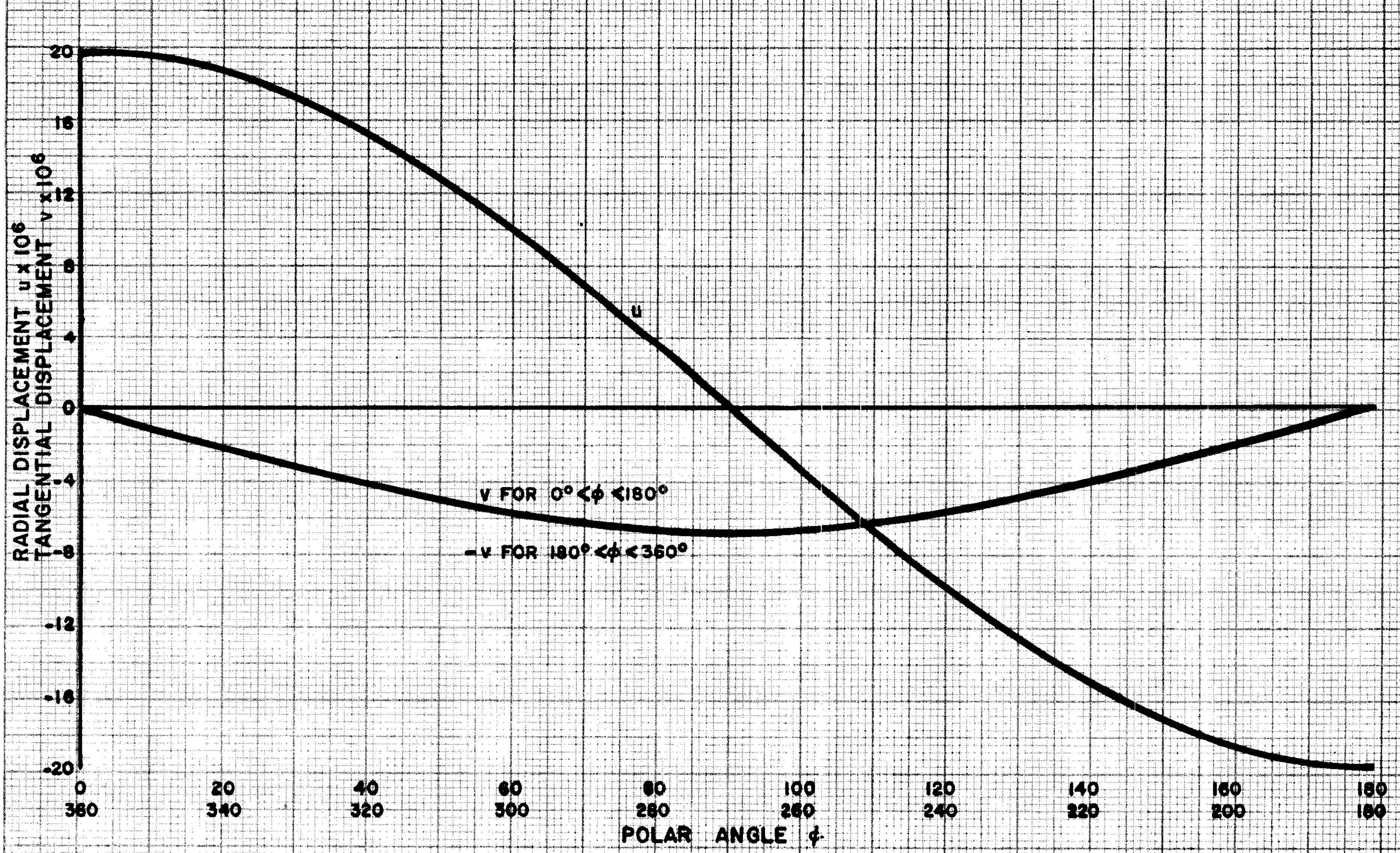


FIGURE 4-10 DISPLACEMENTS vs. POLAR ANGLE

V. DISCUSSION OF PROBLEMS

In this section an analysis of the problems associated with valves and subcomponents is made. The analysis was made with the aid of charts that list the functional parameters and space and planetary environments with the components and subcomponents under consideration. Values were assigned to the various combinations of components and parameters, and have the following definitions:

VALUE	DEFINITION
1	A value of 1 was assigned to those combinations in which a serious problem exists for which there is no satisfactory solution.
2	A value of 2 was assigned to those combinations in which a problem exists, but for which a remedy may be available. That is, the combination of component and parameter is deemed to be acceptable, with QUALIFICATION.
3	A value of 3 was assigned to those combinations which were deemed to be satisfactory, i.e., within the present state-of-the-art.
U	A designation of U was made where the necessary information upon which to base a judgment was unavailable.
NA	Where a parameter was not applicable, the letters NA were used.

In some cases, as indicated on the chart, a differentiation in values was made between manned and unmanned vehicles.

Tables 5-3 through 5-28 summarize those combinations of parameters and components having designations of 1 or 2. Each of the subcomponents shown on the charts (Tables 5-1 and 5-2) is considered in relation to the functional and environmental parameters included at the top of the charts. The tables list the parameters and give a brief description of their effects on the component under consideration. For those combinations with a designation of 2, the qualifications required to mitigate the problem are given. For those combinations with a designation of 1, the nature of the problem or justification for assigning the value of 1 is shown.

No comments were made on several of the subcomponent ratings, e.g., operating life, squib, because of the obvious nature of the relationship.

It is important to note that the evaluations, with one exception*, were made on an absolute basis. This means that a subcomponent was evaluated in relation to the parameters only, and not by comparison with another component. That is, it is a single parameter study.

After the values for the subcomponents were established, the values for the five valve types were determined. However, it was felt that the conclusions with respect to the valves could better be presented in prose form rather than on the charts, as more detail is required to describe the status of the completed assemblies. A delineation of these problems, using Tables 5-1 and 5-2 as a guide, follows:

Fill Valves (Disconnects)

Fill valves may assume numerous configurations with respect to type of valve used and method of connecting and disconnecting. In the simplest case wherein a man-rated tank is to be filled to a low pressure, the valve can be of almost any type of manual shutoff. For added insurance against leakage, a secondary closure such as a cap can be attached and locked in place. An example of such a fill valve for a low-pressure gas system consists of an AN bulkhead fitting which has been fitted with a conventional aircraft tire valve core. The system is charged with a tire chuck, and a cap is installed after filling. This fill valve represents the ultimate in simplicity and the leakage is essentially zero. As the requirements become more rigorous, fill valves become more complex. High pressures and toxic, corrosive, or cryogenic fluids must be transferred by more elaborate couplings

*Time, which must necessarily be considered with other parameters.

which may include requirements for remote operation, balanced valve design, and very low spillage upon engagement or disengagement.

Disconnects are required to meet extremely stringent leakage requirements because of the necessity of preventing pressurant or propellant loss and the need to avoid hazards to personnel that might result from spillage or leak. Soft seats are used in these valves almost exclusively in order to meet the requirements. However, it will be noticed by referring to the charts that the disconnects are rated '2' for flow media, indicating that a serious but solvable problem exists. The problem arises from the fact that no known polymers are compatible with fluorine and fluorine vapors, and thus all metal construction would be required for these propellants. However, great care would be required in producing metal-to-metal leak-free closures for this application. As such closures are very sensitive to contamination, a low rating is assigned to this parameter, and to those where the incidence of contamination would be high, e.g., from products of combustion in a "turn-around" maneuver, and in a lunar landing or launch, because of the dust clouds that would result from engine blast.

Other problems that exist for disconnects include that of the effects of sterilization temperatures on soft seats in contact with propellants. It is considered very possible that the combination of high temperature for long periods (36 hours) and propellant contact would degrade elastomeric materials used as seals or seats.

As the disconnect port would be exposed to the vacuum of space, sublimation of the material would occur to some degree, and radiation effects could degrade the polymers if the dosage became sufficiently high.

Two possibilities are suggested for advancing the state-of-the-art of disconnects:

1) Use of existing disconnect in conjunction with the solder valve. In this arrangement, the solder valve would be used downstream (inboard) of the disconnect to act as the final shutoff.

2) Design of a disconnect using the solder valve principle. A valve could be designed which would have as its sealing member a soldering arrangement similar to that shown in the body of the report. The solution chosen would depend upon the particular mission requirements involved.

Summary: Fill Valves (Disconnects)

Disconnect valves have reached a rather high state of development through numerous applications over the years. Suitable products are available for many applications, and modifications to meet special applications can be made with a minimum of development time. However, for space missions of long duration or for those involving "in space" fluid transfer, special efforts will be required to circumvent the problems caused by the space environments.

Shutoff Valves

The term shutoff valve is very general; it usually means a valve that has only an on-off function—that is, it does not modulate pressure or control flow in a variable way. A great variety of shutoff valves exists, since such a valve may be of almost any configuration and still satisfy the function. It can be a simple petcock, commonly called a plug valve, or it can use any of numerous other closure mechanisms, e.g., butterfly, poppet, slide, pinch, etc. The closures may use elastomers for sealing or a metal-to-metal seat. The valve can have a variety of actuators — manual, electrical, hydraulic, electro-hydraulic, or pneumatic.

The particular configuration selected for a given system depends upon the detail requirements of the system. The choice of seat material, for instance, depends upon the degree of contamination that must be contended with, the operating and ambient temperature ranges the valve will experience, and the flow medium the valve is required to control. The choice of actuator is also strictly dependent upon system requirements.

From the almost limitless possible combinations described above, it is possible to select and procure an adequate shutoff valve for most applications. However, there remains distinct and pressing problems to be solved with shutoff valves intended for use on space vehicles.

Many of the problems, e.g., those of sterilization, contamination susceptibility and possibility of damage from radiation, are identical to those encountered by disconnects. In addition to these, the shutoff valve will be required to operate at higher temperatures than a disconnect and is thus rated lower. Above 500°F the choice of seat material is restricted to metals only. Continuously operating attitude control valves may use significant amounts of electrical energy, and the response of a valve for this application must be quite high. If metal-to-metal seats are used, the possibility of cold welding in high vacuum exists. Contamination from space debris and lunar dust could contribute to failure, and measures must be taken to exclude such dirt from the valve.

Summary of Shutoff Valves

Shutoff valves are available for performing a wide variety of tasks. Adequate valves exist for "in line" operation of a space vehicle, where the valve is immersed in the operating fluid and does not have its internal parts exposed in space. However, the "last valve" in the system, which will have one port exposed to the space environment, may be degraded from the effects of vacuum, space debris and other external contaminants, and radiation. The extent of these problems is not known and requires further investigation.

FLOW METERING VALVES

The function of a flow metering valve is to control the flow of the propellants to the engines at some specific rate. The control may be effected by a sharp edged orifice in the line with an on-off function being supplied by a conventional valve upstream, or the orifice may be incorporated into the valve itself.

Variable thrust rocket engines employ a movable pintle in a fixed orifice. Bi-propellant engines employ a dual pintle arrangement in which the pintles are operated in tandem through a linkage. The valves can be designed to operate in the cavitating regime, which makes the flow rate independent of changes in the downstream pressure, within limits.

Flow metering valves are peculiar in that they are not subject to failure from contamination to the same degree that is found in other valves because they are not normally used for the shutoff function with valves, i.e., that of meeting stringent leakage requirements is eliminated.

Flow metering valves can be of all metal construction or can be designed to include polymers, the choice being dependent upon the particular application. All metal construction permits a higher range of operating temperature, and eliminates the concern over possible radiation damage to the polymeric seals. The use of all metal construction would involve bellow shaft seals which would also incorporate a hermetically sealed lubrication system. Some development work would be required for this aspect of the design as there apparently is no fund of experience in this field.

If polymers are used in the construction, previous comments regarding the limitations imposed by temperature, propellant compatibility, radiation, and vacuum apply. Polymeric seals have the additional advantages of preventing a more compact, lighter design and alleviates the lubrication problem.

Table 2-6 notes that only two manufacturers reported that they produced flow metering valves. While it is very probable that others could employ their known design techniques and manufacturing know how to build such valves, the implication is that the availability is limited. Relatively long lead time should be allowed for the procurement of this equipment.

VENT VALVES

Cryogenic vent valves presented one of the most severe problems to be encountered in the ICBM program. A vent valve is required to perform to exacting requirements under widely varying conditions of ambient temperature, vibration, and acceleration. It must have a large capacity to be able to handle the large flow rates resulting from boiloff during loading, and after loading and cooldown, it must have a high response to maintain tank pressures within close limits.

As a result of an extensive development program over more than 5 years, satisfactory valves have been produced to satisfy the vent function on ICBM's. The techniques of design, manufacture test, and operation that have been developed can be utilized in supplying a vent valve for space operations.

Among the problems that must still be considered with cryogenic vent valves are the following:

1. Care must be taken to insure that the tank is purged of all water vapor prior to loading. If this is not done, the vapor may freeze in the control section and render the valve inoperative.
2. If plastic liners or other components are used for seals, the plastics must be dimensionally stable over the expected range of temperatures. Ideally, this stability is achieved through the proper selection of material. However, if stable material is not available, suitable processing techniques must be used to achieve the desired result.

3. Under zero gravity conditions, the location of the liquid in the tank may be random and indeterminate. To avoid the excessive loss of oxidizer which would result if liquid were vented instead of gas, it will be necessary to insure that only the vapor phase has access to the discharge ducting. Studies have indicated that the liquid tends to collect in the center of the tank under zero g conditions. If additional tests substantiate this position, it may only be necessary to provide an annular collector ring inside the tank to effect the separation of liquid and gas. However, additional test data are required before any firm conclusions may be drawn.
4. If polymers are used in the construction, the effects of the propellants, sterilization temperature and the vacuum and radiation environments of space must be considered. The comments made in the previous section with respect to these parameters would apply.

Summary: Vent Valves

Vent valves for spacecraft must perform to extremely stringent requirements under very adverse conditions. As one port will be exposed to atmosphere, sublimation of polymers, if used in the closure, must be considered. If all metal seats are used, the possibility of cold welding exists. Radiation and contamination from external sources could also impair or destroy the valve. In addition to these normal environmental effects with which the valve must contend, the vent valve is faced with a unique problem peculiar to the venting function, i.e., the zero gravity condition. The valve must be capable of discriminating between a gaseous and liquid flow medium, or must be capable of separating the two phases so that only the gas is relieved.

In the vendor survey only two manufacturers were found who have attempted to design a vent valve capable of meeting the requirements imposed by the zero gravity field. Because of the difficulty of testing such devices, little or no test data is available.

It must be concluded that considerable development time and effort would be required to produce a satisfactory valve for a venting operation. Additional studies are also needed to determine the actual valve requirements. For instance, some tank studies have indicated that the location of the liquid in the tank can be predicted or controlled, and temperature studies have indicated that venting may not be necessary for some specific missions.

PNEUMATIC REGULATORS

COLD-GAS REGULATORS

The function of a pressure regulator is to reduce a higher pressure to a lower pressure to within rather narrow limits of accuracy. The regulator must perform this task in spite of many variables that occur during the process. For example, the upstream pressure decays with time and the temperature of the flowing medium may increase or decrease. The flow rate may vary from zero to the maximum capacity of the regulator. The temperature in the ullage downstream of the regulator may vary widely with time, and the regulator may be subjected to extremely variable environmental conditions, such as abrupt changes in ambient temperature and pressure and variable conditions of acceleration, vibration, and shock.

The development of ICBM pressure regulators was conducted concurrently with the development of vent valves. The requirements for regulators are more severe in several respects than are those for the vent valves, in that the operating temperature range is wider (from -300° to +400°F) and the valves must control helium gas which imposes stringent seal requirements.

Two general types of regulators have been employed in tank pressurization, the modulating and the on-off, sometimes called the bang-bang. In the former, tank pressure is sensed and a pneumatic signal is fed to a controller on the regulator. In brief, the controller matches the signal against a preset requirement, and the main valve within the regulator responds to eliminate any error between signal and tank pressure. In the bang-bang control system, tank pressure is sensed by a pressure switch, which in turn actuates a solenoid valve. A particular advantage of the bang-bang concept is that the sensing elements, i.e., the pressure switch, can be isolated from the temperature effects of the flowing medium, as it can be located remotely from the valve.

Among the problems that must still be considered with cold gas regulators are the following:

1. Contamination

Contamination is the largest source of trouble in regulator operation. The close fits of the moving parts and the small orifices that are often used in the control sections dictate that the flowing medium be exceptionally clean. In addition, extreme care must be used in the final cleansing of the tanks, lines, and fittings upstream of the regulator prior to operation.

2. Sterilization

Sterilization temperatures are sufficiently high (270°F, 36 hours) to cause damage to polymers and elastomers, and possible to effect permanent dimensional changes in some metal parts.

3. Radiation

Long term exposure to intense radiation could result in degradation of non-metallic parts. However, solutions are available for this problem, in that all metal regulators can be supplied if required.

HOT GAS REGULATORS

A requirement for a hot gas regulator was anticipated by the Air Force in 1957, and a development program was conducted by STL to produce a unit that would operate at temperatures between -300° to +500°F, at 5000 psig. The valve was to be of all metal construction. The end item produced under the contract met the requirements of the work statement, and a subsequent modification to the valve greatly extended the operating temperature range. Numerous tests of approximately 1 minute duration using 3000-psig helium at 1200°F have been conducted at Edwards Air Force Base in California. No apparent damage to the unit has resulted and it is probable that the upper temperature range can be extended to at least 1500°F for 1 minute runs.

A second regulator, supplied by a private firm, has been tested at the same location at temperatures of about 1500°F. It is believed that the range for this regulator can be extended to at least 1700°F for short periods of time.

Summary: Hot Gas Regulators

Satisfactory regulators can be produced for short duration runs, using clean gas in the 1500 to 1700°F range. Extended operation at these temperatures would require much development work; no equipment is available for operation on a continuous duty basis at these temperatures. Similarly, an extension of the temperature to 2000°F for even short duration runs would require an advance in the state-of-the art.

The use of the on-off (bang-bang) concept for hot gas regulation would seem to be particularly attractive because of the possibility of isolating the control section entirely from the effects of the high temperature. The valve actuator could also be isolated to a degree, by means of a standoff or other insulation method, which would permit use of conventional actuation means such as solenoids.

The high temperature portion of the regulator is thus reduced to the valving portion only, i.e., a housing and closure mechanism. While it is probable that a regulator of this type could be successfully built, considerable development and test time would be required.

TABLE 5-1 VALVE COMPONENT RATING ANALYSIS
FUNCTIONAL & ENVIRONMENTAL CONSIDERATIONS

		FUNCTIONAL PARAMETERS													SPACE FLIGHT ENVIRONMENTAL PARAMETERS													
		MEDIA													VACUUM		RADIATION											
		LIQUID	GAS	STERILIZATION	OPERATING TEMPERATURE	OPERATING PRESSURE	WEIGHT	POWER REQUIREMENTS	LEAKAGE	OPERATING LIFE	CONTAMINATION	SPACE MAINTENANCE	RESPONSE	VIBRATION AND SHOCK	ATMOSPHERIC TO 10-9mm Hg	10-9mm Hg AND HIGHER	COSMIC	ULTRA-VIOLET	GEOMAGNETIC (VAN ALLEN BELT)	AURORAL SOFT	SOLAR FLARES	INDUCED (BREMSSTRAHLUNG)	ZERO G	TIME	TEMPERATURE	METEOROIDS	PRODUCTS OF COM-BUSTION (TURN AROUND)
TYPE OF VALVE	DISCONNECT	2	2	2	3	3	3	NA	1	3	1	1	NA	3	2	2	3	3	2	3	U	2	3	2	3	2/1M	1
	SHUTOFF	3	3	2	2	3	3	2	1	2	1	1	2	3	1	1	3	3	2	3	U	2	3	2	3	2/1M	2
	FLOW METERING	3	3	2	3	3	3	3	NA	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3	3	2/1M	3
	VENT	2	2	2	3	3	3	NA	1	3	3	1	2	3	2	2	3	3	2	3	U	2	1	2	3	2/1M	2
	REGULATOR	NA	3	2	3	3	3	NA	2	2	1	1	2	3	3	3	3	3	2	3	U	2	3	2	3	2/1M	3
CLOSURE	BALL	1	1	3	1	3	3	2	3	3	3	NA	2	3	2	2	3	3	1	3	2	2	NA	2	3	NA	3
	POPPET	3	3	3	3	3	3	3	3	3	2	NA	3	2	3	3	3	3	3	3	2,3	3	3	3	3	NA	3
	BUTTERFLY	3	3	3	3	2	3	2	3	3	3	NA	2	3	3	3	3	3	3	3	2,3	3	3	3	3	NA	3
	BURST DIAPHRAGM	3	3	3	3	3	3	3	3	1	3	NA	3	3	3	3	3	3	3	3	3	3	3	3	3	NA	3
SEALS	METAL	3	3	2	2	3	3	NA	1,2	3	1	NA	NA	3	1	1	3	3	3	3	3	3	NA	3	3	NA	1
	POLYMERIC	1	1	2	1	3	3	NA	3	3	3	NA	NA	3	2	2	3	3	1	3	2	2	3	2	2	NA	3
ACTUATOR	SOLENOID	NA	3	3	2	NA	2	2	NA	3	3	1	3	3	2	2	3	3	2	3	2	2	3	3	2	2/1M	3
	PNEUMATIC	NA	3	3	3	3	3	3	3	3	3	1	3	3	3	3	3	3	2	3	3	3	3	3	3	2/1M	3
	HYDRAULIC	3	NA	3	3	3	3	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3	3	2/1M	3
	ELECT. MOTOR	NA	NA	3	NA	NA	2	2	NA	3	NA	1	2	3	2	2	3	3	2	3	2	2	3	3	2	2/1M	3
	SQUIB	NA	NA	U	NA	NA	3	3	NA	1	NA	1	3	3	3	3	3	3	U	3	U	U	3	U	U	2/1M	3
LUBRI-CANT	DRY	1,3	2	3	2,3	NA	3	NA	NA	3	3	1	NA	3	2	2	3	U	U	U	U	U	3	3	3	NA	3
	LIQUID	1,3	1,3	3	1	NA	3	NA	1	3	3	1	NA	3	2	2	3	3	2	3	U	2	2	2	3	NA	3
FITTINGS AND FASTENERS	AN FLARE	3	3	3	3	3	2	NA	2	3	3	1	NA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	MS FLARELESS	3	3	3	3	3	2	NA	2	3	3	1	NA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	WELDED	3	3	3	3	3	3	NA	3	3	3	1	NA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	BOLTS & SCREWS	3	3	3	NA	NA	3	NA	NA	3	NA	1	NA	3	3	3	3	3	3	3	3	3	3	3	3	3	3
FILTERS		3	3	3	1,3	3	3	NA	NA	3	2	1	NA	2	3	3	3	3	3	3	3	3	3	3	3	NA	3

LEGEND

RATING CHARACTERISTICS

1 - POOR
2 - FAIR
3 - GOOD
U - UNAVAILABLE INFORMATION
NA - NOT APPLICABLE

EXAMPLE:

UNMANNED (DIGIT ONLY)

2/1M

MANNED (SUBSCRIPT)

3 = SAME VALUE FOR MANNED AND UNMANNED (DIGIT ONLY)

TABLE 5-2 VALVE COMPONENT RATING ANALYSIS
PLANETARY MISSIONS(MANNED & UNMANNED)

		EARTH MOON					VENUS							MARS							JUPITER						
		ATMOSPHERIC PRESSURE ≈ 10^{-14} mm Hg	TEMPERATURE -243°F TO 260°F	MISSION TIME ≈ 3-6 DAYS	LUNAR DUST	LUNAR MAINTENANCE	ATMOSPHERIC COMPOSITION 95% N_2 5% CO_2	ATMO. PRESSURE (a) ≈ 16 EARTH ATMO.	TEMPERATURE ≈ 620°F (a)	MISSION TIME	RADIATION BELT (UNKNOWN) (b)	VENUS DUST	VENUS MAINTENANCE	ATMO. COMPOSITION 95% N_2 5% CO_2	ATMO. PRESSURE << 1 ATMO (a)	TEMPERATURE -180°F TO 90°F	MISSION TIME	RADIATION BELT (UNKNOWN) (b)	MARTIAN DUST	MARTIAN MAINTENANCE	ATMO COMPOSITIO CH_4, NH_3	ATMO PRESSURE >>1 ATMO (a)	TEMPERATURE ≈ -200°F (a)	MISSION TIME	RADIATION BELT (UNKNOWN) (c)	DUST	MAINTENANCE
TYPE OF VALVE	DISCONNECT	2	2	3	1	1	3	3	1	3	3	U	1	3	3	3	2	3	U	1	3	U	3	2	U	U	1
	SHUTOFF	1	2	3	2	1	3	3	1	3	3	U	1	3	3	3	2	3	U	1	3	U	3	2	U	U	1
	FLOW METERING	3	2	3	3	1	3	3	1	3	3	U	1	3	3	3	2	3	U	1	3	U	3	2	U	U	1
	VENT	2	2	3	2	1	3	3	1	3	3	U	1	3	3	3	2	3	U	1	3	U	3	2	U	U	1
	REGULATOR	3	2	3	3	1	3	3	1	3	3	U	1	3	3	3	2	3	U	1	3	U	3	2	U	U	1
CLOSURE	BALL	2	1	3	2	NA	3	3	1	3	U	2	NA	3	3	3	3	U	2	NA	3	3	1	3	U	2	NA
	POPPET	3	3	3	2	NA	3	3	3	3	U	2	NA	3	3	3	3	U	2	NA	3	3	3	3	U	2	NA
	BUTTERFLY	3	3	3	2	NA	3	3	3	3	U	2	NA	3	3	3	3	U	2	NA	3	3	3	3	U	3	NA
	BURST DIAPHRAGM	3	3	3	3	NA	3	3	3	3	U	3	NA	3	3	3	3	U	3	NA	3	3	3	3	U	3	NA
SEAL	METAL	2	2	3	1	NA	3	3	2	3	U	1	NA	3	3	3	3	U	1	NA	3	3	3	3	U	1	NA
	POLYMERIC	2	1	3	2	NA	3	3	1	3	U	2	NA	3	3	1	3	U	2	NA	3	U	1	3	1	2	NA
ACTUATOR	SOLENOID	2	3	3	2	1	2	2	2	3	U	2	1	3	3	3	3	U	2	1	2	2	3	3	U	2	1
	PNEUMATIC	3	3	3	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1
	HYDRAULIC	3	1	3	3	1	3	3	1	3	U	3	1	3	3	1	3	U	3	1	3	3	1	3	U	3	1
	ELECT. MOTOR	2	3	U	2	1	3	3	U	3	U	2	1	3	3	3	3	U	2	1	3	3	U	3	U	2	1
	SQUIB	3	U	3	NA	1	3	3	U	3	U	NA	1	3	3	U	3	U	NA	1	3	U	U	U	U	NA	1
LUBRI-CANT	DRY	3	3	3	2	1	3	3	3	3	U	2	1	3	3	3	3	U	2	1	3	3	3	3	U	2	1
	LIQUID	2	3	3	2	1	3	3	1	3	U	2	1	3	3	3	3	U	2	1	3	3	3	3	1	2	1
FITTINGS & FASTENERS	AN FLARE	3	3	3	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1
	MS FLARELESS	3	3	3	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1
	WELDED	3	3	3	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1
	BOLTS & SCREWS	3	3	3	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1	3	3	3	3	U	3	1
FILTERS		3	3	3	NA	1	3	3	3	3	U	NA	1	3	3	3	3	U	NA	1	3	3	3	3	U	NA	1

LEGEND

RATING CHARACTERISTICS:
1 - POOR
2 - FAIR
3 - GOOD
U - UNAVAILABLE INFORMATION
NA - NOT APPLICABLE

NOTES (a) Estimated
(b) Assumed to be small.
(c) Assumed to be much greater than Van Allen level.

TABLE 5-3 ANALYSIS TABLE

DISCUSSION OF BALL CLOSURE WITH APTITUDE RATING OF 1

PARAMETER	**RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS**	NATURE OF THE PROBLEM
Liquid and Gas Media (Ref. P. 3-2)	Polymeric seals are normally used in ball valves. Fluorine liquid and vapors attack all known polymers.	No polymeric seals compatible with fluorine liquid or vapor are available. NOTE: Ball closures are available with plastic seals for all other propellants including LH_2. Life cycles at cryogenic temperatures may be limited.
Operating Temperature (Ref. P. 3-17)	High operating temperatures destroy seal.	Upper limit of temperature is approximately $600^{\circ}F$.
Radiation (Ref. P.3-50)	Radiation can degrade most polymers subjected to long term exposure in Van Allen belt.	Insufficient data exists to make accurate estimate of effects of radiation on polymers.
Planetary Environment (Venus) (Ref. P. 3-122)	Temperature of Venus estimated at $600^{\circ}F$ to $1100^{\circ}F$.	No polymers are available for use at these temperatures.

TABLE 5-4 ANALYSIS TABLE

DISCUSSION OF BALL CLOSURE WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Power Requirements (Ref. P. 3-23)	Ball valves are not pressure balanced and use polymeric seals with relatively high friction; power requirements may be high at high operating pressures.	Use of ball closure must be considered in terms of operating pressure and power available.
Response (Ref. P. 3-31)	Friction effects described above restrict response of the closure.	Response limitations must be considered in selecting this type of closure.
Space Vacuum (Ref. P. 3-36)	Loss of unreacted additives or other constituents in polymers may aggravate leakage or reduce initial compression required for sealing.	Use materials with minimum number and quantity of additives and modifiers. Complete cure of plastics must be obtained by extended time or elevated temperature. Post curing required to ensure the elimination of unreacted, low molecular fractions. Consider preconditioning in vacuum at elevated temperatures to reduce potential loss of material to space.
Time (Ref. P. 3-76)	This parameter must be considered in combination with other parameters. Longer exposure to environments usually degrades performance.	Polymeric seal life must be considered in relation to expected mission duration.

TABLE 5-5 ANALYSIS TABLE

DISCUSSION OF POPPET CLOSURE WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATIONS
Contamination (Ref. P.3-27)	Leakage and wear leading to failure may result.	Achieving and maintaining system cleanliness to acceptable level is extremely difficult.
Vibration and Shock (Ref. P. 3-33)	Axial level of 10 g to 50 to 1000 cps is assumed. May cause valve to open, close, or change position, especially under axial loading.	Spring force and damping force must be high in proportion to the mass of the poppet and forcing function. Orientation of valve on the spacecraft should be such as to minimize the effect of the inputs.
Lunar and Planetary Dust (Ref. P. 3-120)	Rock flour to 0.3mm dia. of high silica content dust exists, assuming large clouds on landing and launch. For valve seats exposed to the cloud, contamination leading to possible leakage can occur.	Some solutions may be possible; however, no metal-to-metal seated valves are known to exist to prevent dust filtration.

TABLE 5-6 ANALYSIS TABLE

DISCUSSION OF BUTTERFLY CLOSURE WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Operating Pressure (Ref. 3-19)	High operating pressure can cause deflection of butterfly closure because of limited support afforded by this design.	Structural limitation must be considered in defining maximum operating pressure
Power Requirements (Ref. P.3-23)	Butterfly valves have characteristically high breakaway forces, requiring relatively high power on opening and closing.	Possible high transient peak loads must be considered.
Response (Ref. P.3-31)	Breakaway forces, closing forces and non-linear torque vs angle of opening characteristics adversely affect response.	Individual applications may be satisfactory. High response through full range of operation may not be attainable.

TABLE 5-7 ANALYSIS TABLE

DISCUSSION OF BURST DIAPHRAGM CLOSURE WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF PROBLEM
Operating Life (Ref. P. 3-26)	Operating Life is limited by design.	The operating cycle available from a burst diaphragm closure is obviously 1. Less obvious is the fact that operating life prior to rupture is affected by such factors as erosion and corrosion, and if the element is other than metal, other effects e.g., those caused by ultraviolet radiation may tend to reduce the life. In particular, pressure cycling or pulsations in a system over a period of time can lower the burst point to less than the design value, leading to failure of the valve.

TABLE 5-8 ANALYSIS TABLE

DISCUSSION OF METAL SEALS AND SEATS WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Leakage (Ref. P. 3-24)	Extremely low to zero leakage is required for many of the propellants, especially fluorine.	Difficult to achieve low leakage with metal-to-metal seat. Zero leakage unattainable.
Contamination (Ref. P. 3-27)	Leakage and wear leading to failure may result.	Achieving and maintaining system cleanliness to acceptable level is extremely difficult.
Vacuum of Space (Ref. P.3-36)	Solid state bonding (cold welding) may result from long exposure to vacuum.	Seizure may occur between mating surfaces. Additional studies to determine the effects of vacuum on surfaces of materials and between clean metals are required to establish design criteria.
Products of Combustion (Ref. P. 3-119)	Contaminates formed by products of combustion cause leakage.	Severity of problem unknown. Protective measures to prevent this contamination have not been developed.
Lunar and Planetary Dust	Rock flour to 0.3mm dia. of high silica content dust exists, assuming large clouds on landing and launch. For valve seats exposed to the cloud, contamination leading to possible leakage can occur.	Some solutions may be possible; however no metal-to-metal seated valves are known to exist to prevent dust filtration. Methods of shielding against dust must be devised.

TABLE 5-9 ANALYSIS TABLE

DISCUSSION OF METAL SEALS AND SEATS WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Sterilization (Ref. P.3-5)	Temperature soak of 270°F max. for 36 hours maximum may cause distortion due to relieving residual stresses or polymorphic changes in the material.	Proper selection of materials of heat treatment is required.
Operating Temperatures (Ref. P.3-17)	May cause distortion of valve seat due to relieving residual stress or polymorphic changes in the material.	Requires proper selection of materials and heat treatment is required.
Leakage (Ref. P.3-24)	Low leakage is required for all propellants and pressurants.	Substitute elastomer seals where possible. Establish realistic leakage requirement.
Lunar and Venus Temperatures	Lunar temperatures of -243°F to 260°F and Venus temperatures of 620°F to 1150°F may cause distortion of valve seat, polymorphic changes in the materials and chemical reaction with Venus atmosphere.	Proper selection of materials and heat treatment is required.

TABLE 5-10 ANALYSIS TABLE

DISCUSSION OF POLYMERIC SEALS WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Liquid and Gas Media (Ref. P. 3-2)	Reactions may cause softening, swelling, embrittlement, or solution of polymeric material. Basis for evaluation includes weight gain or loss, volume change, hardness, tensile strength, elongation, and general appearance.	Limited selection of materials is available for use with the propellants. No soft seals are known to be compatible with fluorine (liquid or gas), chlorine trifluoride, liquid hydrogen, liquid nitrogen and LOX for dynamic application. No polymeric materials are compatible with fluorine (liquid or gas) for either static or dynamic application. Teflon and Kel-F have been used on dynamic seals in ball and butterfly valves at cryogenic temperatures. However, life is limited to relatively few cycles.
Operating Temperature (Ref. P. 3-17)	Possible temperature range from -423°F to 2000°F.	No elastomeric seals are available for use at temperatures above 600°F or below -120°F. Teflon and Kel-F have been used to -423°F in some applications.
Radiation (Ref. P. 3-50)	Radiation can degrade most polymers in long term application in the Van Allen belts.	A problem exists where shielding is impractical because of the weight penalty and the choice of polymers is limited because of propellant compatibility. Insufficient data exists to make accurate analysis of the effects of radiation on polymers in various propellant environments.
Planetary Temperatures	Temperature extremes from -243°F to -180°F for Moon, Jupiter and Mars and to 600°F for Venus.	No elastomeric seals available for use at at these temperatures. Teflon and Kel-F have been used to -423°F in some applications.
Jovian Radiation	Assumed to be several times more intense than the earth belt.	See comment under radiation.

TABLE 5-11 ANALYSIS TABLE

DISCUSSION OF POLYMERIC SEALS WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Sterilization (Ref. P. 3-5	Temperature soak at 270°F maximum for 36 hours may cause degradation of polymeric materials.	Several polymeric compounds are available for this temperature range. However, limited information on the compatibility of materials with propellants at this temperature exists.
Vacuum of Space (Ref. P. 3-36	Loss of unreacted additives or other constituents in polymers may aggravate leakage or reduce initial compression required for sealing.	Use materials with minimum number and quantity of additives and modifiers. Complete cure of plastics must be obtained by extended time or elevated temperature. Post curing required to ensure the elimination of unreacted, low molecular fractions. Consider preconditioning in vacuum at elevated temperatures to reduce potential loss of material to space.
Time (Ref. P. 3-76)	Time will aggravate the effects of vacuum, radiation and planetary atmospheres on the polymeric materials.	1. See comments under Vacuum. 2. Adequate radiation shielding must be provided. 3. Substitute metal seals, if possible.
Lunar Atmosphere	Lunar atmosphere estimated to be 10^{-14} mm Hg. Loss of unreacted additives or other constituents in polymers may aggravate leakage or reduce initial compression required for sealing.	See comments under Vacuum of Space.
Lunar and Planetary Dust	Rock flour to 0.3 mm dia. of high silica content dust exists assuming large clouds on loading and launch. For valve seats exposed to the cloud, contamination leading to possible leakage can occur.	Shielding must be provided to exclude the dust.

TABLE 5-12 ANALYSIS TABLE

DISCUSSION OF SOLENOID ACTUATORS WITH APTITUDE RATING OF 1

PARAMETER	**RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS**	NATURE OF PROBLEM
Space & Planetary Maintenance	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5- 13 ANALYSIS TABLE

DISCUSSION OF SOLENOID ACTUATOR WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Operating Temperature (Ref. P. 3-17)	Operating temperature of flow media in the range from $200^{\circ}F$ to $2000^{\circ}F$. High temperatures cause breakdown of insulation materials and will cause a decrease in the magnetic properties if the materials reach the curie point.	The normal allowable temperatures of some magnet wire insulators range from $220^{\circ}F$ to $482^{\circ}F$. Other high temperature magnetic wire insulators not yet thoroughly tested are: a) Anodize aluminum wire $800^{\circ}F$. b) Ceramic-insulated nickle plated copper wire $930^{\circ}F$ to $1100^{\circ}F$. For higher operating temperatures thermal cooling is necessary.
Weight (Ref. P. 3-20)	Solenoid actuators are suitable for low force requirements. Weight becomes excessive when high forces are required.	Substitute pneumatic or hydraulic actuators for high force requirements.
Power Requirements (Ref. P. 3-23)	Power requirements are excessive for high forces.	Substitute pneumatic or hydraulic actuators.
Vacuum of Space (Ref. P. 3-36)	Loss of unreacted additives or other constituents in polymer used in insulation which may cause changes in dielectric properties.	1. Use materials with minimum number and quantity of additives and modifiers. Complete cure of plastics must be obtained by extended time or elevated temperature. Post curing required to ensure the elimination of unreacted, low molecular fractions. Consider preconditioning in vacuum at elevated temperatures to reduce potential loss of material to space. 2. Use hermetic seal solenoid.

TABLE 5-13 ANALYSIS TABLE

DISCUSSION OF SOLENOID ACTUATOR WITH APTITUDE RATING OF 2 (Cont'd)

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Radiation (Ref. P. 3-50)	Van Allen Belt Dosage for long term orbital flight degrades most polymers. May also degrade electrical properties of materials, e. g., dielectric strength of insulators.	A problem exists where shielding is impractical because of the weight penalty. May choose metal-ceramic magnet wire insulators.
Temperature in Space (Ref. P. 3-79)	Temperature may range from extremely high to extremely low depending on space mission or orbit and the heat generated internally in the space vehicle.	Thermal protection can be provided. Select coatings or thermal shields with optimum α / ε ratio.
Meteoroids (Ref. P. 3-91)	Meteoroid impact may puncture the hermetically sealed casing or solenoid causing failure.	Shielding can be provided by bumpers or other spacecraft structures.
Lunar Atmospheric Pressure	Lunar atmospheric pressure is approximately 10^{-14} mm Hg. Can cause loss of unreacted additives or other constituents in polymeric materials used in insulation.	Use materials with minimum number and quantity of additives and modifiers. Complete cure of plastics must be obtained by extended time or elevated temperature. Post curing required to ensure the elimination of unreacted, low molecular fractions. Consider preconditioning in vacuum at elevated temperatures to reduce potential loss of material to space.
Venus and Jovian Atmospheres	Venus atmospheric pressure is estimated at 16 earth atmospheres composed 95% H_2 and 5% CO_2. Jupiter atmospheric pressure is estimated at several thousand psi and composed of CH_4 and NH_3.Atmosphere may cause dielectric changes in insulation use in solenoids exposed to vacuum previous to planet re-enter. High pressures may cause collapse of solenoid housing.	Use hermetically sealed units with positive pressure in coil housing or select metal-ceramic type magnet wire insulators.

TABLE 5-13 ANALYSIS TABLE

DISCUSSION OF SOLENOID ACTUATORS WITH APTITUDE RATING OF 2 (Cont'd)

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Lunar and Planetary Dust	Rock flour to 0.3 mm dia. of high silica content dust. For exposed actuators damage to the actuator bearings may occur.	Hermetically seal unit or provide other means of bearing support such as flexure pivots.

TABLE 5-14 ANALYSIS TABLE

DISCUSSION OF PNEUMATIC ACTUATORS WITH APTITUDE RATING OF 1

PARAMETER	**RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS**	NATURE OF THE PROBLEM
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5-15 ANALYSIS TABLE

DISCUSSION OF HYDRAULIC ACTUATOR WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future space craft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.
Lunar and Planetary Temperatures (Ref. P. 3-79	Temperatures from $-243^{\circ}F$ to $620^{\circ}F$ are estimated. These temperatures could either freeze or boil liquid used in actuator, causing permanent damage.	Hydraulic actuators operating at these extreme temperatures do not appear to be within the present state of the art.

TABLE 5-16 ANALYSIS TABLE

DISCUSSION OF ELECTRIC MOTOR ACTUATOR WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5-17 ANALYSIS TABLE

DISCUSSION OF ELECTRIC MOTOR ACTUATOR WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Vacuum of Space (Ref. P. 3-36)	Loss of unreacted additives or other constituents in polymers used in insulation which may cause changes in dielectric properties.	1. Use materials with minimum number and quantity of additives and modifiers. Complete cure of plastics must be obtained by extended time or elevated temperature. Post curing required to ensure the elimination of unreacted, low molecular fractions. Consider pre-conditioning in vacuum at elevated temperatures to reduce potential loss of material to space. 2. Hermetically seal motor to eliminate effect.
Radiation (Ref. P. 3-50)	Van Allen Belt Dosage for long term orbital flight degrades most polymers. May also degrade electrical properties of materials, e.g., dielectric strength of insulators.	A problem exists where shielding is impractical because of the weight penalty. May choose metal-ceramic magnet wire insulators.
Temperature in Space (Ref. P. 3-79)	Temperatures may range from extremely high to extremely low depending on space mission or orbit and the heat generated internally in the space vehicle.	Thermal protection can be provided. Select coatings or thermal shields with optimum α / ε ratio.
Meteoroids (Ref. P. 3-91)	Meteoroid impact may puncture the hermetically sealed casing or solenoid causing failure.	Shielding can be provided by bumpers or other space craft structures.
Lunar Atmospheric Pressure	Lunar atmospheric pressure is approximately 10^{-14} mm Hg. Can cause loss of unreacted additives or other constituents in polymeric materials used in insulation.	See 1. under Vacuum of Space

TABLE 5-17 ANALYSIS TABLE

DISCUSSION OF ELECTRIC MOTOR ACTUATOR WITH APTITUDE RATING OF 2 (Cont'd)

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Venus and Jovian Atmospheres	Venus atmospheric pressure is estimated at 16 earth atmospheres composed 95% N_2 and 5% CO_2. Jupiter atmospheric pressure is estimated at several thousand psi and composed of CH_4 and NH_3. Atmosphere may cause dielectric changes in insulation use in motors exposed to vacuum previous to planet re-enter. High pressures may cause collapse of motor housing.	Use hermetically sealed units with positive pressure in coil housing or select metal-ceramic type magnet wire insulators.
Lunar and Planetary Dust	Rock flour to 0.3 mm dia. of high silica content dust.For exposed actuators, damage to the actuator bearings may occur.	Hermetically seal all units.

TABLE 5-17 ANALYSIS TABLE

DISCUSSION OF ELECTRIC MOTOR ACTUATOR WITH APTITUDE RATING OF 2 (cont'd)

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Weight (Ref. P. 3-20)	Motors are relatively heavy when light actuation forces are required.	Substitute solenoids or fluid actuators for light force applications.
Power Requirements (Ref. P. 3-23)	Power requirements for motors are relatively high.	Limit use of motors to high force applications.
Response (Ref. P. 3-31)	Response of motors is inherently low, especially when used in conjunction with gear trains.	Use other actuators where high response is required.

TABLE 5-18 ANALYSIS TABLE

DISCUSSION OF SQUIB ACTUATOR WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF PROBLEM
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5-19 ANALYSIS TABLE

DISCUSSION OF DRY LUBRICANTS WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Liquid and Gas Media (Ref. P. 3-2)	Chlorine trifluoride, fluorine, bromine pentafluoride and vapors thereof may react with lubricants.	A dry film lubricant is unavailable for use with these propellants. No information is available on compatibility with pentaborane.
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5-20 ANALYSIS TABLE

DISCUSSION OF DRY LUBRICANTS WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Operating Temperature (Ref. P. 3-17)	Decomposition of MOS_2 at $1800^{\circ}F$ occurs. Life expectancy of 45 days is expected when exposed to vacuum at $1800^{\circ}F$. High temperature service to $1800^{\circ}F$ considered.	Use dry lubricants utilizing ceramic bonding. NASA currently investigating calcium fluoride solid lubricants.
Vacuum of Space (Ref. P. 3-36)	Material may be lost when used over extended periods of time. Rate of loss is aggravated by wear. Replenishment is not possible as in liquid lube systems.	Reduce exposed surfaces to vacuum and bearing loads and speeds. Use in moderate temperature environments. May substitute plastics or use flexure supports where applicable.
Planetary Dust	Assumed particle range from rock flour to .3 mm dia. Dust could abrade and remove coating.	Shielding must be provided to exclude the dust.

TABLE 5-21 ANALYSIS TABLE

DISCUSSION OF LIQUID LUBRICANTS AND GREASES WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Liquid and Gas Media (Ref. P. 3-2)	Chlorine trifluoride, fluorine, hydrogen and bromine pentafluoride and their associated vapors may react with liquid lubricants.	No liquid lubricants or greases known to be compatible with these propellants. No information available on compatibility with pentaborane.
Operating Temperature (Ref. P. 3-17)	Temperatures considered are from 600°F to 2000°F. High temperatures will cause destruction of lubricants.	No liquid lubricants or greases known to exist for use at these temperatures.
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.
Venus Temperature	Temperature of Venus atmosphere assumed from 620°F to 1150°F. High temperature will cause destruction of lubricants.	No liquid lubricants or greases known to exist for use at these temperatures.
Jupiter Radiation Belts	Jovian Radiation Belt assumed to be several times more intense than the earth radiation belts.	A problem exists where shielding is impractical because of the weight penalty incurred. Insufficient data exists to make an accurate analysis of the effects of the Jovian radiation on lubricants.

TABLE 5-22 ANALYSIS TABLE

DISCUSSION OF LIQUID LUBRICANTS AND GREASES WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Vacuum of Space (Ref. P. 3-36)	A loss of lubricants owing to tendency of lubricants to evaporate in vacuum over extended periods of time.	Liquid lubricants and greases may be used for limited time. For longer durations substitute dry films or metal coatings such as silver and gold. Some plastics may be used. Use other means of bearings supports such as flexure pivots.
Radiation (Ref. P. 3-50)	At exposures from 10^7 to 10^9 Roentgens changes such as increase in acidity, viscosity and tendency to foam are noted. Metallic soap greases harden and solidify under continued exposure.	Use petroleum lubricants (little damage noted at 10^8r). Aromatic hydrocarbons exhibit very little change up to 10^8r. Provide as much shielding as possible for materials in the Van Allen Belts. For worst radiation exposure in belts .06 mils aluminum shielding is adequate for 2 months duration.
Zero Gravity (Ref. P. 3-75)	Normal gravity for lubrication systems cannot be used.	Use pressure fed systems or capillary systems. Substitute dry films, metal coatings or plastics.
Time (Ref. P. 3-76)	Time will aggravate the effects of vacuum and radiation stated above.	Same comments apply as in vacuum and radiation stated above.
Lunar Atmosphere	Lunar atmospheric pressure is approximately 10^{-14} mm Hg. Lubricants will evaporate at this pressure for extended periods of time.	Liquid lubricants may be used for limited duration of time. For longer durations substitute dry films or metal coatings such as silver and gold. Some plastics may be used. Use other means of bearing supports such as flexure pivots.
Lunar and Planetary Dust	Planetary dust assumed consist of rock flour to 0.3 mm dia. particles.	Shielding must be provided to exclude the dust.

TABLE 5-23 ANALYSIS TABLE

DISCUSSION OF AN FLARE AND MS FLARELESS FITTING WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed. Possibility of cold welding or seizure of parts because of exposure to vacuum may require new design concepts.

TABLE 5-24 ANALYSIS TABLE

DISCUSSION OF AN FLARE AND MS FLARELESS FITTING WITH APTITUDE RATING OF 2

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	QUALIFICATION
Weight (Ref. P. 3-20)	On a relative basis these fittings are much heavier than welded connector.	Substitute welded connection if possible and if weight requirements indicate need.
Leakage (Ref. P. 3-24)	Leakage can occur because of poor quality control in manufacturing and assembly procedure.	100% inspection of parts required. MS fittings required skilled technicians for assembly. May substitute welded connection or use soft "nose" (e.g., copper or plastic) on AN flares.

TABLE 5- 25 ANALYSIS TABLE

DISCUSSION OF WELDED FITTINGS WITH APTITUDE RATING OF -1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF PROBLEM
Space and Planetary Maintenance	Repairs in space and on planets will be required on future space vehicles.	Techniques for repair in space of welded equipment are not known. New design concepts will be required.

TABLE 5- 26 ANALYSIS TABLE

DISCUSSION OF BOLTS AND SCREWS WITH APTITUDE RATING OF -1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF PROBLEM
Space and Planetary Maintenance (Ref. 3-28)	Repairs in space and on planets will be required on future space vehicles.	Techniques for repair in space and on planets have not been developed. Possibility of cold welding or seizure of parts because of exposure to vacuum may require new design concepts.

TABLE 5-27 ANALYSIS TABLE

DISCUSSION OF FILTERS WITH APTITUDE RATING OF 1

PARAMETER	RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS	NATURE OF THE PROBLEM
Operating Temperature (Ref. P. 3-17)	Filters are required for products of combustion gases at temperatures of 1700°F to 2000°F.	Filters are not available for this operation in this range. Maximum temperature possible for short runs is approximately 1700°F.
Space and Planetary Maintenance (Ref. P. 3-29)	Repairs and maintenance in space and on planets will be required on future spacecraft.	Techniques for effecting repairs or replacements in space and on planets have not been developed.

TABLE 5-28 ANALYSIS TABLE

DISCUSSION OF FILTERS WITH APTITUDE RATING OF 2

PARAMETER	**RELATIONSHIP OF PARAMETER AND EFFECTS ON COMPONENTS**	QUALIFICATION
Contamination (Ref. P. 3-27)	Filters may contain residual dirt from manufacturing processes which may subsequently be dislodged, causing system contamination.	Specify required cleanliness level of filter "as received". Contaminants in excess of absolute rating of filter should be cause for rejection.
Vibration and Shock (Ref. P. 3-33)	Elements may be mounted in a manner to permit movement in housing, creating a bypass for fluid under vibration or shock loads. Vibration and shock may dislodge loose particles of manufacturing dirt in filter.	Design must preclude possibility of bypass through movement of element. Receiving inspection tests should include vibration test simultaneous with flush to insure all loose particles have been removed.

VI. NEW DESIGN CONCEPTS

One of the goals of the program was to develop new concepts where such requirements were indicated by the study. Within the limitations of time and money available under the contract, preliminary investigations were made in three areas, as follows:

1) Fusion Valve

A zero leak, contamination insensitive multicycle valve was found to be an unfulfilled requirement for space vehicles. Accordingly, a brief development program was conducted which resulted in the production and test of a prototype valve having the potential to meet the above requirements.

2) Seal Material Experiments

Seal materials available are subject to performance limitations, particularly with respect to permeability and cold flow characteristics. A material was developed with greatly improved cold flow properties, and a study indicated that means are available to reduce or eliminate the permeability of the formulation to N_2O_4.

3) "In-Tank" Design Study

The analysis of problems that may be encountered by valves on space vehicles suggested the concept of installing certain of the valves inside the tanks to afford some protection from the environments and to improve some functional characteristics. Accordingly, an analysis of the potential advantages and disadvantages was made.

The details of these three studies are presented in this section.

FUSION VALVE

Existing low or zero leak valves were examined and it was found that squib operated valves or burst diaphragm valves approached or met the requirement of zero leakage for extended duration. Both types, however, are normally limited to a single actuation. (Some squib units having 6 cycles of operation are available). Squib valves have additional disadvantages such as degradation from radiation and possible inadvertent firing caused by high energy radars. A development program was therefore undertaken to produce a unit having the following capabilities:

1. Seal any fluid at substantially any working pressure
2. Maintain zero leakage for very extended periods of time
3. Be capable of many cycles of operation
4. Be relatively insensitive to contamination
5. Be operable at temperatures up to 1000°F

An examination of existing closure mechanisms reveals that each fails to meet the requirements in one respect or another. Soft seats are eliminated by temperature considerations, and in addition no known plastics are compatible with fluorine. Metal to metal seats can be produced that will give excellent leakage control, approaching zero depending upon the quality of the seating surfaces. However, the slightest contamination from the fluid, the system, or from the moving parts within the valve itself can raise the leakage rates very quickly to an unacceptably high level. Accordingly, a new approach in a sealing method was sought.

It was reasoned that one method that might satisfy the requirements would involve fusing the mating parts of the valve together with a solder, through the application of heat from an electrical heating element. De-mating would be accomplished by a re-application of heat to raise the solder to the melting point, at which time the parts could be separated. Provisions would have to be made to prevent the liquid solder from blowing out of the valve closure mechanism, and to maintain a reservoir of solder to insure a seal at each application.

A fixture was manufactured to test the basic concept of the seal, and consisted of a bushing machined from porous sintered bronze material and a short piece of .500 dia cold rolled steel. The bushing was saturated with 50-50 lead tin solder and the center portion of the shaft was tinned with the same alloy. When the assembly was heated by a torch and allowed to cool it was observed that good fusion between the parts was effected. Numerous cycles were conducted in which the fixture was heated and the shaft and bushing were separated. The parts were allowed to cool, after which heat was again applied to fuse the bushing and shaft together again. In each case the quality of the bond appeared to be good, and design layouts of a prototype valve were made. Figure 6-2 shows the valve assembled, Figure 6-3 shows the valve disassembled. The initial valve consisted of a movable shaft, sealing ring, heating element and housing. An isometric drawing and explanation of the operation is presented in Figure 6-1. Details of these individual components are presented below.

Heating Element

The basic requirements of the heating element for the valve were as follows:

- Operation with 28v dc.
- High wattage per unit volume
- Low heat loss to the valve housing
- Efficient transfer of heat to the sealing ring and shaft
- High temperature insulation for the element wire

The heating element consisted of a suitable length of resistance wire insulated with a specially-developed ceramic insulation. The wire was wound around the outside portion of the sintered bronze sealing ring, after which it was encapsulated by a steel bushing. The ceramic insulation permitted an extremely wide range of power inputs to the unit as demonstrated in one test in which the assembly was brought to a red heat momentarily without damage to the electrical unit. Heat loss to the housing is prevented by an annular gap between the element and the housing. The intimate contact between the seal bushing and the wire coils provided efficient transfer of heat from the wire and through the wall of the bushing to the solder.

Seal Bushing

The seal bushing was machined from a bar of sintered bronze material and provided a flanged section on the outer periphery to retain the heating element, and a series of grooves on the inner periphery to provide additional reservoirs of solder during the actuation of the valve. Figure 6-4 shows the bushing without heating element installed, and the element encapsulating ring.

The choice of solder is dictated by such considerations as the operating temperature, operating pressure, flow rate, material of the bushing and desired time of operation. In the experiments conducted on this valve, approximately 18 alloys were tested for such characteristics as viscosity, plastic range, capillarity, oxidization rate and wettability of the valve closure materials.

Shaft Assembly

The shaft assembly is made of stainless steel and incorporates a tinned bronze ring near the center of the section. The shaft is hollow and has a series of co-planar holes located to permit alignment with the annular discharge section of the housing when the valve is moved to the open position.

Housing

The housing is a stainless steel shell with provisions for mounting the sealing ring in which the shaft slides. An end cap with an 'O' ring groove and a retainer for the sealing ring completed the housing assembly. Rubber 'O' rings were used in the prototype because of the necessity of numerous assembly and disassembly operations during development.

Test Results

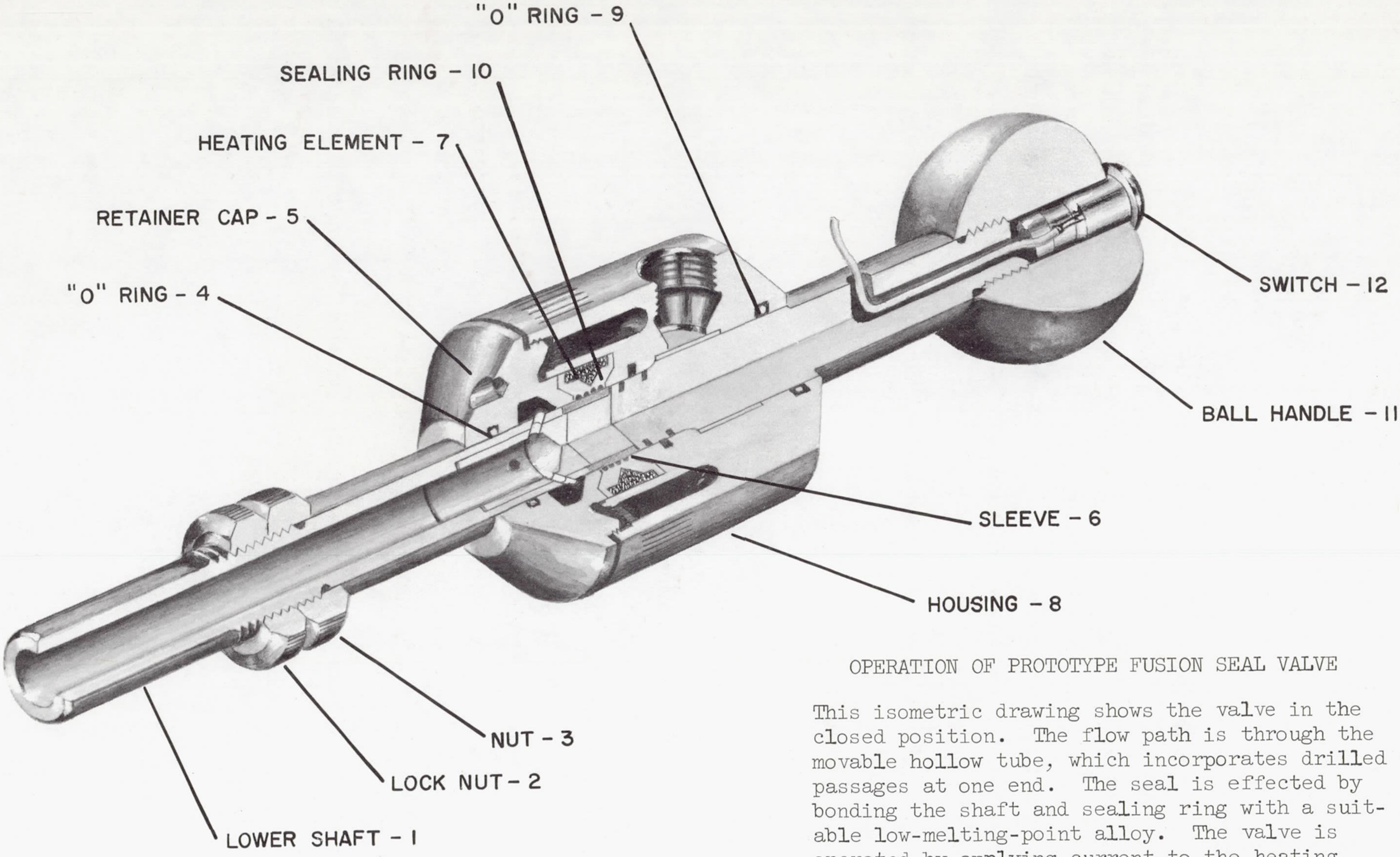
Limited testing was accomplished on the program and consisted primarily of cycling the valve from open to closed and closed to open under pressures varying from 15 psi to 1200 psi. The maximum number of consecutive cycles that were made was 25. No failure or significant loss of solder was observed during this test. The maximum pressure applied during a cycle was 1200 psi. No measurable leakage was observed in any of the above tests. Figure 6-5 shows the test setup.

The minimum time required to open the valve was approximately 3 seconds. Power levels ranging from 200 to 1000 watt seconds were used for operation.

Conclusions

Tests on a prototype fusion valve indicate that a zero leak, multi cycle, contamination insensitive valve is feasible. A wide variation of valve and actuator configuration is possible for use on systems operating at substantially any pressure. Many refinements of the present prototype are possible including one in which the valve seal would be sheared by impact from the actuator, thus providing a very rapid opening time if desired, and reducing the amount of electrical power required for actuation. Other possible improvements include a large reduction in the mass of the heating element with a consequent increase in response and decrease in power consumption.

A patent disclosure on this invention has been filed by the STL Patent Office.



OPERATION OF PROTOTYPE FUSION SEAL VALVE

This isometric drawing shows the valve in the closed position. The flow path is through the movable hollow tube, which incorporates drilled passages at one end. The seal is effected by bonding the shaft and sealing ring with a suitable low-melting-point alloy. The valve is operated by applying current to the heating coil, which melts the alloy and permits shifting the valve shaft to a position where the drilled shaft passages are coincident with mating passages in the body.

FIGURE 6-1 FUSION VALVE

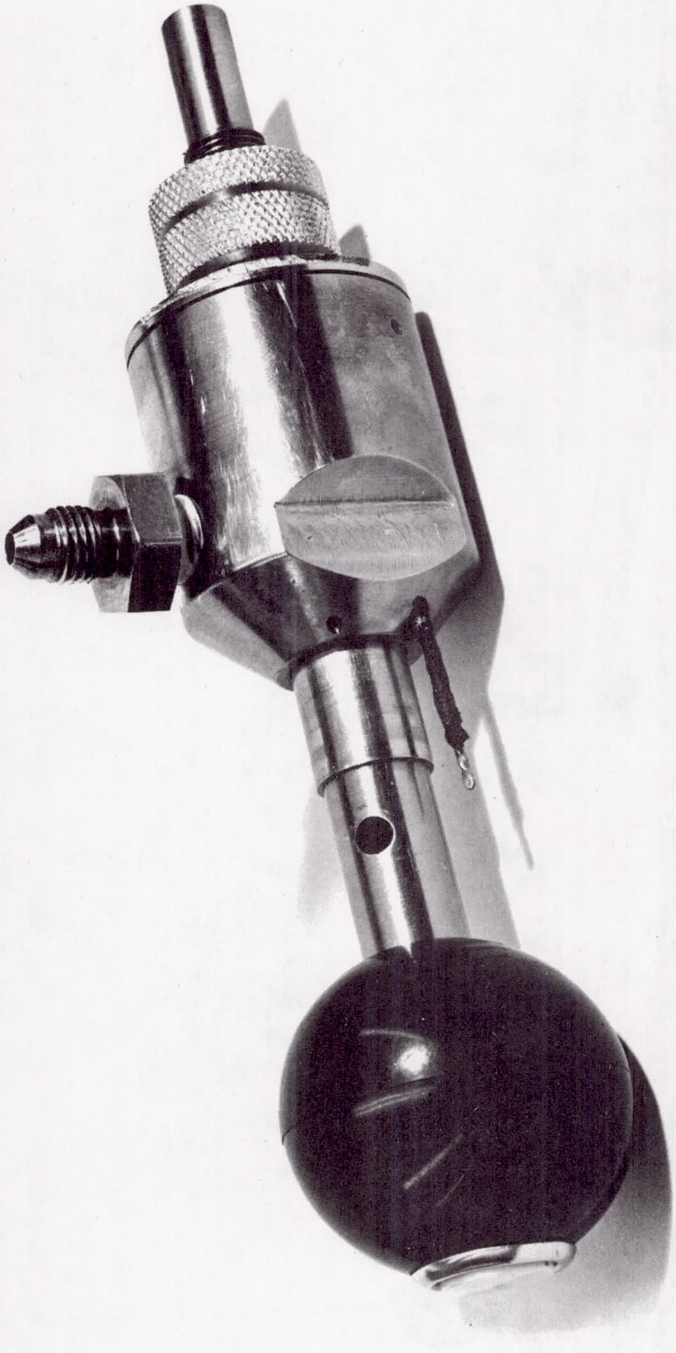


FIGURE 6-2 SOLDER VALVE - ASSEMBLED

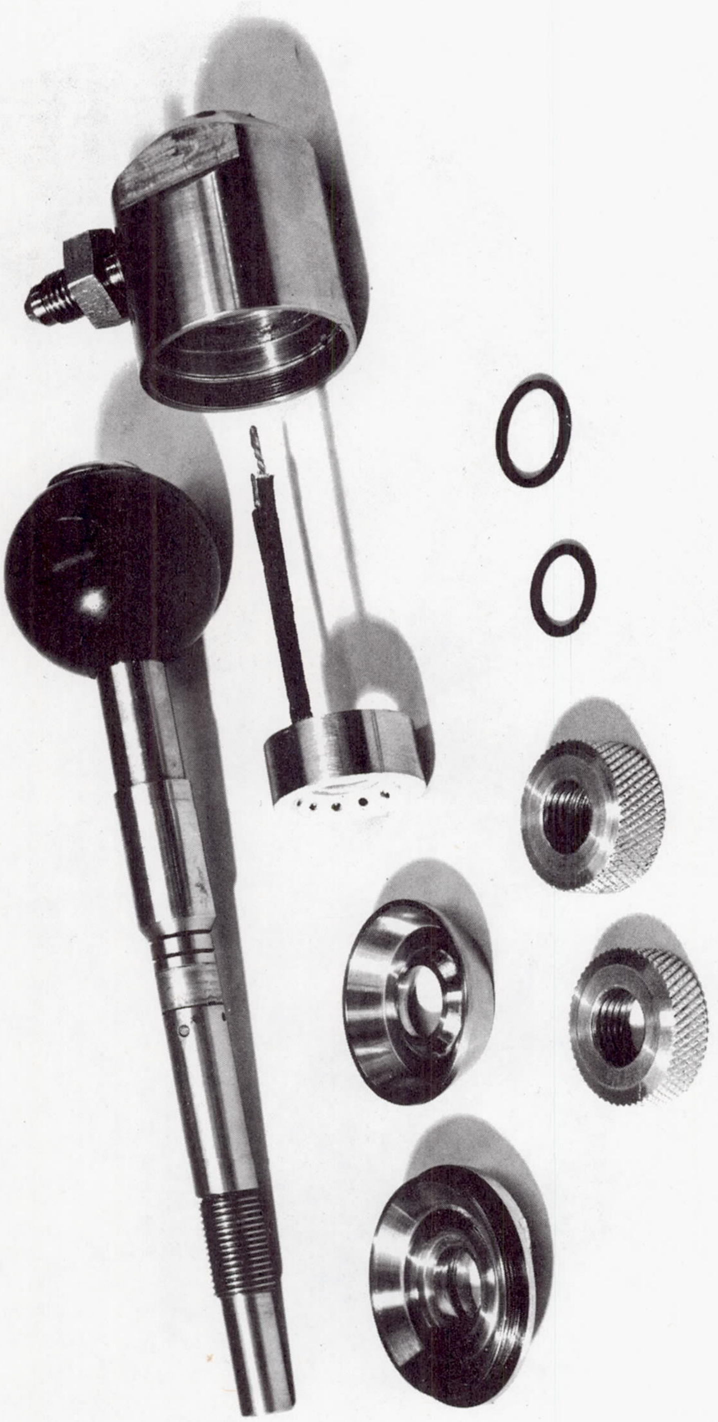


FIGURE 6-3 SOLDER VALVE - DISASSEMBLED

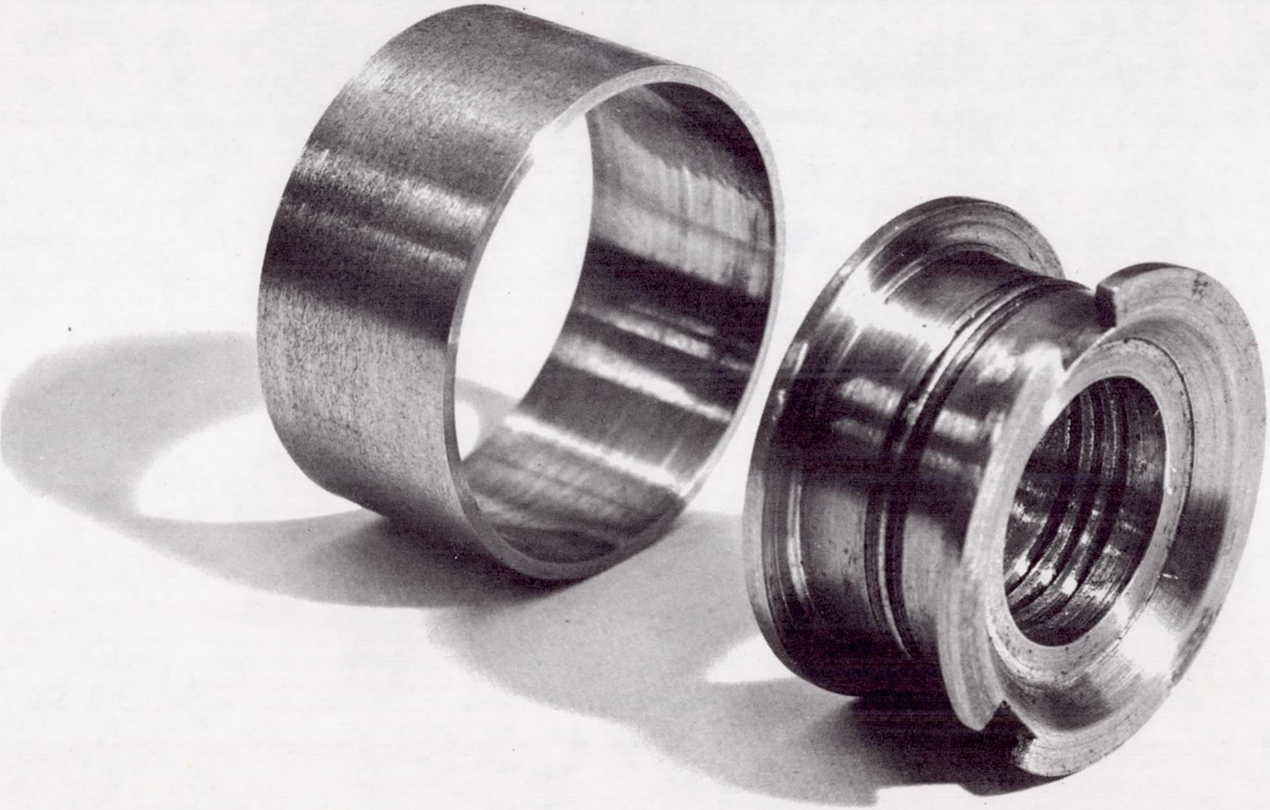


FIGURE 6-4 BUSHING WITHOUT HEATING ELEMENT INSTALLED,
AND ELEMENT ENCAPSULATING RING

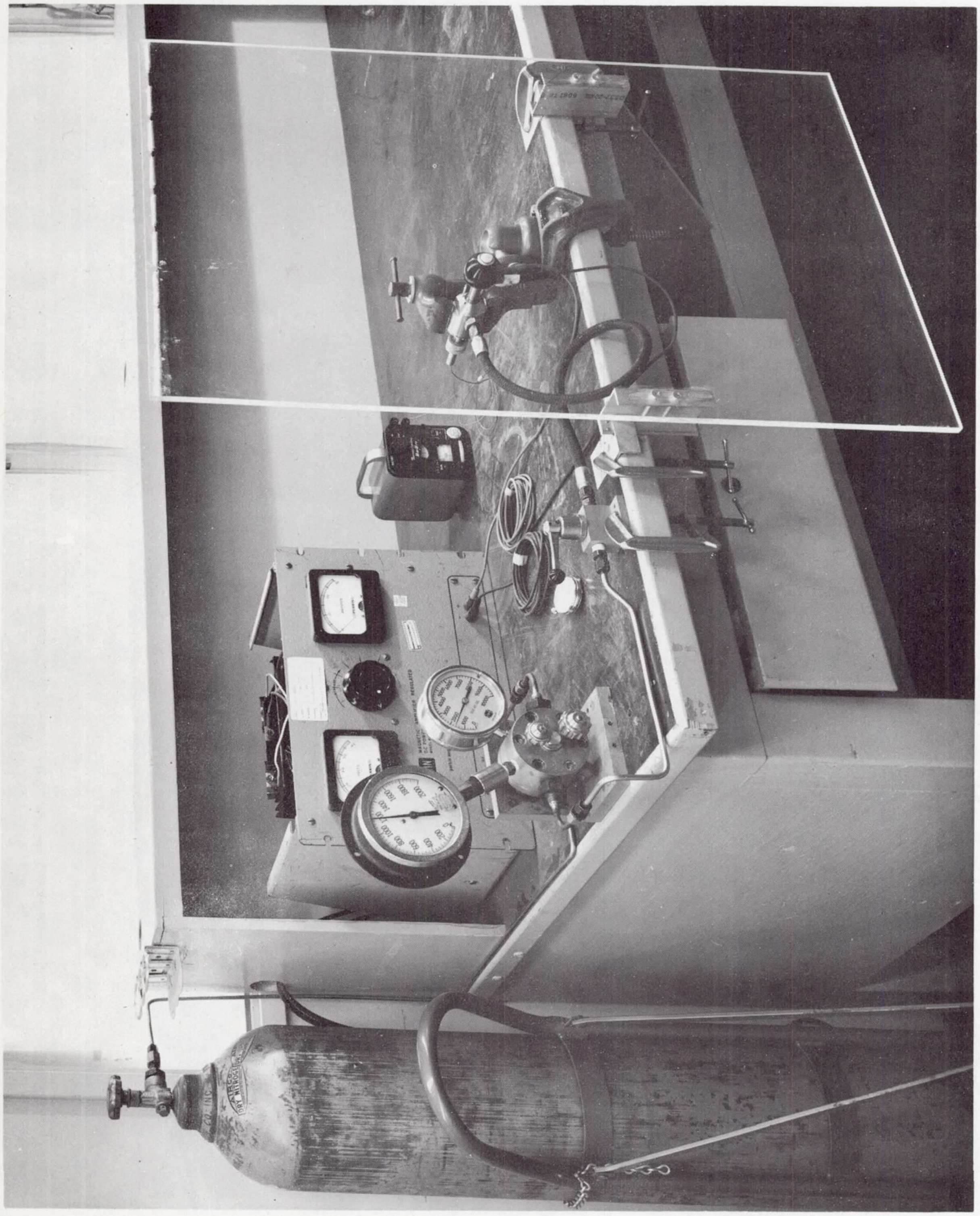


FIGURE 6-5 TEST SETUP FOR SOLDER VALVE

SEAL MATERIAL EXPERIMENTS

Teflon is an excellent engineering material and finds many applications in valves and other components used on spacecraft. However, two of its characteristics, the tendency to cold flow under load and its permeability to some fluids, especially N_2O_4, preclude its use in some cases. Therefore, a study was conducted to determine if a formulation could be produced that would have improved cold flow and permeability characteristics without sacrifice of other qualities.

A search of the literature disclosed that many mixtures of Teflon and other compounds, e.g., glass fibers and metal powders have been produced, but the test data available indicated that further improvements were needed to reduce the cold flow characteristics to acceptable limits.

Experiments were conducted in which Teflon powder and steel wool fibers were mixed and compacted into discs of 2.0 in. dia x .08 thick. Pressures in the order of 30,000 psi were used in the molding operation, and some of the samples were sintered while under pressure at 740°F.

A test fixture was manufactured to determine the permanent set resulting from load, and several discs for two of the mixtures were tested. The results are as follows:

Using a unit bearing stress of 2000 psi over a 24 hour period, the permanent set varied from .5% for a mixture of 90% steel and 10% Teflon to 3% for a mixture of 20% steel and 80% Teflon. For comparison, a permanent set of 6% for a mixture of 60% bronze and 40% Teflon represents the best obtainable commercial compound.

A second test fixture was used to evaluate the effectiveness of the material for use in gasketing. The fixture clamped a ring of the material measuring 2.00 in. dia x .10 in. land width x .08 in. thick between two flanges. Nitrogen pressure of 2000 psi was applied to the fixture for a period of 24 hours, after which a leakage measurement was made. The pressure was then reduced to zero, and then raised again to 2000 psi. The test was continued in this manner for 14 days. No leakage was recorded, and there was no observed tendency of the material to flow.

The literature search also disclosed that some experiments had been conducted with Teflon and gold foil in an attempt to reduce the permeability of Teflon to N_2O_4.* On the basis of the favorable results obtained in this work, a procedure was devised to disperse finely divided gold powder in the mixture of the Teflon and steel wool. Unfortunately, procurement delays prevented the conclusion of this portion of the development.

It must be noted that the tests conducted on the sealing material were necessarily minimum in nature because of the time limitations of the program. Although the test results obtained were very encouraging, much additional work is required in this area.

A patent disclosure on this development has been filed by the STL Patent Office.

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* Quantum, Incorporated,
Wallingford, Connecticut

"IN-TANK" DESIGN STUDY

A study was made to determine the advantages and disadvantages of locating certain spacecraft valves inside the propellant and pressurization tanks rather than outside as is conventionally done. The advantages and disadvantages of this plan are as follows:

ADVANTAGES

External leakage through the valve housing seals or through the tubing connectors would be zero. While external leakage through a well designed housing is not common, leakage difficulty with the various tubing connectors is quite common so this consideration is of significance.

Contamination potential is reduced by the elimination of tubing and fittings upstream of the valve. Threaded fittings are a common source of contamination unless care is used in assembly.

Exposure to the several hazards of the space environments, e.g. vacuum, micrometeoroids, and radiation is reduced or eliminated.

More usable space would be available with the valve installed inside the tank than outside. For an internal installation the volume required would be precisely equal the volume of the valve, and if this volume were significant, the volume of the tank would have to be increased accordingly. An external installation requires brackets and the valve location may be such as to make portions of the surrounding area unusable because of lack of accessibility.

Stable temperatures would be provided for the valve which would simplify the design as the operating temperature would be known within close limits. In the case of solenoid valves operating in cryogenic fluids, the power requirements would be very significantly less because of the lower resistance of the coil wire. A smaller coil could be employed if it were known that the solenoid would be actuated under low temperature conditions.

Pressure drop characteristics would be improved because of the reduction in entrance losses to the valve due to the absence of upstream tubing, fittings, changes of fluid direction within the valve, etc.

Weight of the valve system would be reduced because of the absence of the valve housing and the tubing fittings. In place of the housing, a guide or support would have to be provided for the closure mechanism, but this assembly would be significantly lighter than a complete housing. Greater weight savings are possible with higher pressure systems than with low pressure systems for the same valve size.

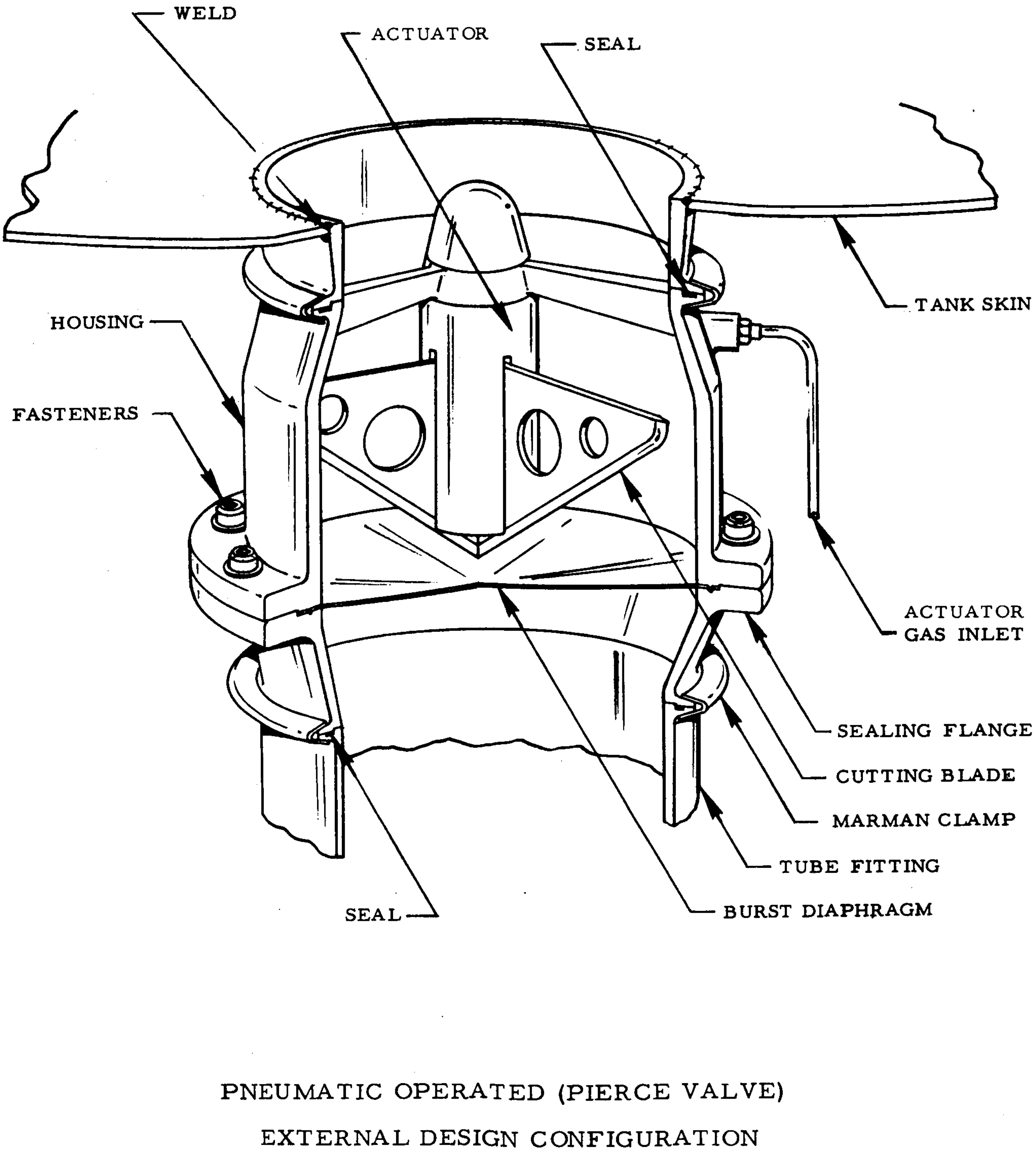
A study was made of the potential weight savings possible with the STL pierce diaphragm valve, assuming that it were modified for an internal tank installation, and a weight reduction of 37% was indicated. Figure 6-6 shows the valve mounted in the conventional manner, and Figure 6-7 shows the modified valve in an internal installation.

DISADVANTAGES

The most obvious disadvantage of an in-tank design is inaccessibility for maintenance. This would be especially true if a valve were installed in a tank prior to final assembly, for example installed inside a hemisphere after which the mating half is joined by welding. An alternative installation could be made in which the valve is mounted on a flange and the flange is then bolted to the tank. With this latter method, however, some of the weight savings would be lost and an even greater probability of leakage through the flange would exist than would leakage through the valve housing.

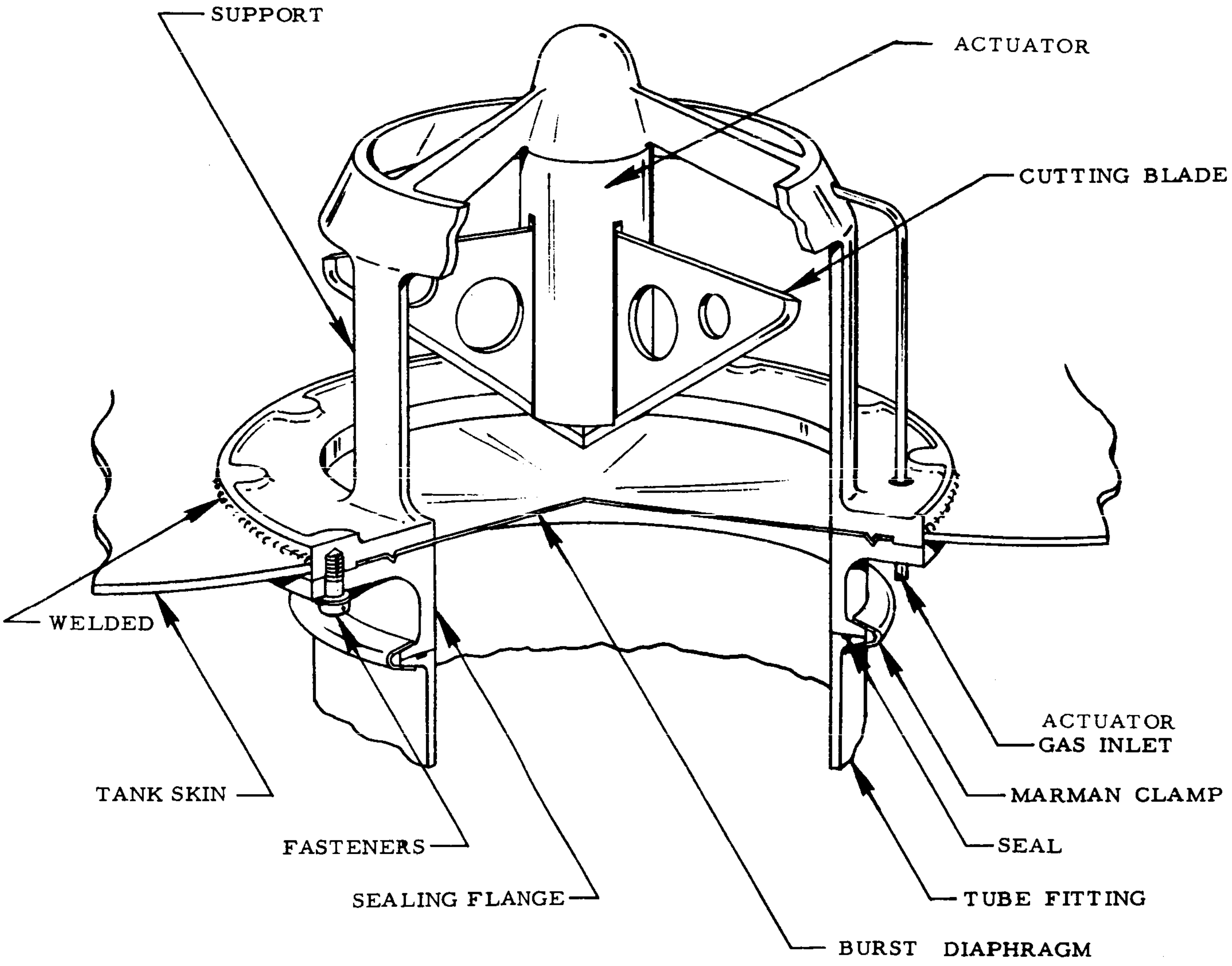
Only valves with a known high reliability should be considered for an in-tank installation and the greatest possible care would be taken to be certain that the unit was operating properly before the installation was made. In addition, the penalty that would be incurred if it became necessary to discard a tank because of a valve failure, would have to be considered. However, in many instances pressurization tankage consists of small spheres which can normally be removed readily, and in cases where this is true the risk does not seem to be great.

An additional penalty may be imposed if the qualification test procedures for the tank were altered because of the addition of the valve. For example, if vibration and shock tests were required of the valve it might be necessary to perform these tests with the valve in its normal mounting, i.e., in the tank. However, such a requirement is not considered to be of great consequence.



PNEUMATIC OPERATED (PIERCE VALVE)
EXTERNAL DESIGN CONFIGURATION

Figure 6-6



PNEUMATIC OPERATED (PIERCE VALVE)

INTERNAL DESIGN CONFIGURATION

Figure 6-7

APPENDIX

TABLE A-1

LIST OF PATENTS BY COMPONENT CATEGORY

VENT AND RELIEF VALVES

569,943
1,891,119
2,017,297
2,226,732
2,264,656
2,279,002
2,520,893
2,591,528
2,595,528
2,635,627
2,640,332
2,643,673
2,675,021
2,690,669
2,704,085
2,729,228
2,753,882
2,761,468
2,774,373
2,787,126
2,816,561
2,821,996
2,827,911
2,840,106
2,856,947
2,870,781
2,894,532
2,902,296
2,905,484
2,906,289
2,909,192
2,910,998
2,912,992
2,922,436
2,924,236
2,946,552
2,952,000
2,958,454
2,970,606
2,993,505
2,994,302
2,995,148
2,998,520
3,002,527

FILL VALVES

2,519,358
2,543,590
2,548,368
2,548,528
2,594,244
2,613,908
2,614,866
2,625,410
2,663,315
2,666,656
2,675,829
2,693,111
2,712,454
2,754,656
2,784,561
2,791,401
2,813,402
2,829,492
2,890,718
2,918,086
2,919,144
2,923,567
2,959,024
2,967,541

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

REGULATORS, HOT AND COLD GAS

2, 323, 838
2, 412, 490
2, 522, 913
2, 523, 826
2, 567, 224
2, 582, 088
2, 582, 626
2, 593, 557
2, 603, 235
2, 608, 985
2, 610, 859
2, 611, 218
2, 612, 019
2, 624, 980
2, 638, 292
2, 638, 924
2, 642, 701
2, 649, 115
2, 649, 773
2, 651, 147
2, 656, 848
2, 673, 422
2, 676, 612
2, 689, 583
2, 696, 083
2, 698, 568
2, 707, 378
2, 711, 187
2, 711, 754
2, 714, 895
2, 731, 980
2, 748, 569
2, 771, 905
2, 782, 801
2, 816, 570
2, 837, 108
2, 899, 979
2, 904, 069
2, 917, 066
2, 918, 080
2, 920, 859
2, 922, 434
2, 925, 092
2, 938, 540
2, 950, 733
2, 953, 150
2, 953, 152
2, 964, 304
2, 965, 128
2, 968, 161
2, 970, 609
2, 974, 679
2, 984, 251
2, 988, 108
2, 988, 883
2, 993, 506
2, 993, 507
2, 994, 505
3, 005, 466
3, 007, 481
3, 007, 492
3, 021, 684

ROTARY ACTION VALVES

2, 584, 161
2, 711, 185
2, 826, 202
2, 868, 499
2, 884, 946
2, 911, 008
2, 912, 219
2, 927, 767
2, 961, 214
2, 970, 805
2, 980, 392
2, 989, 990
2, 994, 504
3, 010, 471
3, 022, 039
3, 030, 655
3, 033, 911
3, 040, 777
3, 044, 493

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

VALVE STRUCTURES

1,860,891
2,183,312
2,394,852
2,395,113
2,456,402
2,482,261
2,515,644
2,518,880
2,528,134
2,536,597
2,536,598
2,544,421
2,544,423
2,548,430
2,551,113
2,551,114
2,555,082
2,555,085
2,558,483
2,563,022
2,563,028
2,576,678
2,580,908
2,599,104
2,602,293
2,610,064
2,616,373
2,624,360
2,627,876
2,687,614
2,687,646
2,695,496
2,718,899
2,722,100
2,731,980
2,742,921
2,749,884
2,760,335
2,770,251
2,770,255
2,794,318
2,918,929
2,927,767
2,935,844
2,939,281
2,946,186
2,958,184
2,970,430
2,986,880
3,001,365
3,036,593

FRANGIBLE VALVES

2,154,827
2,204,816
2,347,203
2,353,093
2,371,293
2,587,933
2,589,144
2,593,520
2,620,815
2,673,660
2,707,479
2,725,889
2,765,801
2,788,794
2,804,929
2,808,847
2,831,492
2,853,097
2,860,649
2,877,780
2,888,025
2,912,992
2,919,543
2,925,822
2,932,308
2,937,654
2,939,281
2,947,315
2,954,041
2,960,096
2,966,163
2,997,051
3,013,571
3,016,015
3,017,894
3,026,070
3,027,903
3,033,216
3,034,293
3,038,485
3,039,482
3,042,057

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

FLOW METERING VALVES

430,042
484,843
1,247,027
1,280,451
1,285,769
1,656,269
1,712,245
1,856,825
1,859,876
1,942,426
1,956,101
1,995,052
2,020,773
2,023,143
2,033,348
2,034,573
2,053,611
2,069,309
2,106,300
2,117,182
2,118,232
2,190,725
2,197,271
2,197,685
2,211,646
2,212,343
2,314,827
2,355,458
2,361,655
2,380,631
2,387,792
2,406,178
2,410,946
2,541,176
2,552,552
2,565,950
2,591,528
2,610,859
2,619,162
2,625,953
2,630,676
2,642,254
2,655,173
2,669,418
2,675,204
2,683,463
2,685,334
2,687,314
2,705,829
2,731,983
2,734,527
2,734,528
2,747,613
2,764,175
2,794,318
2,827,260
2,843,149
2,847,020
2,849,015
2,874,924
2,882,866
2,886,058
2,912,011
2,914,088
2,918,087
2,930,401
2,938,337
2,941,357
2,958,193
2,963,034
2,969,801
2,969,809
2,985,566
2,986,990
3,019,804
3,023,775
3,032,984

ACTUATORS, HERMETICALLY SEALED

2,723,108
2,762,601
2,770,255
2,776,105
2,831,326
2,844,168
2,852,038
2,856,151
2,880,620
2,888,037
2,916,061
2,918,221
2,932,203
2,942,622
2,962,040
2,964,289
2,981,515
2,982,516
2,986,372
2,989,283
3,006,375
3,009,479
3,026,082
3,027,916
3,030,065

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

MISC. SEAT CONSTRUCTION AND VALVE MATERIALS FOR CORROSIVE FLUID

801,458
1,213,513
1,456,088
1,466,171
1,804,438
1,813,122
1,844,780
2,003,293
2,048,858
2,062,781
2,078,903
2,088,838
2,133,983
2,169,194
2,210,046
2,345,693
2,415,475
2,454,160
2,467,313
2,525,831
2,535,953
2,539,106
2,584,161
2,595,671
2,665,874
2,675,204
2,688,462
2,693,337
2,695,628
2,696,967
2,701,119
2,713,987
2,716,421
2,725,211
2,727,715
2,729,420
2,735,645
2,736,645
2,741,453
2,762,601
2,771,900
2,776,104
2,792,845
2,810,397
2,822,824
2,845,248
2,853,097
2,865,596
2,868,499
2,875,978
2,886,283
2,893,684
2,903,236
2,903,564
2,904,065
2,905,197
2,926,884
2,929,606
2,961,214
2,965,123
2,973,008
2,987,295
3,026,899

FUSIBLE ACTION VALVES

1,864,380
2,144,125
2,181,523
2,302,029
2,402,826
2,569,554
2,620,815
2,637,333
2,666,448
2,668,412
2,702,179
2,723,108
2,729,221
2,731,803
2,741,084
2,765,802
2,791,239
2,843,052
2,859,758
2,860,649
2,873,754
2,903,006
2,919,710
2,925,247
2,929,225
2,942,615
2,945,504
2,962,035
2,965,116
2,971,521
2,992,017
2,997,052
2,998,018
3,008,479
3,015,337
3,035,609

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

VALVE SEAT STRUCTURES

801, 458
1, 216, 974
1, 709, 807
1, 721, 324
1, 804, 438
1, 950, 267
2, 035, 165
2, 078, 903
2, 210, 046
2, 290, 177
2, 302, 029
2, 398, 370
2, 399, 102
2, 403, 165
2, 412, 913
2, 418, 447
2, 429, 778
2, 484, 102
2, 518, 852
2, 525, 799
2, 590, 702
2, 643, 679
2, 657, 708
2, 662, 348
2, 670, 173
2, 685, 297
2, 715, 911
2, 716, 911
2, 722, 232
2, 726, 843
2, 727, 715
2, 736, 529
2, 761, 463
2, 768, 806
2, 771, 092
2, 778, 598
2, 784, 739
2, 788, 192
2, 792, 845
2, 800, 142
2, 819, 035
2, 819, 868
2, 822, 818
2, 829, 670
2, 833, 299
2, 839, 265
2, 840, 336
2, 844, 352
2, 845, 085
2, 852, 038
2, 854, 021
2, 860, 850
2, 863, 473
2, 890, 017
2, 893, 687
2, 895, 496
2, 907, 548
2, 917, 075
2, 918, 078
2, 918, 249
2, 921, 768
2, 927, 767
2, 928, 417
2, 928, 646
2, 930, 401
2, 934, 088
2, 934, 090
2, 934, 315
2, 938, 533
2, 938, 704
2, 939, 479
2, 940, 724
2, 942, 622
2, 944, 567
2, 946, 551
2, 947, 320
2, 952, 274
2, 959, 188
2, 960, 998
2, 962, 035
2, 963, 261
2, 966, 164
2, 966, 165
2, 969, 219
2, 970, 609
2, 971, 090
2, 979, 067
2, 982, 512
2, 983, 278
2, 985, 421
2, 985, 422
2, 985, 424
2, 989, 990
2, 994, 340
2, 994, 343
3, 002, 527
3, 006, 375
3, 009, 680
3, 009, 681
3, 010, 695
3, 011, 758
3, 018, 797
3, 022, 978
3, 025, 874
3, 026, 897
3, 027, 909
3, 029, 830
3, 029, 835
3, 032, 312
3, 035, 809
3, 038, 193
3, 038, 487

TABLE A-1 (Continued)

LIST OF PATENTS BY COMPONENT CATEGORY

SHUTOFF VALVES

152,844
328,370
342,801
408,706
481,332
982,195
1,138,284
1,662,289
1,834,038
1,845,135
1,856,505
1,859,932
1,998,239
2,050,750
2,181,219
2,206,370
2,357,795
2,362,984
2,400,570
2,410,404
2,436,411
2,449,481
2,453,766
2,471,880
2,472,056
2,476,175
2,477,566
2,496,711
2,526,221
2,576,985
2,577,613
2,580,649
2,584,161
2,599,103
2,608,342
2,644,313
2,695,628
2,749,081
2,749,925
2,762,602
2,771,900
2,776,104
2,792,845
2,805,040
2,841,167
2,865,596
2,883,145
2,893,684
2,902,249
2,903,249
2,919,543
2,930,187
2,930,401
2,930,575
2,934,090
2,935,844
2,937,656
2,939,281
2,946,554
2,964,053
2,969,218
2,974,681
2,974,682
2,980,177
2,983,286
2,985,424
2,986,004
2,987,295
2,988,321
2,994,338
3,002,525
3,007,674
3,015,201
3,021,671
3,021,857
3,024,803
3,028,874
3,030,772
3,032,312

TABLE A-2	VALVE TYPE												SERVICE							
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media	
3	x												x	x	x	x	x	x	x	
			x										x	x		x	x	x	x	
				x									x				x	x		
					x								x	x			x	x	x	
							x						x	x			x	x	x	
									x				x				x	x		
											x		x	x		x	x	x	x	
7			x										x			x	x	x		
							x						x			x	x	x		
									x				x			x	x	x		
8			x										x	x	x	x	x	x	x	
				x													x	x	x	
							x						x	x		x	x	x	x	
									x				x			x	x	x		
											x		x	x		x	x	x	x	
9				x									x	x	x	x	x	x	x	
					x								x	x		x	x	x	x	
13				x									x	x	x	x	x	x	x	
					x								x	x	x	x	x	x	x	
							x						x	x	x	x	x	x	x	
											x		x	x	x	x	x	x	x	
14	x												x	x	x	x	x	x	x	
					x												x		x	
											x		x	x	x	x	x	x	x	
15			x										x	x	x	x	x	x	x	
				x																
					x									x		x	x	x	x	
									x				x	x	x	x	x	x	x	
18			x										x		x	x	x	x	x	
					x								x		x	x	x	x	x	
							x						x		x	x	x	x	x	
									x				x		x	x	x	x	x	
											x		x		x	x	x	x	x	
19							x						x					x		
									x				x					x		

Table **A-2** Tabulation of Valves by Manufacturer, Type and Service

TABLE A-2	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
20	x												x	x		x	x	x	x
			x										x	x	x	x	x	x	x
					x									x		x	x	x	x
							x						x	x		x	x	x	x
									x				x	x		x	x	x	x
29			x										x			x	x	x	x
					x											x			x
							x									x	x	x	x
32							x						x	x	x	x		x	
									x				x	x	x	x		x	x
33					x								x	x		x	x	x	
							x						x	x	x	x	x	x	
											x		x	x		x	x	x	
34			x										x	x	x	x	x	x	x
				x									x	x	x	x	x	x	x
					x								x			x	x	x	
							x						x	x	x	x	x	x	x
									x				x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
35	x																		
			x										x	x		x	x	x	
				x									x	x		x	x	x	
							x						x	x		x	x	x	
											x		x	x		x	x		
37	x												x			x	x	x	
			x										x	x	x	x	x	x	x
				x												x	x	x	x
							x									x		x	
											x		x				x		
44		x											x	x					
							x						x	x		x	x	x	
								x									x	x	
45							x										x	x	
									x									x	
											x							x	
46									x				x				x	x	
											x		x				x	x	
												x					x	x	

TABLE A-2	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
48	x															x	x	x	x
49		x													x		x	x	
55	x												x	x		x	x		
							x							x		x	x	x	
									x					x				x	
57	x												x	x	x	x	x	x	x
			x										x	x	x	x	x	x	x
					x								x	x	x	x	x	x	x
							x						x	x	x		x	x	x
									x				x	x	x	x	x	x	x
59	x															x	x	x	
			x										x		x	x		x	x
							x						x		x	x		x	
									x				x		x	x		x	x
											x		x			x	x	x	
60							x											x	
									x				x					x	
61	x												x		x	x	x	x	x
			x										x		x	x	x	x	x
				x									x				x		x
					x								x		x	x	x	x	x
							x						x		x	x	x	x	x
									x				x	x	x	x	x	x	x
										x			x		x	x	x	x	x
												x	x	x	x	x	x	x	x
62												x	x	x	x	x	x	x	x
65			x										x				x		
							x						x			x	x	x	x
									x				x				x	x	
										x			x				x	x	
											x		x				x	x	
66	x															x	x	x	
			x										x	x		x	x	x	x
					x									x	x	x	x	x	
							x							x	x	x	x	x	
									x				x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
67										x					x		x	x	x
											x		x		x	x	x	x	

TABLE A-2	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
68											x		x				x	x	
69												x	x	x	x	x	x	x	x
81									x				x	x					
82			x										x	x					
							x												
83			x										x	x	x	x	x	x	x
							x						x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
85			x										x	x	x	x	x	x	x
					x										x		x	x	
							x								x		x	x	
91											x		x	x	x	x	x	x	x
93			x										x	x	x		x	x	
				x									x	x	x		x	x	
					x								x	x	x		x	x	
							x						x	x	x		x	x	
95	x												x	x	x	x	x	x	x
96	x												x	x	x	x	x	x	x
			x										x	x	x	x	x	x	x
					x								x	x		x	x	x	x
							x						x	x		x	x	x	x
									x				x	x	x	x	x	x	x
										x			x	x		x	x	x	x
											x		x	x	x	x	x	x	x
103			x										x	x		x	x	x	x
					x								x			x	x	x	x
									x				x				x	x	x
											x		x	x		x	x	x	x
105			x										x	x	x	x	x	x	x
							x						x	x		x	x	x	x
106			x										x	x		x	x	x	x
							x						x	x	x	x	x	x	x
									x				x	x	x	x	x	x	x
										x			x	x		x	x	x	x
											x		x	x	x	x	x	x	x

TABLE A-2

	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
109	x															x	x	x	x
			x										x	x		x	x	x	x
							x									x	x	x	x
110			x										x						
							x						x						
									x				x						
112					x								x	x	x	x	x	x	x
							x						x	x	x	x	x	x	x
										x			x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
												x	x	x	x	x	x	x	x
113			x										x	x	x	x	x	x	x
				x														x	
					x											x	x	x	
							x						x	x	x	x	x	x	x
									x				x	x	x	x	x	x	x
117			x										x	x			x		
							x						x	x			x		
									x				x	x			x		
118	x															x	x	x	x
			x										x			x	x	x	x
				x										x		x	x	x	x
					x											x			
							x						x	x		x		x	
									x				x	x		x		x	
											x		x			x	x	x	x
135											x		x	x		x	x	x	x
136			x										x			x	x	x	x
					x								x			x	x	x	x
							x						x				x	x	x
									x				x					x	
137									x										x
141	x												x			x	x	x	x
			x										x	x		x	x	x	x
					x											x	x	x	x
							x						x				x	x	x
									x				x				x	x	
											x		x			x	x	x	x

TABLE A-2	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
142	x												x			x	x	x	x
			x										x	x		x	x	x	x
							x						x			x	x	x	x
											x			x		x	x		x
154	x												x				x	x	x
			x										x	x		x	x	x	x
							x						x			x	x	x	x
									x				x			x	x	x	x
											x		x	x		x	x	x	x
165						x													
									x				x				x	x	x
										x			x	x		x	x		
											x		x	x		x	x	x	x
166	x													x	x	x	x	x	x
					x									x	x	x	x	x	x
							x							x	x	x	x	x	x
172	x												x					x	
			x										x					x	
					x								x					x	
							x						x					x	
									x				x					x	
											x		x				x	x	
												x	x				x	x	
175			x															x	
					x													x	
							x						x					x	
178			x										x	x	x	x	x	x	x
				x									x	x	x	x	x	x	x
					x								x		x	x	x	x	x
179							x						x	x		x	x		
180			x										x	x	x	x	x	x	x
							x						x	x	x	x	x	x	x
181			x										x	x		x	x	x	x
					x								x				x	x	
							x						x	x		x	x	x	x
									x				x	x		x	x	x	x

TABLE A-2	VALVE TYPE												SERVICE						
Manufacturer (Code)	Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
183			x										x	x		x	x	x	x
							x						x	x		x	x	x	x
189	x												x	x		x	x	x	x
			x										x	x		x	x	x	x
				x									x		x	x	x	x	x
					x											x		x	x
							x						x	x		x	x	x	x
									x				x	x		x	x	x	x
											x		x	x		x	x	x	x
190	x												x					x	
					x								x	x	x	x		x	x
							x						x	x	x	x		x	x
									x				x	x	x	x	x	x	
											x		x	x	x	x	x	x	x
195			x										x	x		x	x	x	
				x									x					x	
					x								x	x		x		x	
							x						x	x		x			
									x				x			x			
197	x												x					x	
			x											x	x	x		x	
					x								x			x		x	
							x						x			x		x	
									x				x			x		x	
198				x									x	x	x	x		x	x
					x								x	x	x	x		x	x
201	x												x	x	x	x	x	x	x
202					x								x	x	x	x	x	x	x
							x						x	x		x	x	x	x
									x				x	x		x	x	x	x
205					x												x	x	
											x		x	x	x	x	x	x	x
206										x			x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
210	x												x					x	
			x										x	x	x	x	x	x	x
					x										x	x	x	x	x
							x						x		x	x	x	x	x
									x				x		x	x	x	x	x
											x		x	x	x	x	x	x	x

TABLE A-2

Manufacturer (Code)	VALVE TYPE Disconnect	Flow Metering	Check	Pierce Diaphragm	Vent	Attitude Control	Relief	Latching Solenoid	Regulator	Solenoid (Slide)	Solenoid (Poppet)	Solenoid (Plug)	SERVICE High Pressure	High Temperature	High Vacuum	Low Temperature	Liquid	Gas	Corrosive Media
211	x												x	x	x	x	x	x	x
			x										x	x	x	x	x	x	x
				x									x	x	x	x	x	x	x
					x								x	x	x	x	x	x	x
							x						x	x	x	x	x	x	x
									x				x	x	x	x	x	x	x
										x			x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
												x	x	x	x	x	x	x	x
213								x									x		
215			x										x	x			x	x	x
											x		x	x		x	x	x	x
218							x												
											x		x				x	x	x
220				x													x	x	
					x											x		x	
							x											x	
										x							x		
											x		x			x	x	x	x
221			x										x						x
							x						x						x
										x			x						x
222	x												x	x		x	x	x	x
224	x												x	x		x	x	x	
229			x										x	x	x	x	x	x	x
					x								x	x	x	x	x	x	x
							x						x	x	x	x	x	x	x
											x		x	x	x	x	x	x	x
241	x												x		x	x	x	x	x
243									x				x	x		x	x	x	x
												x	x	x		x	x	x	x
247			x											x			x	x	
											x			x		x	x	x	x
249	x																x		
			x										x	x			x		x
							x						x	x					
250									x					x					

TABLE A-3

AEROSPACE VALVE MANUFACTURERS

1. Vacuum Research Company
420 Market Street
San Francisco 11, Calif.
YU 2-3565

2. Chiksan Company
330 N. Pomona Avenue
Brea, Calif.
JA 9-2121

3. Tavco, Incorporated
612 Colorado Avenue
Santa Monica, Calif.
EX 4-3781

4. Caltron Products Company
3518 West Pico Boulevard
Los Angeles 19, Calif.
RE 4-2420

5. Dragon Engineering Company
13457 Excelsior Drive
P. O. Box 185
Norwalk, Calif.
UN 8-5224

6. Cardair Division
Marmon-Herrington Company
510 Indianapolis Avenue
Lebanon, Indiana

7. Rudolph E. Krueger Company
2808 N. Naomi Street
Burbank, Calif.
VI 9-4004

8. The J. C. Carter Company
671 West 17th Street
Costa Mesa, Calif.
LI 8-3421

9. Holex, Incorporated
Hollister, California

10. Firestone Tire & Rubber Co.
Guided Missile Division
2525 Firestone Boulevard
South Gate, Calif.

11. Coppus Engineering Corporation
344 Park Avenue
Worcester 10, Massachusetts

12. Alloy Products Corporation
1045 Perkins Avenue
Waukesha, Wisconsin

13. Aeroflow Dynamics
1842 Flower Street
Glendale 1, Calif.
CH 5-8901

14. On Mark Couplings, Incorporated
4440 York Boulevard
Los Angeles 41, Calif.
CL 4-2501

15. Accessory Products Company
Division of Textron, Inc.
616 W. Whittier Boulevard
Whittier, Calif.
OX 3-3747

16. Automatic Valve Company
37415 Grand River
Farmington, Michigan

17. Deleted

18. Frebank Company
711 West Broadway
Glendale 4, Calif.
CH 5-6558

19. Benbow Manufacturing Corp.
11920 W. Jefferson Boulevard
Culver City, Calif.
EX 8-5766

20. Parker Aircraft Company
5728 West Century Boulevard
Los Angeles 45, Calif.
OR 0-1221

21. American Power Jet Co.
705 Grand Avenue
Ridgefield, New Jersey
WH 5-8203

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

22. Rocket Power, Incorporated
Box 231
Mesa, Arizona

23. Research Controls, Inc.
P. O. Box 15864
Tulsa, Oklahoma

24. Associated Valve Company (AVECO)
337 West Walnut Street
North Wales, Pennsylvania

25. Skyvalve Incorporated
831 W. Fayette Street
Syracuse 4, New York
GR 8-3195

26. Hamilton Thomas Corp.
Klipfel Valves Division
1075 Lincoln Avenue
Hamilton, Ohio

27. Barber-Colman Company
Rockford, Illinois

28. Victor Equipment Company
844 Folsom Street
San Francisco 7, Calif.

29. The Firewel Company, Inc.
3695 Broadway
Buffalo 25, New York

30. The Bruning Company
Box 147
Lincoln, Nebraska

31. Instruments Incorporated
P. O. Box 556
Tulsa, Oklahoma

32. Fluidgenics
2640 Coolidge Avenue
National City, Calif.
GR 7-3121

33. Langley Corporation
310 Euclid Avenue
San Diego 12, Calif.
CO 4-3181

34. Pneu-Hydro Valve Corporation
52 Horse Hill Road
Cedar Knolls, New Jersey

35. Aqualite Corporation
1640 21st Street
Santa Monica, Calif.

36. Alloy Steel Products Company
1300 W. Elizabeth Avenue
Linden, New Jersey
WA 5-4600

37. Peacock Engrg. & Mfg. Company
10620 Firestone Boulevard
Norwalk, Calif.
SP 3-3980

38. Herlo Engrg. Corporation
549 N. Prairie Avenue
Hawthorne, Calif.
OS 5-4435

39. Bertea Products Company
1450 N. Lake Street
Pasadena 6, Calif.

40. Ronson Hydraulic Units Corp.
1313 Lincoln Avenue
Pasadena, Calif.

41. Sierra Engineering Company
123 East Montecito Avenue
Sierra Madre, Calif.
EL 5-4281 or MU 1-1141

42. Whitey Research Tool Co.
5525 Marshall Street
Oakland 8, Calif.

43. Deleted

44. Hyair Corporation
1838 Flower Street
Glendale 1, Calif.

45. Darco Industries, Inc.
2151 East Rosecrans
El Segundo, Calif.

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

46. Sargent Engineering Corp.
2533 East 56 Street
Huntington Park, Calif.

47. Well Equipment Mfg. Corp.
Division of Chiksan Company
Houston, Texas

48. Seaton-Wilson Mfg. Company
911-919 N. Victory Boulevard
Burbank, Calif.
VI 9-3521

49. Waugh Engineering Division
The Foxboro Company
7740 Lemona
Van Nuys, Calif.
TR 3-1055

50. Schutte & Koerting Company
Comwells Heights
Bucks Co, Pennsylvania
ME 9-0900

51. Hoke Incorporated
1 Tenakill Park
Cresskill, New Jersey

52. General Dynamics Corp.
Electric Boat Division
Eastern Point Road
Groton, Connecticut

53. George W. Dahl Co., Inc.
86 Tupelo Street
Bristol, Rhode Island

54. Rockwood Sprinkler Company
Division Gamewell Company
38 Harlow Street
Worcester 5, Massachusetts
PL 6-2426

55. Tapco
Div. of Thompson Ramo Wooldridge
23555 Euclid Avenue
Cleveland 17, Ohio
IV 1-7500

56. General Electric Company
Aircraft Accessory Turbine Dept.
3225 Wilshire Boulevard
Los Angeles 5, Calif.
DU 1-3641

57. Janitrol Aero Division
Midland-Ross Corporation
6214 Manchester Boulevard
Los Angeles 45, Calif.

58. Pacific Valves, Incorporated
3201 Walnut Avenue
Long Beach, Calif.
GA 6-2531

59. Robertshaw-Fulton Controls Co.
Aeronautical & Instrument Div.
Santa Ana Freeway at Euclid Ave.
Anaheim, Calif.

60. Scott Aviation Corp.
Erie Street
Lancaster, New York
RE 5100

61. Rocketdyne
Div. of North American Aviation
6633 Canoga Avenue
Canoga Park, Calif.
DI 7-5651

62. Moog Servocontrols, Inc.
Proner Airport
East Aurora, New York

63. Homestead Valve Mfg. Co.
P. O. Box 348
Coraopolis, Pennsylvania

64. Lockheed Missiles & Space Co.
Sunnyvale, Calif.

65. M. C. Manufacturing Co.
118 Indianwood Road
Lake Orion, Michigan

TABLE A-3(Continued)

Aerospace Valve Manufacturers

66. AiResearch Mfg. Division
The Garrett Corporation
402 South 36th Street
Phoenix, Arizona
BR 5-6311

67. Clary Dynamics
408 Junipero Street
San Gabriel, Calif.
CU 3-2724

68. Spard
Div. of Electric Autolite Co.
511 Hamilton Street
Toledo 1, Ohio

69. Uniflow Valve Corporation
110 Quine Street
Cranford, New Jersey

70. Allenair Corporation
255 E. Second Street
Mineola, New York

71. Allied Control Co., Inc.
2 East End Avenue
New York 21, New York

72. Weba Incorporated
1301 Fourth Avenue
New Hyde Park, New York

73. Vickers, Incorporated
Marine & Ordnance Dept.
172 East Aurora Street
Waterbury 20, Connecticut

74. Transco Products, Inc.
4241 Glencoe Avenue
Venice, Calif.

75. American Instrument Co., Inc.
8030 Georgia Avenue
Silver Spring, Maryland
JU 9-1727

76. Kieley & Mueller Inc.
64 Kenung Street
Middletown, New York

77. Tactair Fluid Controls Corp.
Church Road
Bridgeport, Pennsylvania

78. Technical Development Co.
305 S. Chester Pike
Glenolden, Pennsylvania
LU 3-3330

79. F. J. Stokes Corporation
5500 Tabor Road
Philadelphia 20, Pennsylvania

80. Imperial Brass Mfg. Co.
6300 W. Howard Street
Chicago 48, Illinois

81. Carleton Controls Corp.
East Aurora, New York

82. GAR Precision Parts, Inc.
190 Henry Street
Stamford, Connecticut

83. Eckel Valve Company
1425 First Street
San Fernando, Calif.
EM 1-6251

84. Crosby Valve & Gage Co., Inc.
5436 Jillson Street
Los Angeles 22, Calif.
AN 8-5109

85. Allen Aircraft Products, Inc.
Ravenna, Ohio
AX 6-9621

86. Grove Valve & Regulator Co.
(Walworth-Grove-Aloyco)
Sales Division
1010 Wilshire Boulevard
Los Angeles 17, Calif.

87. Decoto Brothers Aircraft Div.
P. O. Box 1142
Yakima, Washington

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

88. Hydra-Power Corporation
10 Pine Court
New Rochelle, New York

89. High Vacuum Equipment Corp.
2 Churchill Road
Hingham, Massachusetts
RI 9-2430

90. Cimtrol Division
Cincinnati Milling Machine Co.
Cincinnati 9, Ohio

91. Skinner Chuck Co.
Skinner Electric Valve Div.
95 Edgewood Avenue
New Britain, Connecticut

92. Warren Engineering Co.
Route 24
Broadway, New Jersey

93. Propellex Chemical Division
Chromalloy Corporation
Box 187
Edwardsville, Illinois

94. Nuclear Products Company
15635 Saranac Road
Cleveland 10, Ohio

95. Heckerman Corporation
814 West Hyde Park Blvd.
Inglewood 3, Calif.
ORc 4-3229 or ORe 8-2264

96. Stratos Division
Fairchild Engine & Airplane Corp.
Bay Shore, New York

97. Atkomatic Valve Co., Inc.
545 W. Abbott Street
Indianapolis 25, Indiana
ME 8-6545

98. Automatic Timing & Controls
American Mfg. Co., Inc.
King of Prussia, Pennsylvania

99. Altair, Incorporated
19 Hillside Avenue
Terryville, Connecticut

100. Hofman Labs, Incorporated
5 Evans Terminal
Hillside, New Jersey
EL 4-4016

101. Jarry Hydraulics Ltd.
4384 St. Denis Street
Montreal 18
Quebec, Canada

102. Rivett Lathe & Grinder Inc.
18 Riverview Road
Brighton 35, Massachusetts

103. Marotta Valve Corporation
Boonton Avenue
Boonton, New Jersey

104. Kinney Vacuum Division
New York Air Brake Co.
3529 Washington Street
Boston 30, Massachusetts

105. Republic Manufacturing Co.
15655 Brookpark Road
Cleveland 35, Ohio

106. Vinson Engrg. & Sales Corp.
8044 Woodley Avenue
Van Nuys, Calif.
ST 6-7210 or TR 3-3510

107. Fluid Dynamics, Incorporated
12 DeHart Street
Morristown, New Jersey

108. Humphrey Products Division
General Gas Light Co.
Kilgore at Sprinkle Road
Kalamazoo, Michigan

109. Sealol, Incorporated
Warwick Industrial Park
Providence 5, Rhode Island

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

110. Stewart Warner Corp.
South Wind-Aircraft Products Dept.
1514 Drover Street
Indianapolis, Indiana

111. Marsh Instrument Co.
Div. Colorado Oil & Gas Corp.
3501 Howard Street
Skokie, Illinois

112. Valcor Engineering Corp.
365 Carnegie Avenue
Kenilworth, New Jersey

113. Wallace O. Leonard Inc.
373 South Fair Oaks Avenue
Pasadena, Calif.
CH 5-8711

114. Groen Associates, Inc.
2800 Clearwater Street
Los Angeles 39, Calif.
NO 5-5708

115. AerValco Engineering Corp.
1734 S. Del Mar Avenue
San Gabriel, Calif.
CU 3-7271

116. Hupp Aviation Division
Hupp Corporation
6633 West 65th Street
Chicago 38, Illinois

117. The Bendix Corporation
Bendix-Pacific Division
11600 Sherman Way
North Hollywood, Calif.

118. B. H. Hadley, Inc.
1427 South Garey Avenue
Pomona, Calif.
NA 9-5075

119. Jordan Valve Division
Richards Industries, Inc.
6013 Wiehe Road
Cincinnati 13, Ohio
EL 1-1352

120. Eclipse Fuel Engineering Co.
1100 Buchanan Street
Rockford, Illinois

121. J. D. Gould Company
4707 Massachusetts Avenue
Indianapolis 18, Indiana

122. Hydraulic Press Mfg. Co.
Hydraulic Power Division
Mount Gilead, Ohio

123. H. W. Loud Machine Works
969 E. Second Street
Pomona, Calif.

124. Midwestern Instruments Inc.
P. O. Box 7509
Tulsa 18, Oklahoma

125. Copes-Vulcan Division
Blaw-Knox Company
Erie, Pennsylvania

126. Anderson Greenwood & Co.
5425 Rice Avenue
Houston 36, Texas

127. Annin Company
1040 South Vail
Montebello, Calif.
RA 3-9351

128. Autoclave Engineers Sales Co.
2930 W. 22nd Street
Erie, Pennsylvania

129. Ideal-Aerosmith
Div. of Royal Industries Inc.
3913 Evans Avenue
Cheyenne, Wyoming

130. Cadillac Gage Company
P. O. Box 3806
Detroit 5, Michigan

131. Ross Operating Valve Company
120 E. Golden Gate Avenue
Detroit 3, Michigan

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

132. Oilgear Company
1560 W. Pierce Street
Milwaukee 4, Wisconsin

133. Cryogenics Corporation
500 Terrace Street
Meadville, Pennsylvania

134. Deleted

135. Pyrodyne, Inc.
11876 Wilshire Blvd.
Los Angeles 25, Calif.
GR 2-1249

136. Bell Aerosystems Company
Avionics Division
P. O. Box 1
Buffalo 5, New York

137. Randall Engineering Corp.
5933 Bowcroft Street
Los Angeles 16, Calif.

138. Arkwin Industries, Inc.
648 Main Street
Westbury, New York
ED 3-2640

139. The Weatherhead Company
Aviation Division
300 East 131st Street
Cleveland, Ohio

140. Sun Electric Corporation
Harlem & Avondale
Chicago 31, Illinois
NE 1-6000

141. Futurecraft Corporation
15430 Proctor Avenue
City of Industry, Calif.
ED 0-1611

142. Schultz Tool & Mfg. Co.
425 South Pine Street
San Gabriel, Calif.
AT 7-6104 or CU 3-4753

143. Manning, Maxwell & Moore, Inc.
Watertown 72, Massachusetts

144. Deleted

145. Atlas Valve Company
280 South Street
Newark 5, New Jersey

146. Deleted

147. Puritan Equipment, Inc.
1703 McGee Street
Kansas City 8, Missouri
HA 1-0528

148. Waterman Engineering Co.
Evanston, Illinois

149. Lapp Insulator Company, Inc.
Process Equipment Division
42 Gilbert Street
LeRoy, New York

150. Automatic Switch Company
Florham Park, New Jersey

151. Buckeye Iron & Brass Works
P. O. Box 883
Dayton, Ohio

152. Allison Division
General Motors Corp.
Indianapolis 6, Indiana

153. Deleted

154. Pyronetics, Inc.
11973 E. Slauson
Santa Fe Springs, Calif.
OX 8-0456

155. Brenner-Fiedler & Assoc., Inc.
Engineering Representatives
7563 Melrose Avenue
Los Angeles 46, Calif.
OL 1-4300

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

156. Alco Valve Company
865 Kingsland Avenue
St. Louis 30, Missouri
PA 5-2460

157. Aeroquip Corporation
Marman Division
11214 Exposition Blvd.
Los Angeles 64, Calif.
GR 8-0921 or BR 2-8511

158. Deleted

159. Deleted

160. Raymond Atchley Division
American Brake Shoe Co.
2231 South Barrington Ave.
Los Angeles 64, Calif.
BR 2-7904 or GR 7-8245

161. Dill Manufacturing Co.
700 East 82 Street
Cleveland 3, Ohio
UT 1-3200

162. Johnson Corporation
805 Wood Street
Three Rivers, Michigan

163. Versa Products Co., Inc.
150 Coolidge Avenue
Englewood, New Jersey

164. Deleted

165. Weston Hydraulics Ltd.
Sub. Borg-Warner Corp.
7500 Tyron Avenue
Van Nuys, Calif.
ST 1-4000 or TR 3-4340

166. Solar Aircraft Company
2200 Pacific Highway
San Diego 12, Calif.
BE 3-8241

167. James, Pond & Clark, Inc.
2181 East Foothill Blvd.
Pasadena, Calif.
BA 4-1078

168. Nash Controls, Inc.
1275 Bloomfield Avenue
Caldwell, New Jersey

169. Greer Hydraulics, Inc.
5930 W. Jefferson Blvd.
Los Angeles 16, Calif.
UP 0-9161

170. Strahman Valves, Inc.
Nicolet Avenue
Florham Park, New Jersey

171. Consolidated Vacuum Corp.
1775 Mt. Read Blvd.
Rochester 3, New York

172. Kidde Aero-Space Division
Walter Kidde & Co., Inc.
Belleville 9, New Jersey

173. Allis-Chalmers Mfg. Co.
P. O. Box 712
York, Pennsylvania

174. U. S. Rubber Company
Soto & East 46th Streets
Los Angeles 58, Calif.
LU 9-3161

175. Lear, Incorporated
Lear-Romec Division
Abbe Road
Elyria, Ohio
FA 3-3211

176. The Bendix Corporation
Utica Division
117 E. Providencia Ave.
Burbank, Calif.

TABLE A-3(Continued)

Aerospace Valve Manufacturers

177. Pegasus Laboratories, Inc.
3500 West Eleven Mile Road
Berkley, Michigan

178. Components Corporation
35 North Arroyo Parkway
Pasadena, Calif.
681-7448

179. Oil-Dyne, Inc.
2115 W. Marquette Road
Chicago 36, Illinois
HE 4-2300

180. Kohler Company
Kohler, Wisconsin

181. Fluid Regulators Corp.
313 Gillette Street
Painesville, Ohio

182. United Control Corp.
4540 Union Bay Place
Seattle 5, Washington

183. Precision Equipment Co, Inc.
1740 Crenshaw Boulevard
Torrance, Calif.
SP 5-2501

184. Vacuum Electronics Corp.
Terminal Drive
Plainview, New York

185. Kunkle Valve Company
121 S. Clinton Street
Ft. Wayne, Indiana

186. R-P&C Valve Division
American Chain & Cable Co.
Tulpehocken Street
Reading, Pennsylvania

187. Kerns Manufacturing Corp.
45-18 Court Square
Long Island City 1, New York
ST 6-2550

188. Airmatic Valve, Inc.
7313 Associate Avenue
Cleveland 9, Ohio

189. SieBelAir
5686 W. Washington Blvd.
Los Angeles 16, Calif.
WE 9-2183

190. Whittaker Controls & Guidance
Div. of Telecomputing Corp.
16217 Lindbergh Street
Van Nuys, Calif.
TR 3-1950

191. Metal Bellows Corporation
Pacific Division
20977 Knapp Street
Chatsworth, Calif.
DI 1-2611

192. Security Valve Company
909 El Centro
South Pasadena, Calif.
MU 2-3594

193. Deleted

194. Hills-McCanna Company
400 Maple Avenue
Carpentersville, Illinois

195. The Bendix Corporation
Pioneer-Central Division
Davenport, Iowa

196. Hanna Engineering Works
17071 Ventura Boulevard
P. O. Box 232
Encino, California
ST 8-3220

197. Airborne Research &
Development Corporation
7530 San Fernando Road
Sun Valley, Calif.

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

198. Hydro-Space Technology, Inc.
Clinton Road & Route 46
West Caldwell, New Jersey

199. Houdaille Industries, Inc.
Buffalo Hydraulics Division
537 East Delavan Avenue
Buffalo 11, New York

200. Sanders Associates, Inc.
95 Canal Street
Nashua, New Hampshire

201. Jack & Heintz
P. O. Box 6719
Cleveland 1, Ohio

202. Flodyne Controls, Inc.
1701 Elizabeth Avenue East
Linden, New Jersey

203. Grinnell Company, Inc.
260 West Exchange Street
Providence, Rhode Island

204. Dowty Equipment of Canada, Ltd.
Ajax, Ontario
Canada
WH 2-3100

205. General Controls Company
801 Allen Avenue
Glendale 1, Calif.
VI 9-2181

206. Koontz Wagner Electric Co.
516 No. Michigan Avenue
South Bend 1, Indiana

207. Minneapolis-Honeywell Reg. Corp.
Valve Division
300 Commerce Drive
Fort Washington, Pennsylvania

208. Dukes Company, Inc.
3999 N. 25th Avenue
Schiller Park, Illinois
GL 5-5795

209. The Modernair Corp.
400 Preda Street
San Leandro, Calif.
562-6485

210. Consolidated Controls Corp.
750 South Isis Avenue
Inglewood, Calif.
ORe 8-5521 or ORc 1-7589

211. Vacco Valve Company
1445 Lidcombe Avenue
El Monte, Calif.
CU 3-8337

212. United Systems Corp.
918 Woodley Road
Dayton 3, Ohio

213. Temco Electronics
P. O. Box 6118
Dallas 22, Texas

214. Electrol, Incorporated
Kingston, New York

215. United Aircraft Products, Inc.
P. O. Box 1035
Dayton, Ohio

216. Essex Mfg. Company, Inc.
8213 Gravois Avenue
St. Louis 23, Missouri

217. A. O. Smith Corporation
Aero Western Division
900 East Ball Road
Anaheim, Calif.

218. National Water Lift Co.
Div. Pneumodynamics Corp.
2220 Palmer Avenue
Kalamazoo, Michigan

219. The William Powell Company
2503-31 Spring Grove Avenue
Cincinnati 22, Ohio
DU 1-4699

TABLE A-3 (Continued)

Aerospace Valve Manufacturers

220. Aerojet-General Corp.
P. O. Box 1947
Sacramento, Calif.
YU 5-5111

221. Pelton Division
Baldwin-Lima-Hamilton Corp.
2929 Nineteenth Street
San Francisco 10, Calif.

222. E. B. Wiggins Oil Tool Co.
3424 E. Olympic Blvd.
Los Angeles 23, Calif.
AN 9-0181

223. Diesel Equipment Division
General Motors Corp.
2100 Burlingame Ave. S. W.
Grand Rapids, Michigan

224. The Weatherhead Company
Western Division
1736 Standard Avenue
Glendale 1, Calif.

225. Dezurik Corporation
Sartell, Minnesota
BL 1-0221

226. Koehler Aircraft Products Co.
409 Leo Street
Dayton 59, Ohio
BA 6-1821

227. Mason-Neilan
Div. Worthington Corp.
Norwood, Massachusetts

228. Moore Products Company
H & Lycoming Streets
Philadelphia 24, Pennsylvania

229. Sterer Engineering & Mfg. Co.
11423 Van Owen Street
North Hollywood, Calif.
TR 7-3373

230. The West Base Company
31480 Detroit Road
Westlake, Ohio

231. Kearfott Division
General Precision Inc.
Little Falls, New Jersey

232. W-K-M Division
ACF Industries, Inc.
P. O. Box 2117
Houston 1, Texas

233. Belfab Corporation
Suite No. 302, 110 Bldg.
110 East Wilshire Avenue
Fullerton, Calif.
TR 1-6252

234. Daniel Orifice Fitting Co.
9720 Katy Road
Houston 24, Texas

235. Sinclair-Collins Valve Co.
Div. IBEC
454 Morgan Avenue
Akron, Ohio
PR 3-6623

236. Bellows-Valvair Corp.
926 Western Avenue
Glendale 1, Calif.

237. Actuation Research Corp.
1210 W. Burbank Blvd.
Burbank, Calif.
VI 9-6731

238. Marvel-Schebler Prod. Div.
Borg-Warner Corporation
2195 S. Elwin Road
Decatur, Illinois

239. Bastian-Blessing Company
4201 W. Peterson Avenue
Chicago 46, Illinois
MU 5-1121

TABLE A-3(Continued)

Aerospace Valve Manufacturers

240. Resistoflex Corporation
Woodland Road
Roseland, New Jersey

241. Hydromatics, Inc.
5 Lawrence Street
Bloomfield, New Jersey
PI 8-7000

242. George Yardley Associates
2233 S. Wright Street
Santa Ana, Calif.
KI 6-2611 or MA 5-1123

243. A. W. Cash Company
540 N. 18th Street
Decatur, Illinois

244. General Controls Co.
Hammel-Dahl & Foster
Engineering Divisions
Warwick Industrial Park
Warwick, Rhode Island
ST 1-6200

245. Thiokol Chemical Corp.
Reaction Motors Division
Denville, New Jersey
OA 7-7000

246. The Decker Corporation
Bala-Cynwyd, Pennsylvania

247. Hamilton Standard Division
United Aircraft Corp.
Windsor Locks, Connecticut
NA 3-1621

248. Precision Rubber Products Corp.
3110 Oakridge Drive
Dayton 17, Ohio

249. Republic Aviation Corp.
Farmingdale L.I., New York

250. Carl Drescher Company
1951 Ontario Street
Burbank, Calif.
TH 2-8153

BIBLIOGRAPHY

PROPULSION SYSTEMS

Lt. R. M. Spongberg. "Performance Characteristics of the 3,000 Cycle Electrothermal Rocket", Propulsion Laboratory, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, for National IAS/ARS Joint Meeting June 13-16, 1961, Los Angeles, 61-99-1793.

E. Mitchell, A. O. Tischler and W. Cohen. "Liquid and Solid States for a Manned Lunar Landing Vehicle" 2284-61, NASA, Washington, D. C. for ARS Space Flight Report to the Nation, New York Coliseum, October 9-15, 1961.

Lockheed-California Company Aeronautical Systems Division "Study on Minimization of Fire and Explosion Hazards in Advanced Flight Vehicles" Lockheed Report 15156, Contract AF33(616)-7387, October 1961, ASD TR-61-288.

Bruce E. Tinling "Measured Steady-State Performance of Water Vapor Jets for Use in Space Vehicles Attitude Control Systems", NASA TN D-1302, May 1962, Ames Research Center, Moffett Field, California.

Stuart C. Brown "Predicted Performance of On-Off Systems for Precise Satellite Attitude Control, NASA TN-D-1040, July 1961, Ames Research Center, Moffett Field, California.

J. B. Heineck "Propulsion Systems for a Hovering Vehicle", 2286-61, The Boeing Company, Seattle, Washington, to American Rocket Society Space Flight Report to the Nation, New York Coliseum, October 9-15, 1961.

G. C. Szego. "Space Power Systems" 9751-0004-RU-D01, PR No. 40, 4/25/61, Space Technology Laboratory, Inc.

PLANETARY AND SPACE ENVIRONMENTS

P. D. Gray, et al. "Rockets in Space Environment," Phase I: Parameter Study, Report No. 2112, Contract AF04(611)-7441, 10/27/61, Aerojet-General Corp., Space Propulsion Division, Azusa, California.

D. H. Menzel and G. De Vaucouleurs. "Final Report on the Occultation of Regulus by Venus, July 7, 1959," Scientific Report No. 1, ARDC Contract AF19 (604)-7461, 1/10/61, Harvard College Observatory, Cambridge 38, Mass. AD251 664.

H. B. Kallmann. "Electron Density Distribution in a New Model of the Ionosphere," Report No. P-1089, 5/15/57, The Rand Corporation.

M. J. Neder, and T. E. Walsh. "Support Equipment Designers Look at the Moon," ARS No. 994-59/Aerojet-General Corporation, November 1959.

J. A. Van Allen and Louis A. Frank. "Radiation Around the Earth to a Radial Distance of 107, 400 km," Nature Vol. 183 2/14/59 pp. 430-434.

BIBLIOGRAPHY
PLANETARY AND SPACE ENVIRONMENTS

Moss, M. K., and Bergson, B. P. "General Environment Specification For All Agena Programs," LMSC 6117D, PP. 40, 1 March 1962, Lockheed Aircraft Corporation. Missiles and Space Division.

"Military Standard, Climatic Extremes For Military Equipment," MIL-STD-210A, PP. 44, 1 June 1957, plus revised pages 30 November 1958, Department of Defense.

Martin, B.D. "The Mariner Planetary Communication System Design", TR No. 32-85, Rev. No. 1, Contract NASw-6, May 15, 1961, Jet Propulsion Laboratory.

Whipple, F.L. "Dust and Meteorites", Report No. 2253-61, American Rocket Society Space Flight Report to the Nation/New York Coliseum, October 9-15, 1961.

Davidson, J.R. and Sandorff, P.E. "Environmental Problems of Space Flight Structures" October 1961, Preliminary Draft, Massachusetts Institute of Technology.

McIntyre, D.V. "Meteoroidal Damage to Spacecraft Materials", MR-15, 16 February 1962, Space Technology Laboratories, Inc.

Summers, James L. "Investigation of High Speed Impact: Regions of Impact and Impact at Oblique Angles", NASA TN D-94, October 1959, National Aeronautics and Space Administration, Ames Research Center.

Funkhouser, J.O. "A Preliminary Investigation of the Effect of Bumpers as a Means Reducing Projectile Penetration", NASA TN-D-802, April 1961, National Aeronautics and Space Administration, Langley Research Center.

C. Gazley, Jr. "The Penetration of Planetary Atmospheres," P-1322, 2/24/58, The Rand Company.

MATERIALS COMPATIBILITY

R.M. McClintock and H.P. Gibbons, "Compilation of Mechanical Properties of Materials at Cryogenic Temperatures" NBS Report 6064

"Conference on Elastomer" , Sixth Joint Army Navy, Air Force, AD250916, Vol. 2.

Evans, George R. "Construction Materials For Containers of Liquid Propellants; Hydrogen, Fluorine, Hydrazine And Nitrogen Tetroxide: An Annotated Bibliography," AD 271034, PP 18, April 1960. Lockheed Aircraft Corp., Technical Information Center--Research Section.

Mosteller, R. D. and others. "Design Criteria--Materials," 804-1001001, March 1960, The Martin Company, Denver Division.

BIBLIOGRAPHY

PLANETARY AND SPACE ENVIRONMENTS

Schockon, Klaus. "A Study on Emissivities," ABMA Report No. DV-TN-64-58, PP. 23, 16 June 1958, Army Ballistic Missile Agency, Thermodynamics Section.

Wood, C. P., and Carter, A. F. "Predicted Characteristics of an Inflatable Aluminized-Plastic Spherical Earth Satellite With Regard to Temperature, Visibility, Reflection of Radar Waves, and Protection From Ultraviolet Radiation," D-115, NASA TN D-115, PP 26, National Aeronautics and Space Administration, Langley Research Center, October 1959.

Pogo, Alexander and others. "Annotated Bibliography of Physical Observations of the Moon 1920-1960," PP 83, 15 October 1961, California Institute of Technology, Geological Sciences Division.

Magnolia, L. R. and Trew, J. R. "The Lunar Problem," STL/AB 61-5110-40, PP. 269, October 1961, Volume 1--Bibliography, The STL Technical Library, Advanced Research Group.

Magnolia, L. R. and Trew, J. R. "The Lunar Problem," STL/AB 61-5110-40, PP. 35, October 1961, Volume 2--Index, The STL Technical Library, Advanced Research Group.

Ossefort, Z. T., and Ruby, J. D. "The Effects of A Simulated Space Environment on The Properties of Elastomers," 1961 Proceedings of the Institute of Environmental Sciences National Meeting, (April 5, 6, 7, 1961), PP. 651-661.

Van Allen, James A. "On the Radiation Hazards of Space Flight," SUI-59-7, PP. 31, State University of Iowa, Department of Physics and Astronomy.

Johnson F. S., edited by. "Satellite Environment Handbook," LMSD-995006, AD 249 473, PP. 154, December 1960, Lockheed Aircraft Corporation, Missiles and Space Division.

Gazley, C. Jr., Kellogg, W. W., and Vestine, E. H. "Space Vehicle Environment," P-1335, PP. 58, 7 July 1958, Revised 15 June 1959, The Rand Corporation, Engineering Division.

Moncrieff-Yeates, Alex J. "Some Elementary Considerations Concerning Fringe of Space Environmental Conditions," Aero/Space Engineering, December 1959, PP. 32-35.

Hess, Raymond E. and Badertscher, Robert F. "Space Radiation As An Environmental Constituent," Task No. 60001, Project No. 2133, Contract No. AF 33(616)-5171, PP. 49, Battelle Memorial Institute, Radiation Effects Information Center.

Lehr, S. N., Tronolone, V. J., and Horton, P. V. "Equipment Design Considerations For Space Environment," STL/TR-60-0000-09224, PP. 68, September 1960, Space Technology Laboratories, Inc.

Buwalda, E.P. and Hibbs, A.R. "Satellite Temperature Measurements for 1958 Alpha - Explorer I", Ex.Publication No. 481, Contract DA-04-495-Ord 18, 23 April 1958, Jet Propulsion Laboratory.

BIBLIOGRAPHY

PLANETARY AND SPACE ENVIRONMENTS

M. Neugebauer. "Comments on the Question of the Existence of a Lunar Magnetic Field", External Publication No. 800, NASA Contract No. NASw-6, 11/4/59, JPL ASTIA AD 234 180.

"Lunar Atmosphere and Surface Conditions", an annotated bibliography compiled by George R. Evans, LMSD 3-100-61-1, May 1961, Lockheed Missiles & Space Div., ASTIA AD 258 377 SB-61-22.

Albert R. Hibbs (Ed.) "Exploration of the Moon, the Plantets, and Interplanetary Space", Report No. 30-1, Contract No. NASw-6, 4/30/59, JPL

Phyllis Buwalda. "The Lunar Environment", Technical Release No. 34-159, Contract NASw-6, 10/28/60, CIT, JPL, ASTIA AD 246 870.

J. Green, Principal Investigator. "Geophysics as Applied to Lunar Exploration", (Final Report), AFCRC Doc. No. AFCRL-TR-60-409, MD 59-277, AF19(604)-5886, 30 June 1960, North American Aviation, Inc., Aero-Space Laboratories, Missile Division, prepared for Geophysics Research Directorate, Air Force Cambridge Research Center, ARDC, USAF, Bedford, Massachusetts.

M. A. Broner and G. A. Lander, Jr. "How Bad is the Moon Environment?", Space/Aeronautics (April 1962), pp 92-96.

G. Fielder. Structure of the Moon's Surface, Pergamon Press (1961)

P. J. Shlichta. "Geological Aspects of Lunar Exploration", TR No. 34-8, NASA Contract NASw-6, 1/25/60, Jet Propulsion Laboratory.

P. G. Mezger and H. Strassl. "The Thermal Radiation of the Moon at 1420 Mc/s", Planet. Space Sci., Pergamon Press 1959. Vol. 1, pp 213-226.

J.I.F. King. "The Dynamic Stability of the Upper Atmosphere of Venus", T.I.S. Report R60SD453, AFBMD Contract 04(647)-269 October 1960, General Electric Company, Missile and Space Vehicle Dept., Philadelphia, Pa.

H. K. Kallmann. "Properties of the Atmosphere and Ionosphere Between 90 and 300 KM", Report P-1023, 4/16/57, The Rand Corporation.

Y. Mintz. "Temperature and Circulation of the Venus Atmosphere", P-1736, 6/25/59, revised 9/17/59, The Rand Corporation.

S. H. Dole. "The Atmosphere of Venus", P-978, 10/12/56, Rand Corporation.

A. Dollfus. "New Research on an Atmosphere in the Vicinity of the Moon", STL-T-F-15, 60-5111-55, from Comptes Rendus, Acad. Sci., Paris 234, 2046, 1952 (Translated by R. D. Kennedy, STL)

BIBLIOGRAPHY

Planetary and Space Environment

L. L. Hofstein and A. W. Cacciola. "Lunar Surface·Vehicle," ARS 1424-60, December 1960, American Machine and Foundry Company, Greenwich Engineering Division.

V. V. Sobolev. "Scattering of Light in the Atmospheres of Earth and the Planets," from Leningrad State University Scientific Records, Series of Mathematical Sciences No. 18, Astonomy, Report No. 116, 1949, Translated by K. N. Trirogoff, STL.

Arthur Beiser. "Cosmic-Ray Trapping In Interplanetary Space," Journal of Geophysical Research, Vol. 63, No. 1, (March 1958), pp. 1-17.

Elwert, G. "Theory of X-Ray Emission of the Sun," Journal of Geophysical Research, Vol. 66, No. 1, (January 1961), pp. 391-401.

Hottel, H. C. "Radiant Heat Transmission Between Surfaces Separated by Non-Absorbing Media," American Society of Mechanical Engineering, FSP-53-19b, pp. 265-273--reproduced copy.

Hottel, H. C. "Radiant Heat Transmission," American Society of Mechanical Engineers, Vol. 52, No. 7, (July, 1930), pp. 699-704.

De Vaucouleurs, Gerard. Physics of The Planet Mars, Faber and Faber Limited, London,

Kuiper, Gerard P. and others. The Atmospheres of the Earth and Planets, Revised Edition, The University of Chicago Press, Chicago, Illinois, 1952,

Anderson, Kinsey A. "Solar Particles and Cosmic Rays," Scientific American, Vol. 202, No. 1, (January 1960), PP. 64-71.

Hoyle, F., M.A. Some Recent Researches In Solar Physics, The Syndics of The Cambridge University Press, New York, (1949),

Johnson, Francis S., edited by. Satellite Environment Handbook, Stanford University Press, Stanford, California, (1961),

Gazley, Carl Jr. "Deceleration and Heating of a Body Entering a Planetary Atmosphere From Space," Vistas In Astronautics, Vol. 1, No. 8, (1958)

Brandt, John C. "Density of the Lunar Atmosphere," Science, Vol. 131 (27 May 1960), p. 1606

N. T. Bobrovnikoff. "Natural Environment of the Moon," WADC Phase TN-3, AD 242 177 June 1959, Ohio State University Research Foundation, Contract No. AF33 (616)-5914,

BIBLIOGRAPHY

RADIATION EFFECTS ON MATERIALS AND RANGE-ENERGY DATA

Smith, J.H. "Theoretical Range-Energy Values for Protons in Air and Aluminum", Physical Review, Vol. 71, No. 1 (January 1, 1947) pp 32-33.

Surface Effects on Spacecraft Materials, First Symposium Held at Palo Alto, California May 12,13, 1959, John Wiley and Sons, Inc., (1960).

Gardner, R.E. "Effects of Ionizing Radiation on Solid Rocket Motor Components", ARS Journal, Vol. 32, No. 7, (July 1962), pp. 1050-1053.

"Conference on Elastomers", Sixth Joint Army, Navy, Air Force, AD250916, Vol.2.

Hillenbrand, L.J. "The Effect of Nuclear Radiation on Hydrocarbon Fuels", Technical Memorandum No. 11, November 1958, Battelle Memorial Institute, The Radiation Effects Information Center.

Shoffner, J.P. "Effects of Radiation on "Teflon" Resins in Space", The Journal of Teflon, (Jan. 1960) pp. 6-8.

Walbert, J.T. and Reed, J.C. "Teflon Fluorocarbon Resins in Space Environment", DuPont Report.

Broadway, N.J. and others. "The Effect of Nuclear Radiation on Elastomeric and Plastic Materials (Second Addendum)" , REIC Report No. 3, April 30, 1960, Battelle Memorial Institute, The Radiation Effects Information Center.

Cosgrove, S.L. and Dueltgen, R.L. "The Effect of Nuclear Radiation on Lubricants and Hydraulic Fluids", REIC Report No. 19, May 31, 1961, Battelle Memorial Institute, Radiation Effects Information Center.

Fainman, M.Z. and others. "The Behavior of Fuels and Lubricants in Dynamic Test Equipment Operating in the Presence of Gamma Radiation", WADC TR 58-264, 31 March 1958, Cook Electric Company, Inland Testing Laboratories Division.

Rich, M. and Madey, R. "Range-Energy Tables", UCRL-2301, March 1954, University of California, Radiation Laboratory.

Katz, L. and Penfold, A.S. "Range-Energy Relations for Electrons and the Determination of Beta-Ray End-Point Energies by Absorption", Reviews of Modern Physics, Vol. 24, No. 1 (January 1952) pp 28-44.

Davisson,C.M. and Evans, R.D. "Gamma-Ray Absorption Coefficients", Reviews of Modern Physics, Vo. 24, No. 1 (January 1952) pp. 79-107.

Lampert, S. and Younger, D.G. "Multiwall Structures for Space Vehicles", Report No. U-910, Contract AF33(616)-6641, May 1960, Aeronutronic, Division of Ford Motor Company.

BIBLIOGRAPHY
MATERIALS FOR SPACE

Happe, R.A. "Materials in Space", Tech. Release No. 34-143, Contract NASw-6, 18 October 1960, Jet Propulsion Laboratory.

Spalvins, T. and Keller, D.V. "Adhesion Between Atomically Clean Metallic Surfaces", MET.E.905-1-7-62F, Contract NsG-159-61, Syracuse University, Research Institute, Department of Chemical Engineering.

Coffin, L.F., Jr. "A Fundamental Study of Synthetic Sapphire as a Bearing Material", A.S.L.E. Trans. No. 1, October 1956, General Electric Research Laboratory.

Allen, J.M. "Environmental Factors Influencing Metals Applications in Space Vehicles", DMIC Report 142, OTS PB 151101, Contract AF18(600)-1375, December 1, 1960, Battelle Memorial Institute, Defense Metals Information Center.

Holzbauer, C.J. "OGO Sublimation Study", TR 2311-6030-RU000, 30 August 1962, Space Technology Laboratories, Inc.

Ossefort, Z.T. and Ruby, J.D. "The Effects of a Simulated Space Environment on the Properties of Elastomers", TR-61-1999, 15 May 1961, Rock Island Arsenal Laboratory.

Herrmann, W. and Jones, A.H. "Survey of Hypervelocity Impact Information" A.S.L.R. Report No. 99-1, September 1961, Massachusetts Institute of Technology, Aeroelastic and Structures Research Laboratory.

"Hypervelocity Impact" Fourth Symposium, APGC-TR-60-39(III), September 1960, Air Proving Ground Center, Air Research and Development Command.

Jaffe, L.D. and Rittenhouse, J.B. "Behavior of Materials in Space Environments", TR No. 32-150, November 1, 1961, Jet Propulsion Laboratory.

DeWitt, E.A., Podlaseck, S, and Suhorsky, J. "Effect of Low Pressure at Elevated Temperatures on Space Vehicle Materials", RM-29, March 1959, Martin Company.

Clauss, F.J. "Lubricants and Self-Lubricating Materials for Spacecraft Mechanisms" LMSD-894812, 18 April 1961, Lockheed Aircraft Corporation, Missiles and Space Division.

Blackmon, P.H. and others. "Materials Evaluation Under High Vacuum and Other Satellite Environmental Conditions", LMSD 3-77-61-23, Contract AF04(647)-787, January 1962, Lockheed Aircraft Corporation, Missiles and Space Division.

Wall, L.A. and Michaelsen, J.D. "Thermal Decomposition of Polytetrafluoroethylene in Various Gaseous Atmospheres", Journal of Research of the National Bureau of Standards, Vol. 56, No. 1 (January 1956), pp 27-34.

Heller, Gerhard, "Thermal Problems of Satellites", DV-TN-73-58, 22 September 1958, Redstone Arsenal, Development Operations Division.

BIBLIOGRAPHY
FRICTION, WEAR, CONTAMINATION AND LUBRICATION

Ling, F.F. "On Asperity Distributions of Metallic Surfaces", Journal of Applied Physics, Vol. 29, No.8 (August 1958), pp 1168-1174.

Archard, J.F. and Hirst, W. "The Wear of Metals Under Unlubricated Conditions", Journal of Applied Physics, Vol. 236, (25 February 1956), pp 397-409.

Kerridge, M. and Lancaster, J.K. "The Stages in a Process of Severe Metallic Wear", Journal of Applied Physics, Vol. 236, (25 February 1956), pp 250-264.

Rabinowicz, E. "Friction and Wear at Elevated Temperatures" WADC TR 59-603, Contract No. AF33 (616)-5963, January 1960, Massachusetts Institute of Technology, Materials Laboratory.

Barkan, H.E. "Mechanism of Wear", Electro-Technology, Vol. 67-68 (July 1961), pp. 96-102.

Baber, B.B. and others. "Lubrication Research and Test Method Development for Aerospace Propulsion Systems", ASD TR 61-85, Contract AF33(616)-7223, May 1961, Southwest Research Institute.

"STL Tests Lubricants for Satellite Units", Chemical and Engineering News, 41 (March 5, 1962), pp. 88.

Buckley, D.H. and Johnson, R.L. "Effect of Inert, Reducing, and Oxidizing Atmospheres on Friction and Wear of Metals to 1000°F", NASA TN D-1103, October 1961, National Aeronautics and Space Administration, Lewis Research Center.

Dorinson, A and Broman, V.E. "Contact Stress and Load as Parameters in Metallic Wear", Wear, Usure-Verschleiss, Vol. 4, No. 2 (March/April 1961) pp. 93-110.

Wheeler, H.L., Jr. and Sherrill, E.A. "Contamination and Servovalves - Part 3, Contaminants", Hydraulics and Pneumatics (July 1962), pp. 93-95.

Cornell, R.L., Lucas, R.S. and Young, H.L. "Friction and Wear for Water-Lubricated Seals", Product Engineering (July 24, 1961) pp. 38-41.

Goddard, J., Harker, H.J. and Wilman, H. "A Theory of the Abrasion of Solids Such as Metals", Nature, Vol. 184, No. 4683 (August 1, 1959), pp. 333-335.

Peterson, M.B. and Johnson, R.L. "Friction of Possible Solid Lubricants with Various Crystal Structures", TN 3334, December 1954, National Advisory Committee For Aeronautics, Lewis Flight Propulsion Laboratory.

Peterson, M.B. and Johnson, R.L. "Friction and Surface Damage of Several Corrosion-Resistant Materials", RM E51L20, 20 February 1952, National Advisory Committee for Aeronautics, Lewis Flight Propulsion Laboratory.

Rabinowicz, E. "Influence of Surface Energy on Friction and Wear Phenomena", Journal of Applied Physics, Vol 32, No. 8, (August 1958), pp 1440-1444.

Rabinowicz, E. and Foster, R.G. "The Size Distribution of Wear Fragments", Contract No. DA-19-202-ORD-4705, 10 April 1962, Massachusetts Institute of Technology, Surface Laboratory.

BIBLIOGRAPHY

VALVES AND ACTUATORS

General Dynamics/Convair-Astronautics Report No. 2343 AD 272495

Charles P. Bacha, "Supplementary Report - Design, Development, and Testing of Advanced Pneumatic Solenoid Valve (Single-Passage)", Part No. 4683-59302, Report MD60-98, Contract No. AF04(647)-160, September 1960 AFBMD-TR-60-203

Tellier, G. F., Ferguson, M. D., and Mannes, P. "Poppet and Seat Program Phase I - Survey Report," R-3819-1, AF 04(611)-8392, PP 25 and v, October 1962, Rocketdyne, Control Valves Group.

Tellier, G. F., and Mannes P. "Valve Design, A Literature Survey," R-3819-2, AF 04(611)-8392, PP 127 and v, September 1962, Rocketdyne, Control Valves Group.

"Ultra-Thin TFE Film Lubricates Plug Valves," Materials in Design Engineering, Volume 55, No. 1, January 1962, PP. 133-134.

Berg, Robert J. "A Review Of Seal Materials For Guided-Missile Applications," 20-340, PP. 16, 7 March 1958, Jet Propulsion Laboratory, California Institute of Technology.

"Design, Development, and Testing of Advanced Helium Pressure Regulator," Part No. 551302, AFBMD--TR 60-74, July 1960, Rocketdyne, Contract No. AF 04(647)-160.

Frebank Company, "Design, Development and Testing of Non-Modulating Pressure Control Valves," Contract No. AF04(647)-429, December 1961, PP. 120 plus figures, Frebank Company.

Frankford Arsenal Vol I Propellant Actuated Devices Symposium
June 14-16 1961 AD 273019

FILTERS

"Studies on Filters for Missile Hydraulic Systems," DSN-TR-1-60 June 1960

ZERO GRAVITY

Richard C. Andrews, "Zero Gravity Liquid Oxygen Converter", ASD Technical Report 61-431, AD 267 047, Contract AF 33(616)-6189, September 1961, MSA Research Corporation, Callery, Pennsylvania

Elliot T. Benedikt, "*Weightlessness-Physical Phenomena and Biological Effects*", Plenum Press, New York, Symposium on Physical and Biological Phenomena Under Zero G Conditions, held July 1, 1960 at Hawthorne, Calif. QH657 S989p

Kama, William, N. "Speed and Accuracy of Positioning Weightless Objects As A function Of Mass, Distance, and Direction," WADD TR 61-182, PP. 19, March 1961, Wright-Patterson Air Force Base, Wright Air Development Division.

Dzendolet, Ernest. "Manual Application of Impulses While Tractionless," WADD TR-60-129, PP. 12, February 1960, Wright-Patterson Air Force Base, Wright Air Development Division.

SPACE FLIGHTS

"Results of the First U.S. Manned Orbital Space Flight", February 20, 1962, National Aeronautics and Space Administration, Manned Spacecraft Center.

Langley Research Center Staff, "A Report on the Research and Technological Problems of Manned Rotating Spacecraft", NASA TN-D-1504, August 1962, Langley Research Center.

"Research Study to Determine Propulsion Requirements and Systems for Space Missions" Report No. 2150, Vol. III - Mission Studies, Contract NAS 5-915, Aerojet-General Corporation, Spacecraft Division.

Mitchell, E., Tischler, A.O., and Cohen, W. "Liquid and Solid Stages for a Manned Lunar Landing Vehicle", Report 2284-61, American Rocket Society Space Flight Report to the Nation/New York Coliseum, October 9-15, 1961.

"Proceedings of the Manned Space Stations Symposium", Institute of the Aeronautical Sciences, April 1960.

Petersen, N.V., Pode, L., and Hoover, L.R. "Satellite Rendezvous Navigational Requirements", *Navigation, Journal of the Institute of Navigation*, Vol. 6 (Spring 1958) pp. 445-459.

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