NASA TECHNICAL NOTE

NASA TN D-4619

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NASA TN D-4619

CYROGENIC STORAGE SYSTEMS FOR EARTH-ORBITAL AND MARS-FLYBY MISSIONS

by Robert K. Allgeier, Thomas L. Davies, and Robert R. Rice

Manned Spacecraft Center
Houston, Texas

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1968

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ABSTRACT

A study program was undertaken to assess cryogenic gas requirements and storage methods for four design reference missions with respect to present thermal performance. Developed data indicate that anticipated improvements in static insulation techniques will not suffice to meet long-term cryogenic-gas storage requirements unless vessel environmental temperatures are lowered, and the data indicate that there is need for further research on refrigeration techniques. Parametric curves and data are presented to make possible the rapid determination of cryogenic expendable requirements, Dewar sizes, and thermal protection schemes for application similar to the design reference systems.

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FOR EARTH-ORBITAL AND MARS-FLYBY MISSIONS

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SUMMARY

A study program was conducted to assess the cryogenic fluid requirements and methods of cryogenic storage for manned Earth-orbital and Mars-flyby missions lasting 6 to 24 months. The expendables considered were fuel cell reactants, metabolic oxygen, and diluent gases. The storage of cryogenic propellants was not considered. State-of-the-art thermal performance was reviewed and compared with mission requirements. If the present insulation technology failed to satisfy the long-term storage requirements, alternatives were considered. Some aspects of the supercritical and subcritical modes of cryogenic storage are discussed in this paper.

The results of this study indicate that the anticipated improvements in static insulation techniques are not sufficient to meet long-term cryogenic storage requirements if current design environmental temperatures are maintained. If vessel environmental temperatures are lowered, present insulation techniques will satisfy the thermal performance requirements for the manned space station as well as the Mars-flyby mission.

INTRODUCTION

The purpose of this study was to provide parametric curves and data to make possible the rapid determination of cryogenic expendable requirements, Dewar sizes, storage modes, and thermal protection schemes associated with the four design reference missions.

Fuel cell reactants, metabolic oxygen, and diluent gases may be stored under high pressure at ambient temperature, or cryogenically in the supercritical and subcritical states. Experience indicated that cryogenic storage results in the lightest system weights unless the mission is of extremely short duration. Supercritical storage of cryogens has been successfully utilized in the Gemini and Apollo Programs; whereas the high-pressure, ambient-temperature method of gas storage was used on board Project Mercury spacecraft.

The gases considered for use as cabin atmosphere diluents were nitrogen, helium, and neon. The use of nitrogen will result in the highest diluent gas weight penalty; whereas helium, because of low molecular weight, will result in the lowest weight penalty. Neon, which has a liquid density of 77 lb/ft^3, could possibly be used in a vessel designed for oxygen, which has a density of 71 lb/ft^3. Cryogenic neon is not, however, readily obtainable in the quantities required, and the production cost would probably be significantly higher than for either helium or nitrogen.

SYMBOLS

A	area, ft^2
Am	mean area, ft^2
D	diameter, ft
K	thermal conductivity, Btu/hr-ft-°R
L	length, ft
M	mass, lb
m_d	diluent gas mass
m_{O_2}	oxygen mass
mf_d	mass fraction of diluent gas
mf_{O_2}	mass fraction of oxygen
N	number of radiation shields
Q	heat, Btu
Q_L	heat leak, Btu/hr
Q_{LRN}	heat leak (radiation) with N radiation shields, Btu/hr
Q_{LRO}	heat leak (radiation) without radiation shields, Btu/hr
Q_T	total heat leak, Btu/hr

T	temperature, °F or °R
t	time, hr
W	flow rate, lb/hr
ϵ	surface emissivity
σ	Stefan-Boltzmann constant, 0.173×10^{-8}, Btu/hr-ft^2-°R^4

Subscripts:

1	outer surface
2	inner surface

MISSION CONSIDERATIONS

Because crew sizes, mission objectives, and mission durations will vary significantly, it is necessary to consider several design reference missions. For the post-Apollo generation of manned spacecraft, the selected reference missions, shown in the following table, encompass the range of anticipated cryogenic fluid requirements.

Design reference		
Number	Mission type	Duration, months
I	24-man space station	6, 24
II	9-man space station	6, 24
III	5-man Mars flyby	23
IV	3-man Earth synchronous	6, 24

The basic design reference space station and Earth-synchronous missions shown here are of 24-month duration. However, the study results are presented as a function of time, so that the option of resupply in Earth orbit may be planned.

FLUID REQUIREMENTS

The fluid requirements are determined from electrical power needs, leak rates, and metabolic oxygen usage. Fuel cell reactant usage for nominal, average power requirements as a function of mission duration is shown in figure 1. The metabolic oxygen requirement is 2 pounds per man-day. The diluent gases considered are nitrogen, neon, and helium. The oxygen requirements (metabolic and cabin leakage) and the diluent gas requirements for the design reference missions are shown in figures 2 to 5.

Because the diluent gas is not consumed, it is necessary only to compensate for the amounts lost through leakage. The cabin atmosphere and gaseous volume lost through leakage are assumed to be a homogeneous binary gas mixture at 5 psia; that is, the mass fraction of the leakage is the same as the mass fraction in the cabin

$$mf_{O_2} = \frac{m_{O_2}}{m_{O_2} + m_d} \tag{1}$$

$$mf_d = 1 - mf_{O_2} \tag{2}$$

The mass fractions for oxygen and the various diluent gases for the conditions shown are listed in table I. The base leak rates, also listed in table I, are predicted for the reference spacecraft configurations.

It should be emphasized that the fluid requirements discussed do not include the quantities needed for initial spacecraft pressurization or for extravehicular activity (EVA). These two requirements were omitted in this study to avoid selecting a specific space vehicle or mission. Such selections were beyond the scope of this paper and would not have significantly altered the trends indicated.

STATE OF THE ART

Storage Methods

The methods of fluid storage may be divided into two general categories: supercritical and subcritical.

Supercritical storage refers to the stored-fluid state that exists when both storage pressure and storage temperature exceed the critical values. The primary advantage of this method is that the fluid exists in a single phase, thus negating the requirement for liquid-phase orientation during operation in a low-gravity environment, as shown by test evaluation of an Apollo Block I cryogenic storage system conducted at the Manned Spacecraft Center (MSC). As the storage vessel is depleted, the specific volume of the fluid increases, but the fluid continues to occupy the entire vessel as a single, homogeneous phase. Supercritical storage of cryogenic fluids has been successful on both Gemini and Apollo spacecraft.

Subcritical storage includes all instances in which the stored fluid exists as two or three phases in equilibrium such as liquid and gas; or as solid, liquid, and gas. Certain space propulsion systems have utilized short-term subcritical storage vessels.

Subcritical storage-system development and testing have been the subjects of intense study in recent years (ref. 1). The present capability regarding in-space storage of a two-phase cryogen should make possible a significant relaxation of thermal design limits for long-term (i. e., 6 months) Apollo Applications Program missions.

Insulation

The method of insulation must minimize conductive and radiative heat leak to the Dewar contents. Consequently, the insulation scheme must possess the highest quality and result in the highest practical performance. (The exclusive use of a vacuum jacket around the storage vessel eliminates convective heat transfer.)

The Gemini cryogenic vessels are insulated with crinkled, aluminized Mylar. This material is arranged in concentric layers within the vacuum annulus (between the pressure vessel and the vacuum shroud). This laminar insulation and the vacuum annulus provide protection against radiative and convective heat transfer, respectively. The inner pressure vessel is structurally supported by six compressed Fiberglas pads, which are also located in the vacuum annulus.

Gemini cryogenic storage vessels were fabricated in six different sizes to meet the requirements of 2- and 14-day missions. The thermal design goal was based upon the stricter of two requirements: first, of nonventing standby, and second, of minimum flow rate. In general, the latter is the more stringent requirement for missions lasting several months.

The insulation and support scheme for the lunar module cryogenic-helium system is very similar to that used in Gemini vessels. The Apollo Block I hydrogen and oxygen vessels and Block II oxygen vessels are insulated with load-bearing insulation made of alternate layers of aluminum foil and Dexiglas paper spacer material. The Apollo Block II hydrogen vessels have a slightly improved insulation and support scheme. These hydrogen vessels are supported by three laminated straps, each composed of alternate layers of titanium strips and spacer material. In addition, the annular spaces of the Block II hydrogen vessels contain laminated insulation composed of compressed layers of a gold-plated film. Both the Block I and Block II hydrogen and oxygen systems contain vapor-cooled shields in the vacuum annulus.

Several prototype systems have been developed for the NASA Manned Spacecraft Center (MSC). These developmental systems employ Teflon spacers which support discrete radiation shields in the vacuum annulus. The pressure vessel is supported by glass-filled Teflon bumpers. Vessels which contain discrete shields have demonstrated several advantages over systems containing laminar insulation. The assembly time is considerably shorter, the system has a cleaner annulus and better vacuum-life characteristics, and thermal performance is equal to, or better than, the performance of systems containing laminar insulations. Representative performance data from the systems discussed are shown in figure 6.

Since introduction of the multilayer, radiation-shielded insulation concept, the most significant advances in thermal protection schemes have been the introduction of discrete shields and the vapor cooling of shields in general. Gradual improvements in multilayer insulation performance have been noted as a result of insulation application refinements.

Materials and Fabrication Techniques

The materials used for the Gemini and Apollo cryogenic pressure vessels are Inconel 718 for oxygen, and Ti 5Al 2.5Sn Extra Low Interstitial (ELI) for hydrogen. The Gemini pressure vessels are spheres made of hydroformed or deep-drawn hemispheres. The Apollo pressure vessels are spheres fabricated from forged and machined hemispheres. Relative to inturgescent and bulge forming, forging and machining have proved to be expensive fabrication processes, and the titanium forgings presently require a leadtime of more than 1 year. The forged and machined hemispheres are not considered to be of better quality than hemispheres made to the same dimensions by hydroforming, spinning, deep drawing, or hydraulic bulge forming.

The MSC has funded a program[1] to develop a pressure vessel utilizing a material that has a strength-to-density ratio slightly better at cryogenic temperatures than the titanium alloys presently in use (Ti 5Al 2.5Sn, Ti 6Al 4V). The process under development uses a subsized, preformed pressure vessel of 301 stainless steel which may be fabricated by normal processes. The pressure vessel is cold-worked at -320° F by pressurization with liquid nitrogen. The additional strength is obtained from the strain-induced transformation of metastable austenite to martensite at -320° F. No compatibility limitations which might constrain cryogenic applications of this material have been found to date. Cryostretched stainless steel seems to be a suitable material for spacecraft cryogenic-gas storage systems (CGSS); it facilitates vessel fabrication and has good strength characteristics.

Quantity Gaging

Capacitance-gaging techniques have been successfully used for mass measurements of supercritical cryogens on both Gemini and Apollo spacecraft. These applications necessitate sampling only a single point in the storage volume, because the stored

[1]This program has been established under NASA prime contracts NAS 9-2407, NAS 9-2648, and NAS 9-5491.

fluid is homogeneous. An experimental vessel, flown to demonstrate the feasibility of subcritical storage, contained a cubical, thin wire-matrix capacitance gage used to sample the entire two-phase contents (ref. 1). Several other methods, such as radiofrequency attenuation and radiation attenuation can also be used for quantity measuring.

Life-Limited Components

The obvious life-limited components are thermal-destratification motors, valves, and switches. A cryogenic gas equilibration system is desirable, and a motor-development program is underway to study means of fulfilling the current need for motors with extended life expectancy.

Relief valves are cycle life limited because of internal spring friction. However, these valves should not be required to cycle unless a failure occurs in the thermal protection system or unless flow from the vessel is below the design minimum.

Design Pressures

It is desirable to select state points for cryogenically stored fluids which require a maximum amount of heat per unit mass of fluid expelled (dQ/dM). If this is done, the environmental heat leak to the bulk of stored fluid has a minimum effect and reduces or eliminates wasteful venting.

The dQ/dM values for oxygen, nitrogen, and neon are appreciably higher for two-phase (subcritical) storage than for single-phase (supercritical) storage. The storage pressures selected for oxygen, nitrogen, and neon are subcritical. With respect to hydrogen and helium, supercritical pressures were chosen because the supercritical and subcritical dQ/dM values for these fluids are comparable. Supercritical storage is desirable wherever possible because orientation problems associated with subcritical storage are eliminated.

The pressures selected for this study resulted in acceptable pressure-vessel weights, but the pressures were not weight optimized in conjunction with the associated latent heats. These pressures were as follows:

Hydrogen	600 psia
Oxygen	150 psia
Nitrogen	150 psia
Helium	1000 psia
Neon	150 psia

Fluid withdrawal from any storage system results in removal of energy from the system. For constant-pressure operation, the energy withdrawn by the exiting fluid must be replaced. The quantity of energy leaving a cryogenic storage system is strongly dependent upon the storage pressure. Therefore, when missions impose long-term nonventing storage requirements, the storage pressure must also be optimized with the thermal protection scheme.

Thermal Protection

Heat leak is a function of the thermal properties of the insulation, the temperature gradient, and the surface area of the vessel. For a given design and environment, the surface area is the only remaining variable. For a sphere, area is a function of diameter; therefore, the following is applicable.

$$Q_L \propto D^2 \tag{3}$$

The initial stored-fluid mass is the product of the density and the volume. Volume is a function of diameter; thus, the loaded mass is also related to diameter as follows.

$$M \propto D^3 \tag{4}$$

Dividing equation (3) by equation (4) yields

$$\frac{Q_L}{M} \propto \frac{1}{D} \tag{5}$$

The storage vessel will supply fluid for an interval t which is dependent upon the flow rate.

$$t = \frac{M}{W} \tag{6}$$

The heat leak relative to the energy required for mass expulsion determines the equilibrium flow rate. For a given design and for an infinitesimal time interval, the energy required for mass expulsion may be considered a constant; thus, the instantaneous flow rate is a function of the heat leak only.

$$W \propto Q_L \tag{7}$$

Substitution of equation (7) in equation (6), then rearranging, yields a functional relation for time, shown as

$$\frac{Q_L}{M} \propto \frac{1}{t} \tag{8}$$

The foregoing equations show that Q_L/M is related both to diameter (eq. (5)) and to time (eq. (8)). For the curves shown in figure 7, the flow rate is assumed to be constant regardless of the mode of storage. However, figure 7 is independent of the specific cryogen under consideration.

The use of the Q_L/M curves is twofold. First, if a vessel that stores a given mass and has a given heat leak is available, the mission that this vessel will satisfy can be determined. Second, if a mission and the mass requirements are known, the allowable heat leak to the stored fluid bulk may be calculated. It should be noted that the best thermal-performance data observed have been used in the generation of the design curves included in this study.

Beginning with figure 7, the thermal performances of hydrogen, oxygen, nitrogen, helium, and neon Dewars are considered. The mission-life limits for various ratios of heat leak to initial stored mass Q_L/M are shown in figure 7. The number of Dewars and the required Dewar performance for an anticipated mission can be determined from figure 7. To determine the geometry of the required storage system, it is necessary to calculate the heat leak per unit area of the vessel surface Q_L/A. This is obtained directly from the Q_L/M plots in figure 7 when used in conjunction with the geometrical relations presented in figures 8 and 9. The mass-storage capacities and surface areas as functions of vessel diameter for a range of length-to-diameter ratios L/D are shown in figures 8 and 9. The resultant Q_L/A plots, presented in figures 10 to 14, will establish design values for a specific mission time and storage state. During selection of Dewar geometries, integration of the storage system with the spacecraft must also be considered.

To determine which technical areas are subject to improvement, the basic heat-transfer equation must be examined. Because the equation is the sum of conduction (supports, penetrations, and so forth) and radiation terms, it may be expressed in general terms as follows.

$$Q_T = \frac{KA}{\Delta X}\left(T_{\text{ambient}} - T_{\text{fluid}}\right) + \frac{Am\sigma}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}\left(T^4_{\text{ambient}} - T^4_{\text{fluid}}\right) \tag{9}$$

The variables in equation (9) must be examined to find an area of improvement. These possibilities are thermal conductivity, surface emissivity, insulation thickness, and outer-shell temperature.

For a given environmental temperature, an improvement in the overall heat leak may be accomplished by a reduction in the conductive heat transfer. The launch environment imposes the constraint that the pressure vessel be well supported with respect to the spacecraft. However, the dynamics of space flight place a considerably small requirement on the support structures. Retractable annular-support schemes are therefore being considered to reduce conductive heat transfer further. Historically, the research in materials technology and in manufacturing processes related to surface preparation has led to gradual improvements in thermal conductivity and surface emissivity. However, this gradual improvement is not sufficient for a cryogenic storage system which must meet radically more stringent performance requirements. Radiation shields located in the intra-annular volume have been successfully used. However, a point of diminishing returns is rapidly approached with the installation of additional shields. The following equation illustrates the effect of additional shields on the heat leak caused by radiation.

$$Q_{LRN} = \frac{Q_{LRO}}{(N + 1)} \tag{10}$$

If the spacecraft volume is constrained, an increase in insulation thickness cannot be considered, and control of the outer-shell temperature must be given special attention. Radiation can be closely controlled with refrigeration techniques, because radiative heat transfer is a function of the fourth power of the heat-source temperature. A reduction in this fourth-power gradient has proved significant.

A vessel that is required to deliver fluid on a continuous basis may be redesigned to use the refrigeration inherent in the relatively cold fluid that exits the pressure vessel. Several schemes that involve a version of vapor cooling have been successfully tested. The exiting fluid can be used to cool the pressure vessel itself, the intra-annular supports, the insulation and discrete shields, or the vacuum shroud.

Refrigeration

Cooling the vacuum shroud to an intermediate temperature appears to be attractive as a means of positively controlling vessel thermal performance using present insulation schemes. The capacity and temperature levels of the refrigeration equipment needed to chill the outer surface of the cryogenic storage vessels are primarily dependent on the allowable heat leak per unit area of tank surface, and on the magnitude of the surface temperature decrease necessary to achieve the allowable heat leak.

Nominal, state-of-the-art heat leak per square foot as a function of outer-shell temperature is shown in figure 15. In assessing refrigeration requirements, entry into figure 15 with a required Q/A value from figures 10 to 14 will yield a required outer-shell temperature. Sufficient test data on feasible refrigeration systems capable of satisfying the particular requirements are not presently available to allow precise sizing of the unit. However, the data available on heat-pump systems (ref. 2) appear reasonable; the data have been extrapolated to cover the range of temperatures under consideration. Refrigeration load as a function of required outer-shell temperature, based on a spacecraft-environment temperature of 70° F, is shown in figure 16. Entry into figure 16 with an environmental temperature extracted from figure 15 will produce the refrigeration load required to maintain a desired outer-shell temperature. The total refrigeration system weight as a function of outer-shell temperature and refrigeration load is shown in figure 17.

CONFIGURATION SELECTION

Configuration selection involved spacecraft constraints and the CGSS size, weight, thermal performance, and cryogen quantity. Loaded-system weights as a function of mission duration for the design reference missions are shown in figures 18 to 21. The weights are shown for oxygen and three diluent gases stored in spherical vessels. These data are based upon a 5-psia atmosphere. The required neon and helium quantities are low relative to the required quantity of nitrogen because of lower molecular weights. Values from the linear portions of figures 22 and 23 were used to determine figures 18 to 21.

The ratio of fluid weight to loaded-system weight as a function of fluid weight for oxygen, nitrogen, and neon is shown in figure 22. The same parameters for hydrogen and helium are shown in figure 23.

All system unloaded weights were based on use of Inconel 718 pressure vessels, aluminum outer shells, and two discrete aluminum radiation shields. An accessory and mounting weight of 10 percent was added. This design was considered to be representative of the high-performance vessels which will be required for the design reference missions.

It may be seen from figures 22 and 23 that, with increasing fluid weights, the fluid-to-loaded-weight ratio approaches a constant with the same Dewar length-to-diameter ratio L/D. This illustrates that the CGSS loaded weights are essentially independent of the number and size of Dewars. It should be noted that this is valid only when the stored quantities per Dewar are in excess of certain minimum requirements (1200 pounds each of oxygen, nitrogen, and neon; 100 pounds each of hydrogen and helium).

When system weights are estimated, a refrigeration penalty must be assessed for missions lasting longer than approximately 6 months. The refrigeration system weight and power consumption can be reduced by locating the CGSS on the dark side of the spacecraft and isolating it from heat sources, thus passively lowering the environmental temperature.

CONCLUSIONS

Parametric curves and data, with a discussion of various implications, are presented to assist the cryogenic-gas storage-system designer in planning a mission. Careful application of the methods used and the results acquired in this study make possible the rapid determination of cryogenic expendable requirements, Dewar sizes, and thermal protection schemes for applications similar to the design reference missions.

Early in the planning of a mission in which high-performance storage systems will be required, the methods of subcritical storage should be studied carefully and an additional flight experiment should be considered for the selected methods. The subcritical mode of operation should incorporate a method for withdrawal of either liquid or vapor.

The possibility of using neon and helium as diluent gases instead of nitrogen, should be seriously considered with respect to the significant potential weight savings.

A separate study of refrigeration should be performed to trade off the penalties associated with venting, shadow shielding, vehicle orientation, intermediate refrigeration, or any combination of these factors. It is evident that refrigeration will be required for the storage of liquid helium on missions with a duration of 6 months. On Mars-flyby (or similar) missions, refrigeration will be needed for the storage of all cryogens on board the spacecraft.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, March 18, 1968
961-21-35-15-72

REFERENCES

1. Allgeier, Robert K.: Subcritical Cryogenic Storage Development and Flight Test. NASA TN-D-4293, 1968.

2. Anon.: Investigation and Analysis of the Application of a Heat Pump in Thermal Control Systems for a Manned Spacecraft. Final Report. Rep. GD/C-65-120, General Dynamics/Convair, Aug. 1965.

TABLE I. - MASS FRACTIONS AND LEAK RATES FOR OXYGEN AND VARIOUS DILUENT GASES

Mission	Atmosphere	Mass fraction				Leakage, lb/hr			
		O_2	N_2	Ne	He	O_2	N_2	Ne	He
I	Oxygen-nitrogen	0.727	0.273	--	--	1.088	0.408	--	--
	Oxygen-neon	.785	--	0.215	--	1.174	--	0.322	--
	Oxygen-helium	.949	--	--	0.051	1.420	--	--	0.076
II	Oxygen-nitrogen	.727	.273	--	--	.544	.204	--	--
	Oxygen-neon	.785	--	.215	--	.587	--	.161	--
	Oxygen-helium	.949	--	--	.051	.710	--	--	.038
III	Oxygen-nitrogen	.727	.273	--	--	.393	.147	--	--
	Oxygen-neon	.785	--	.215	--	.424	--	.116	--
	Oxygen-helium	.949	--	--	.051	.513	--	--	.027
IV	Oxygen-nitrogen	.727	.273	--	--	.291	.109	--	--
	Oxygen-neon	.785	--	.215	--	.314	--	.086	--
	Oxygen-helium	.949	--	--	.051	.380	--	--	.020

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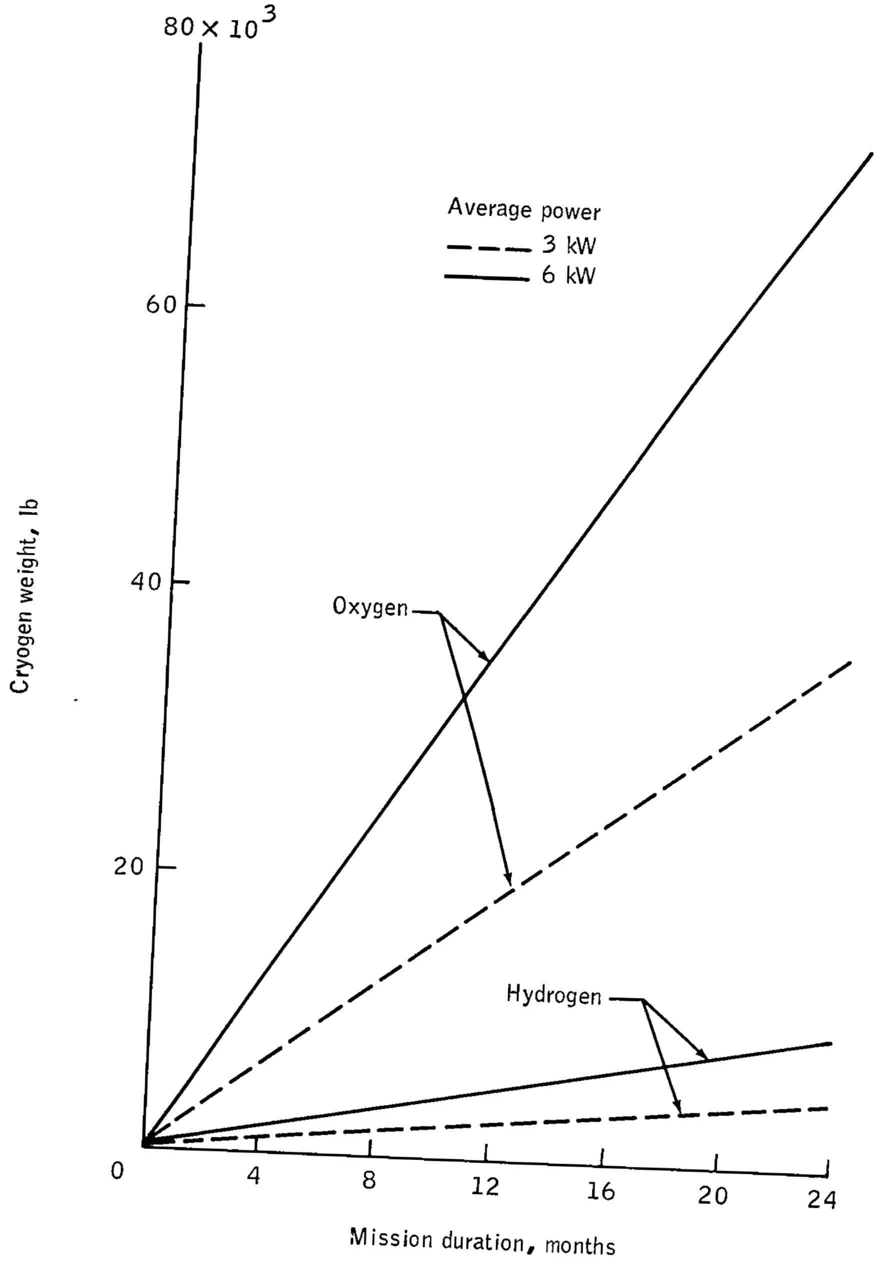

Figure 1. - Fuel cell reactant requirement.

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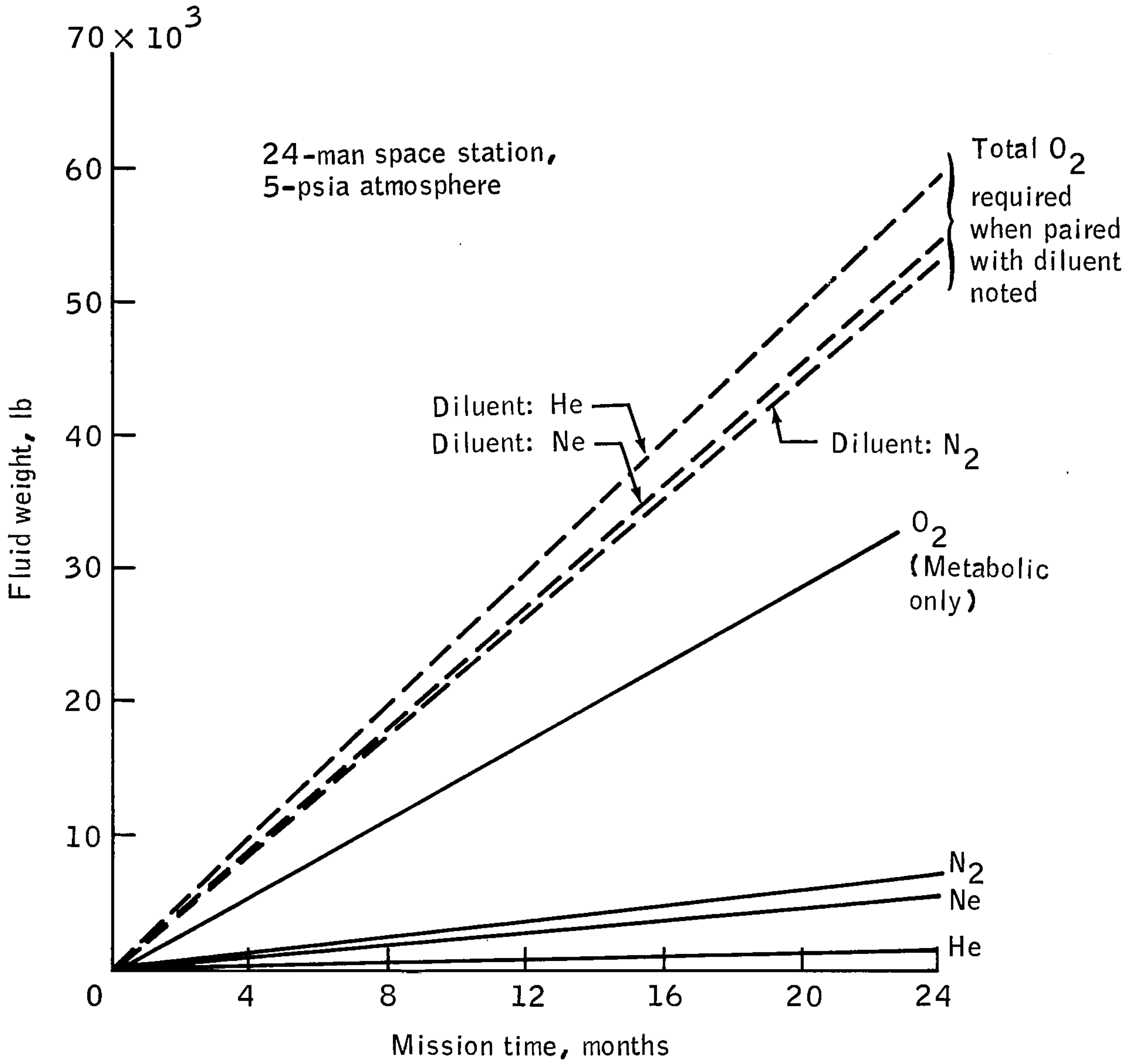

Figure 2. - Combined leakage and metabolic fluid requirements for reference mission I.

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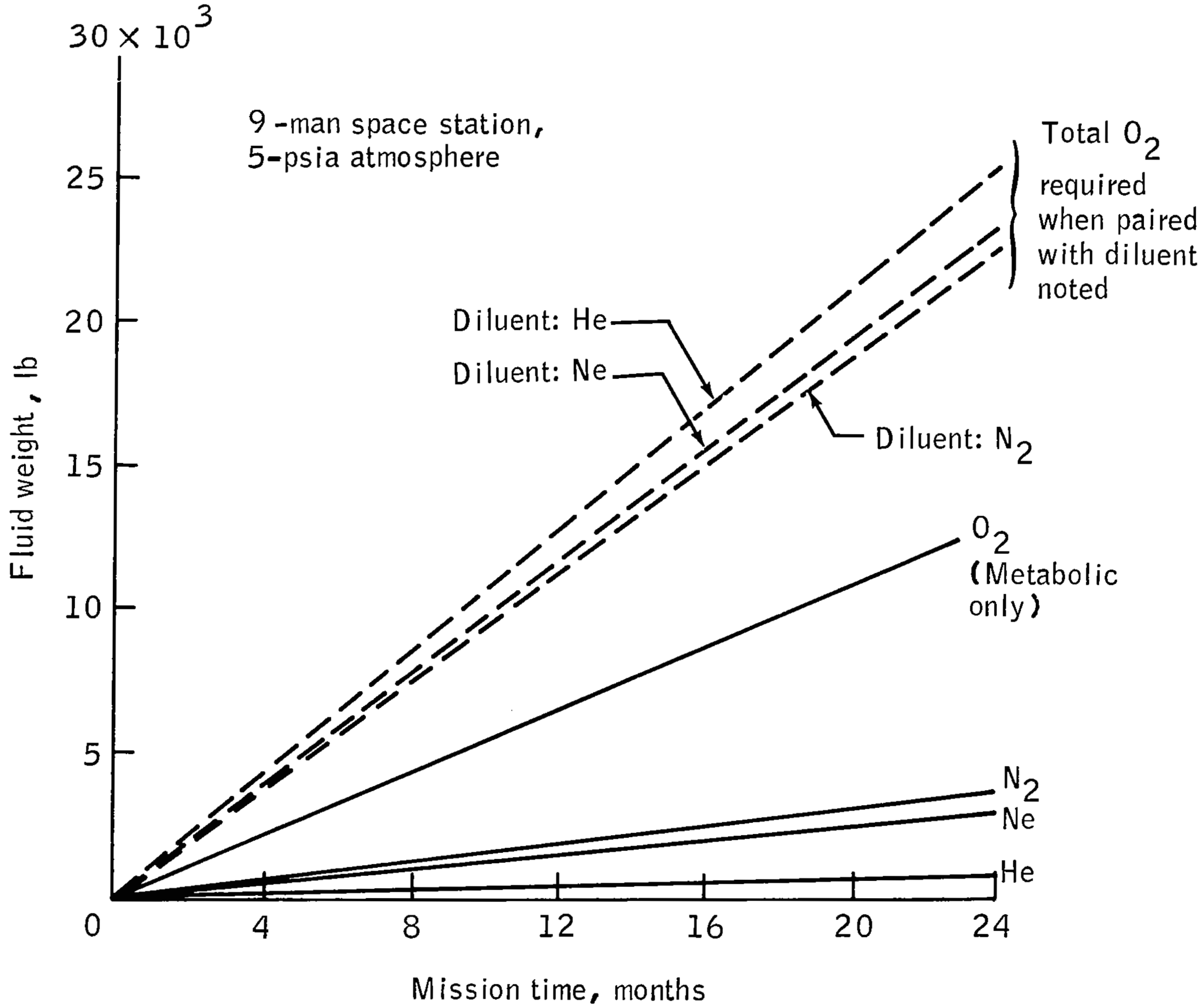

Figure 3. - Combined leakage and metabolic fluid requirements for reference mission II.

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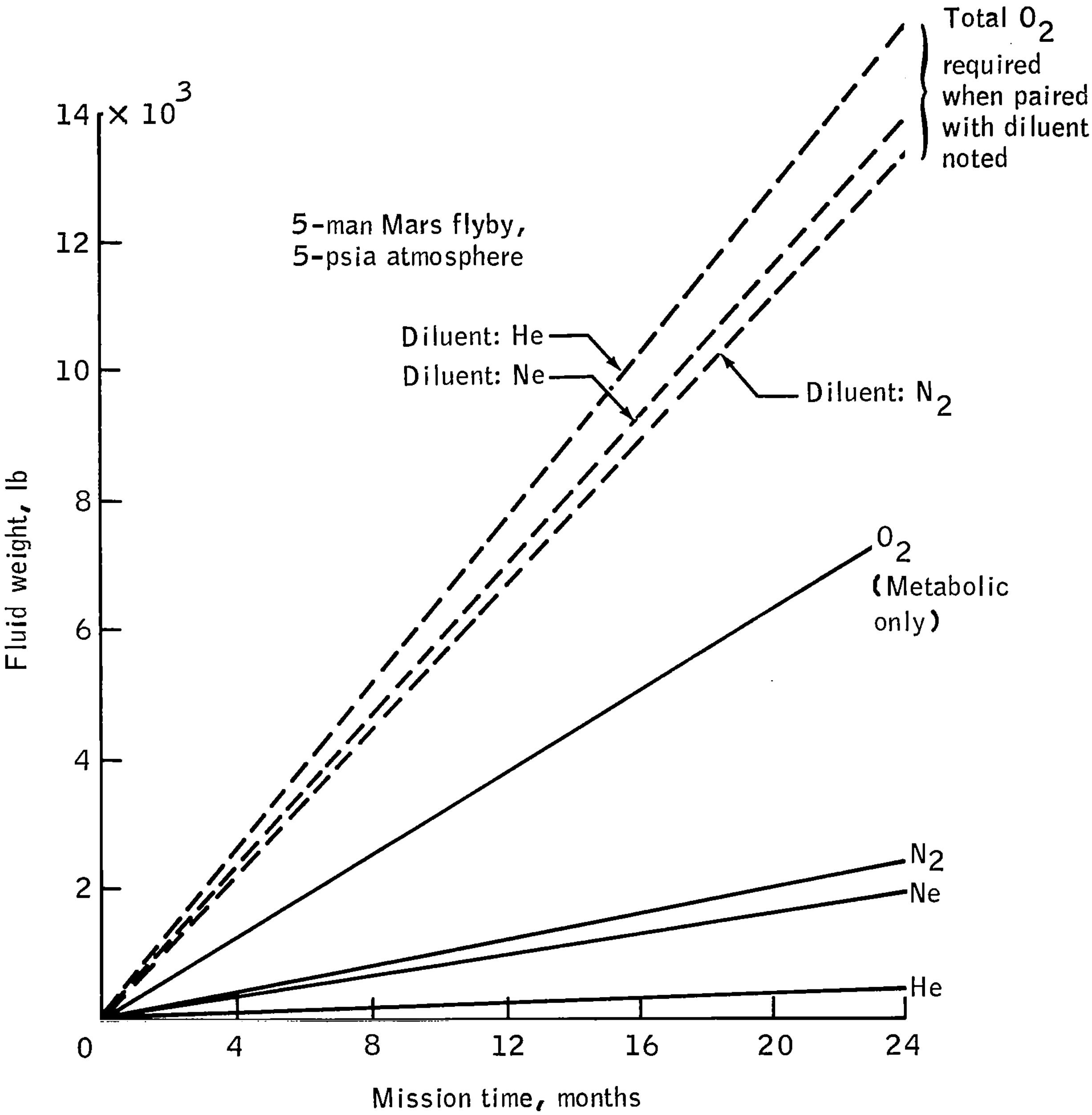

Figure 4. - Combined leakage and metabolic fluid requirements for reference mission III.

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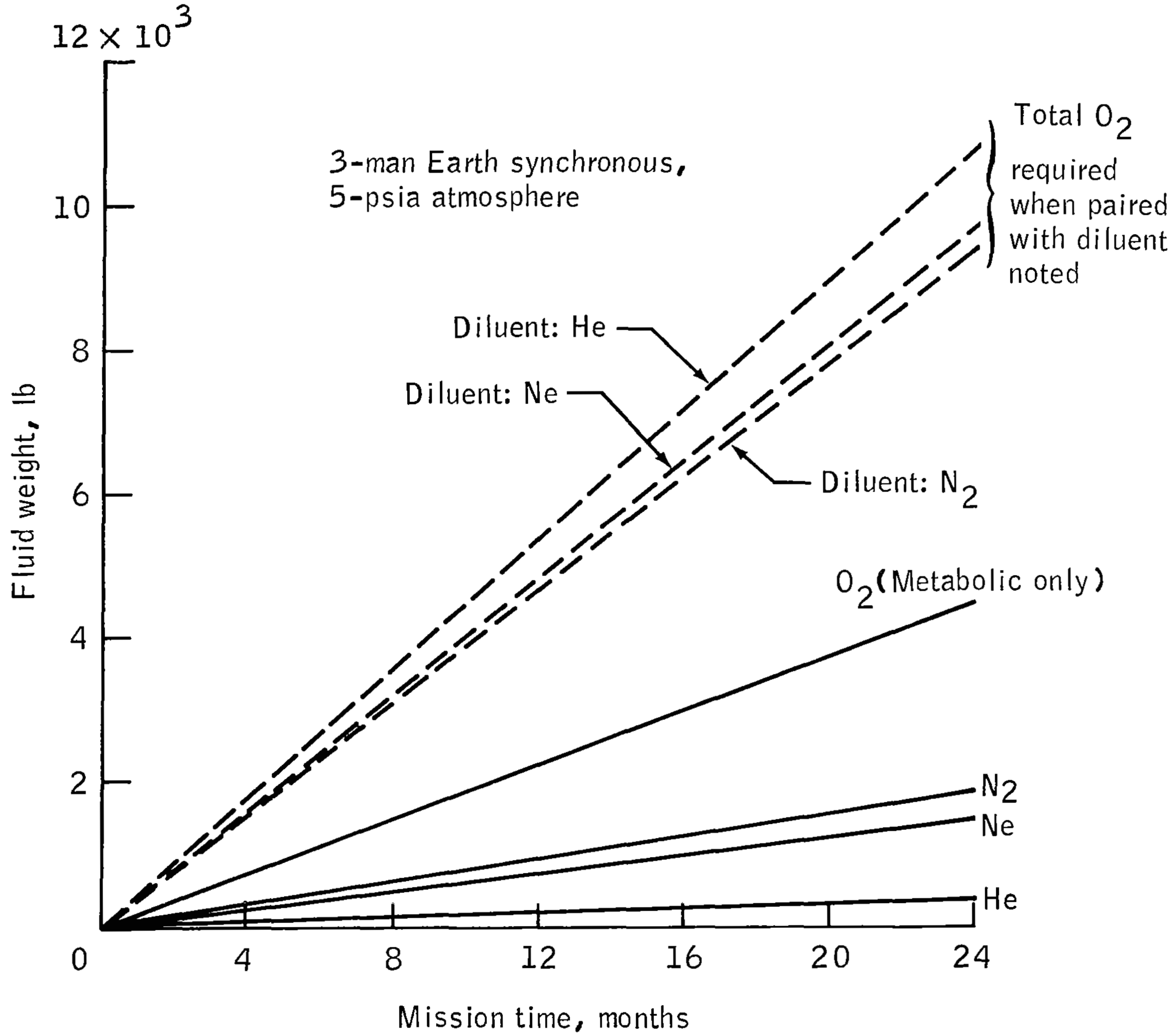

Figure 5. - Combined leakage and metabolic fluid requirements for reference mission IV.

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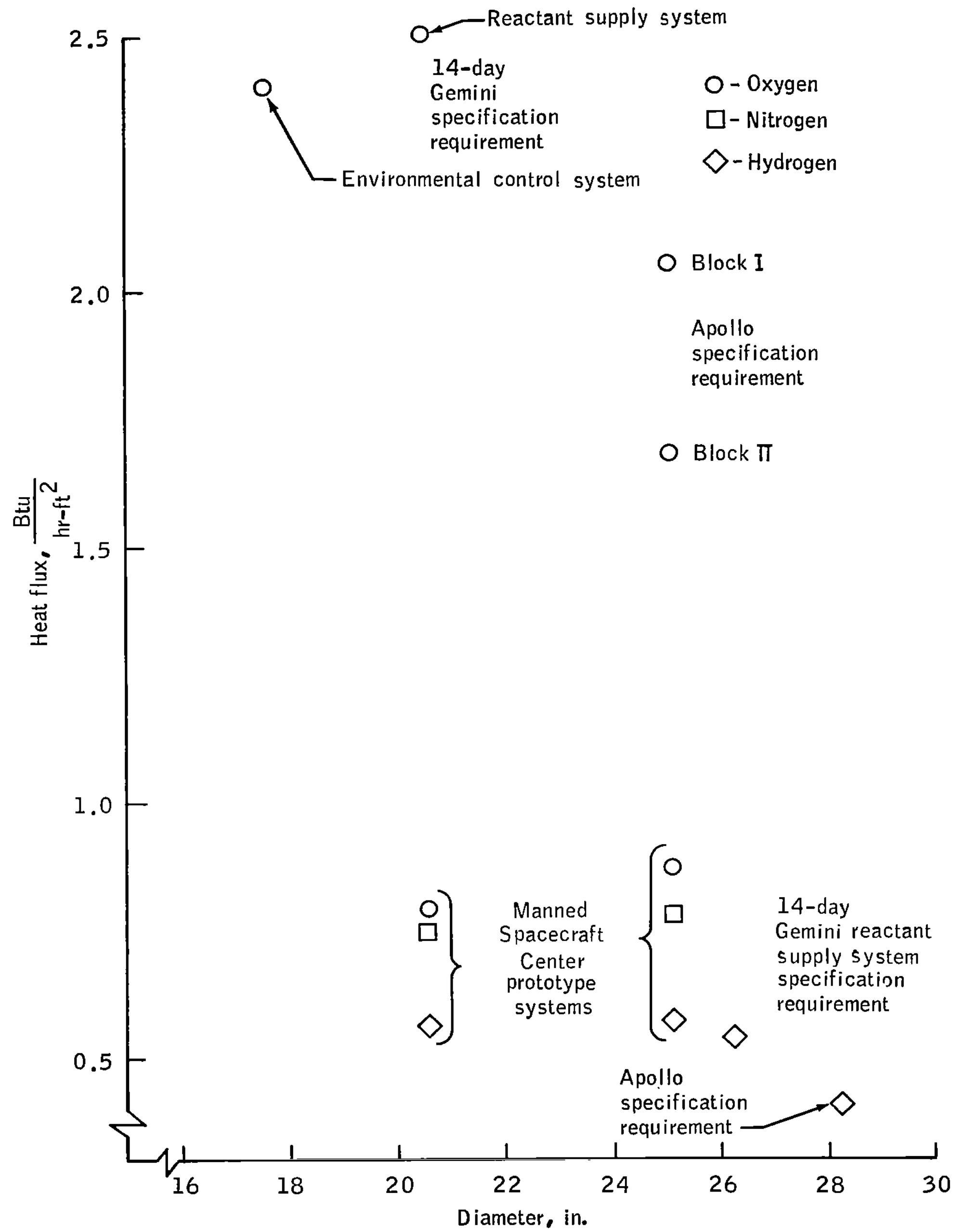

Figure 6. - Heat flux to the pressurized fluid versus inner vessel diameter.

NASA-S-67-5570

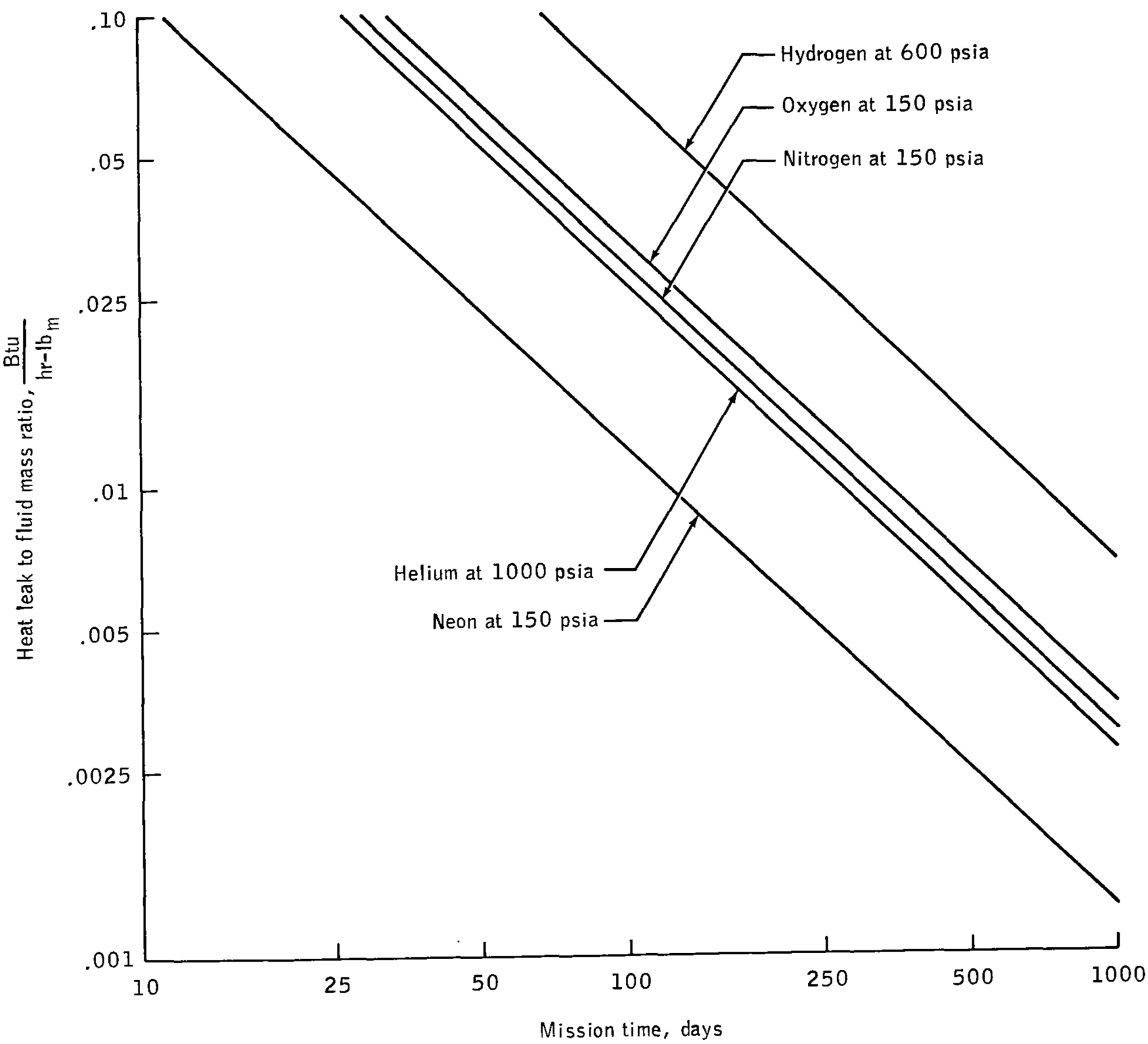

Figure 7. - Heat-leak-to-fluid-mass ratio as a function of mission time.

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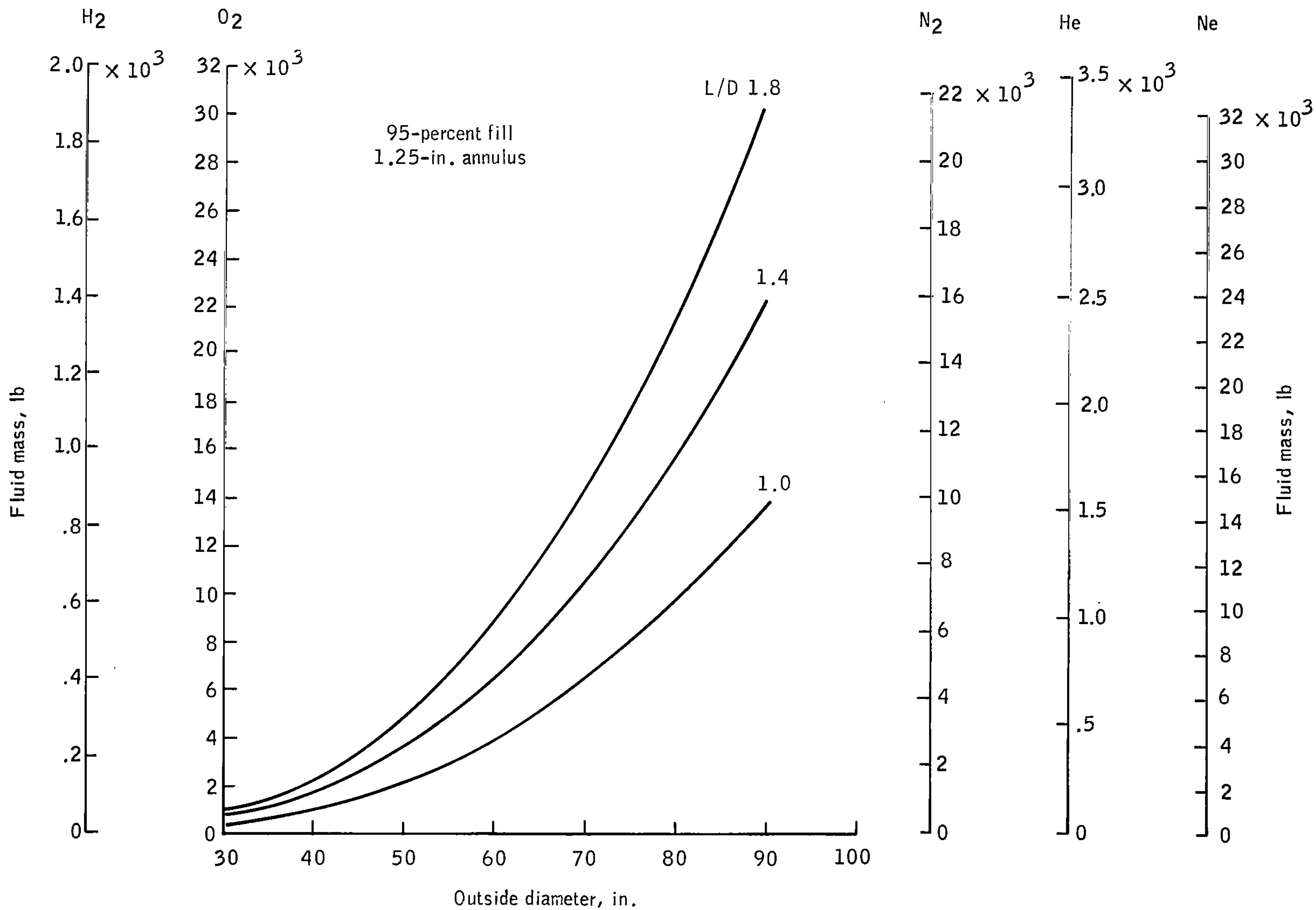

Figure 8. - Fluid mass as a function of Dewar outside diameter for a range of length-to-diameter ratios L/D.

NASA-S-67-5562

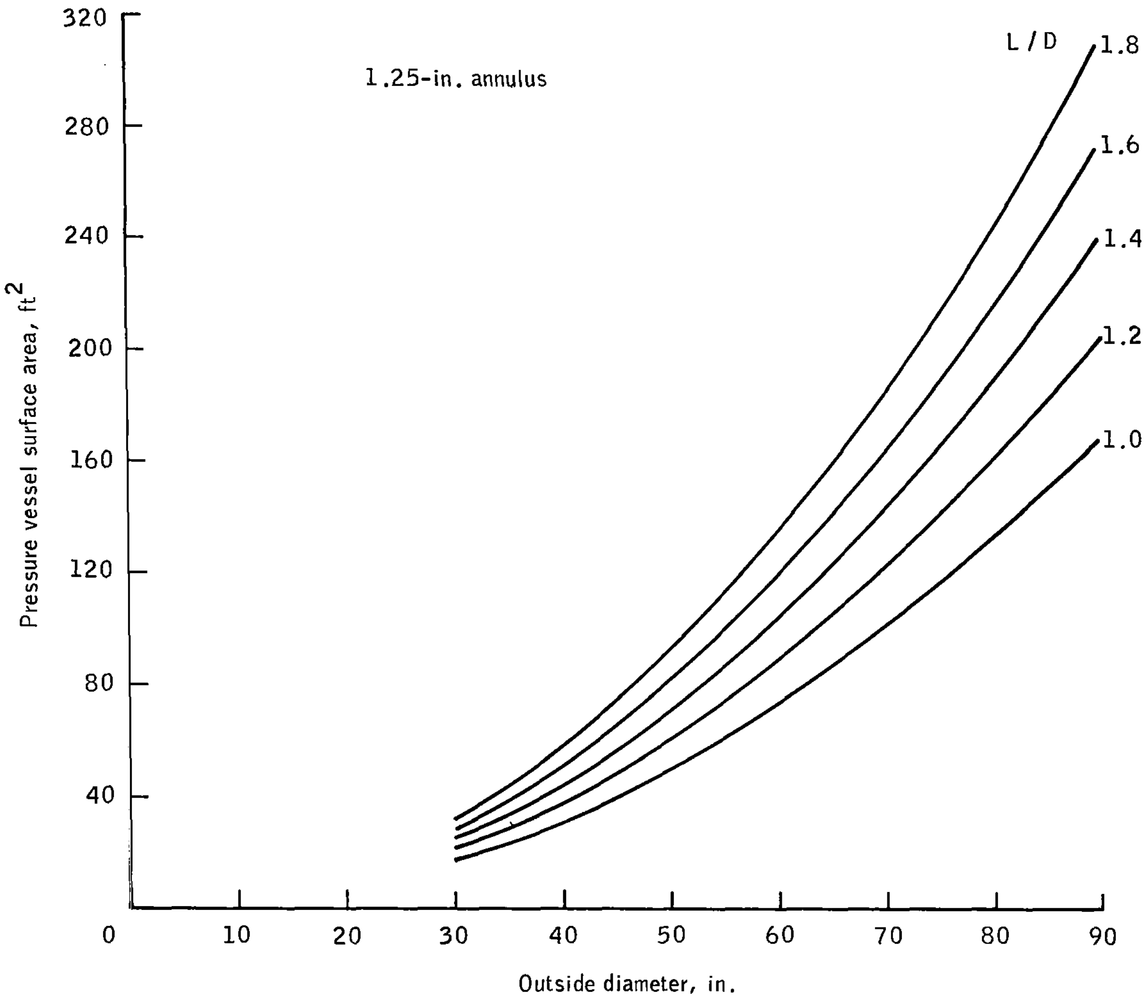

Figure 9. - Pressure vessel surface area as a function of outside diameter for a range of length-to-diameter ratios L/D.

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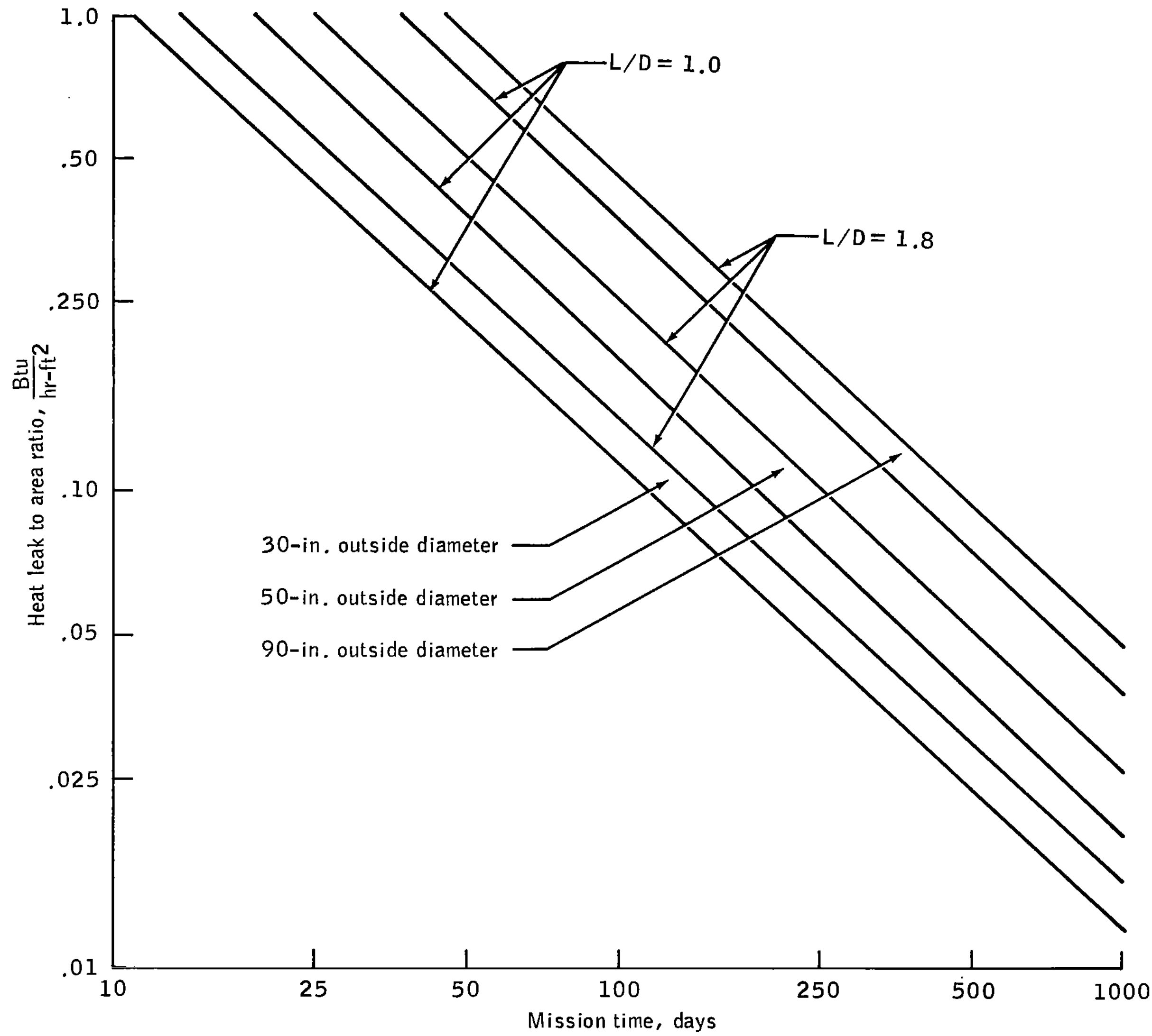

Figure 10. - Heat-leak-to-area ratio as a function of mission time for a range of length-to-diameter ratios L/D (600-psia hydrogen).

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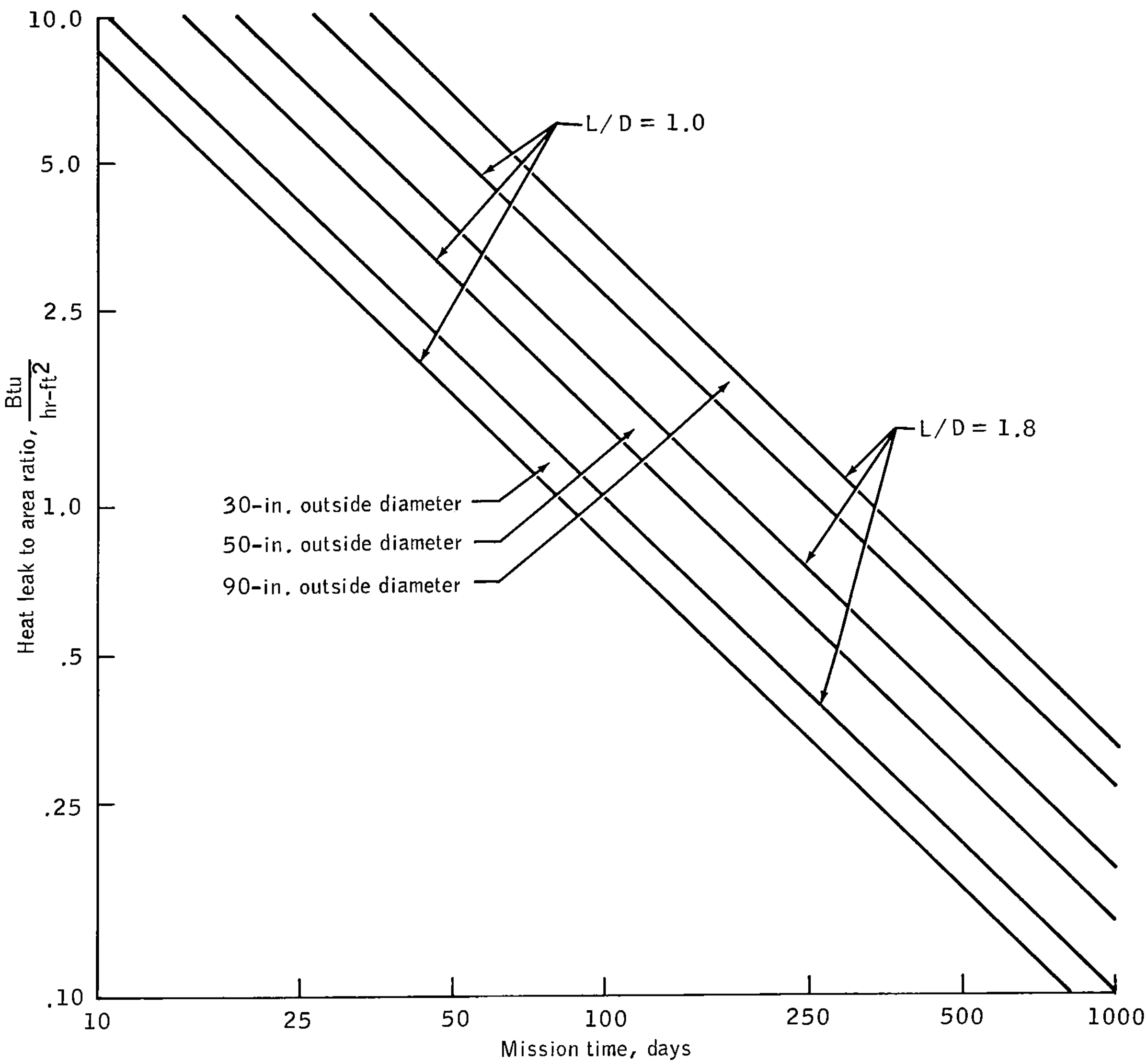

Figure 11. - Heat-leak-to-area ratio as a function of mission time for a range of length-to-diameter ratios L/D (150-psia oxygen).

NASA-S-67-5567

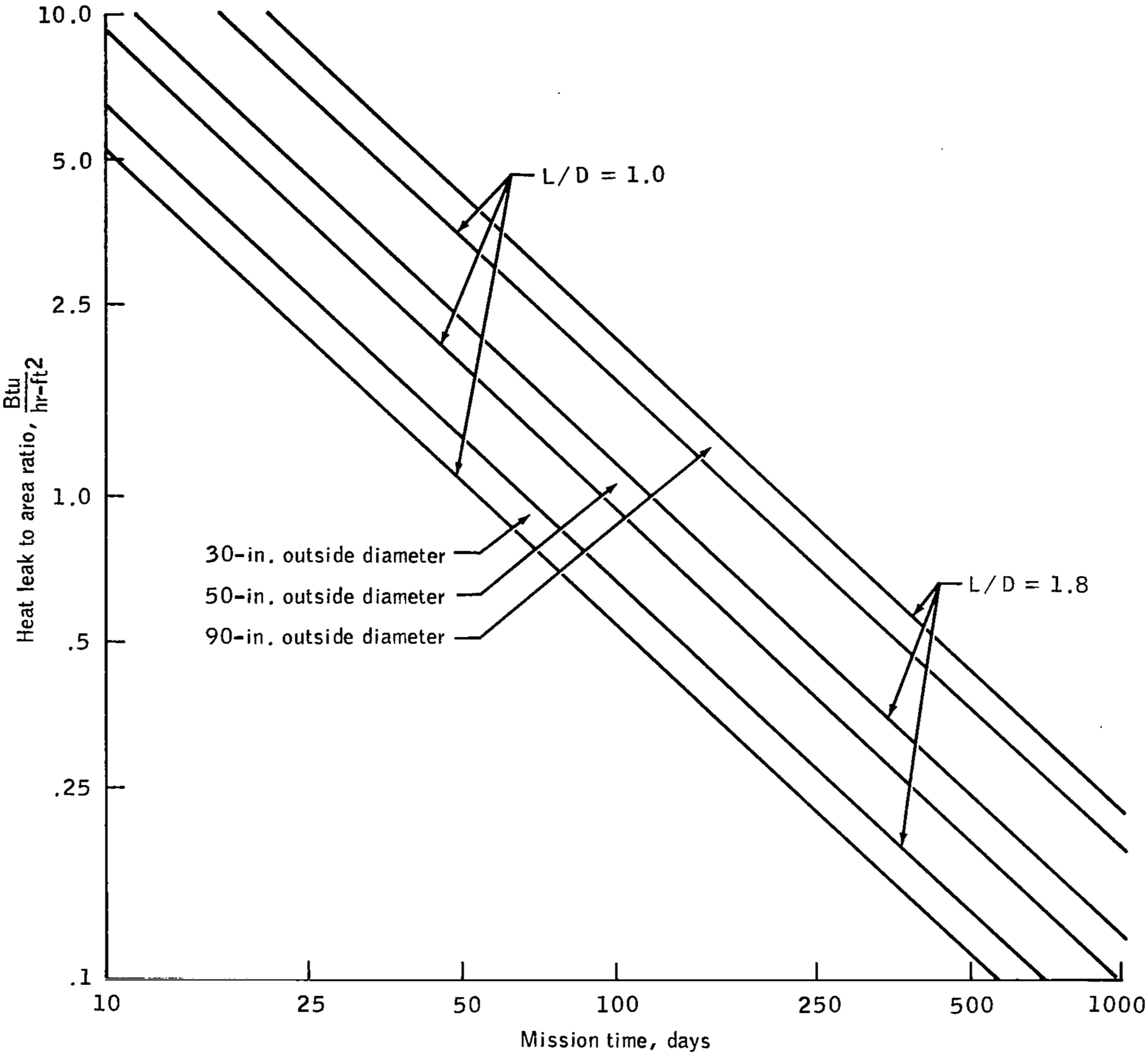

Figure 12. - Heat-leak-to-area ratio as a function of mission time for a range of length-to-diameter ratios L/D (150-psia nitrogen).

NASA-S-67-5566

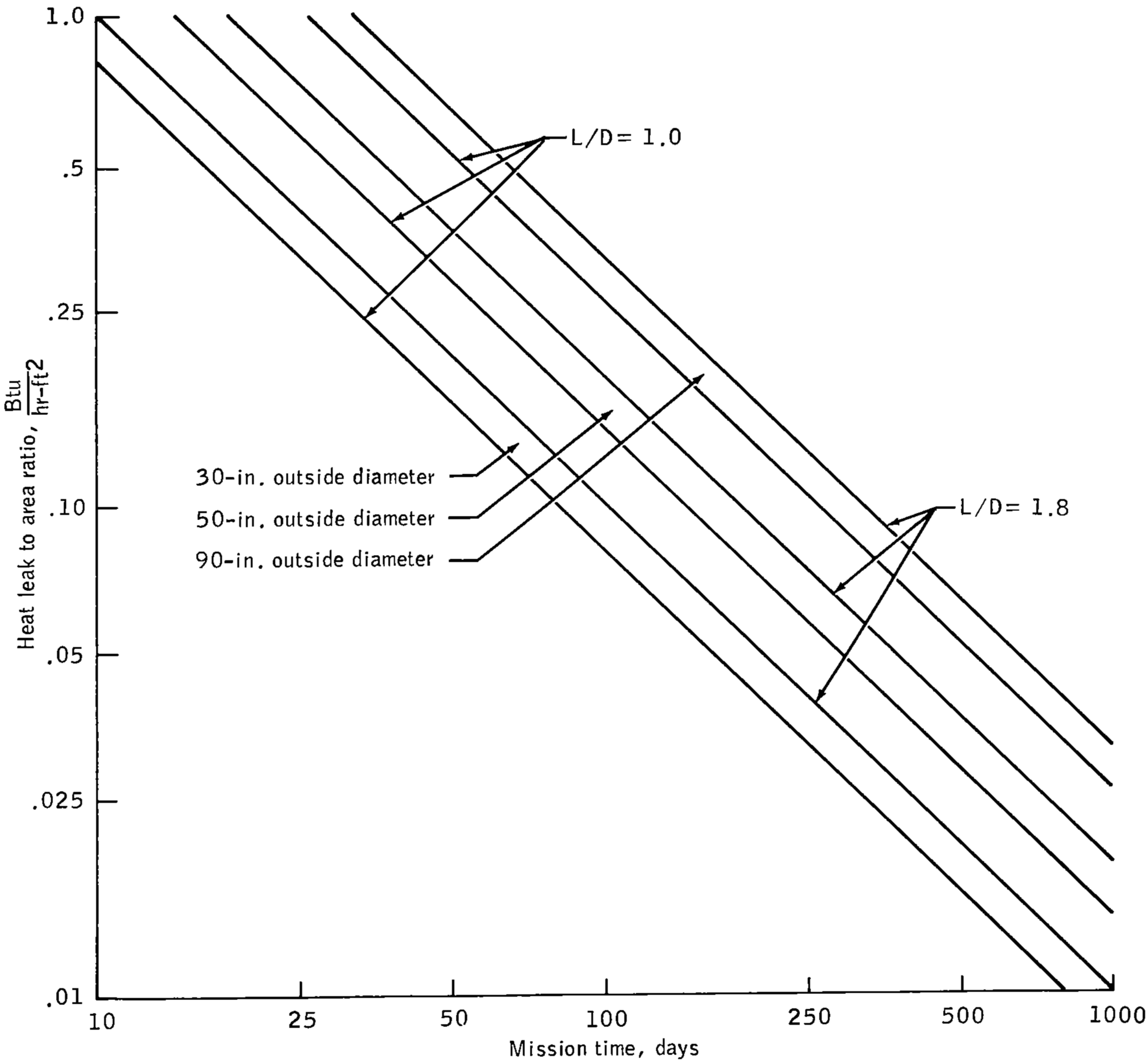

Figure 13. - Heat-leak-to-area ratio as a function of mission time for a range of length-to-diameter ratios L/D (1000-psia helium).

NASA-S-67-5578

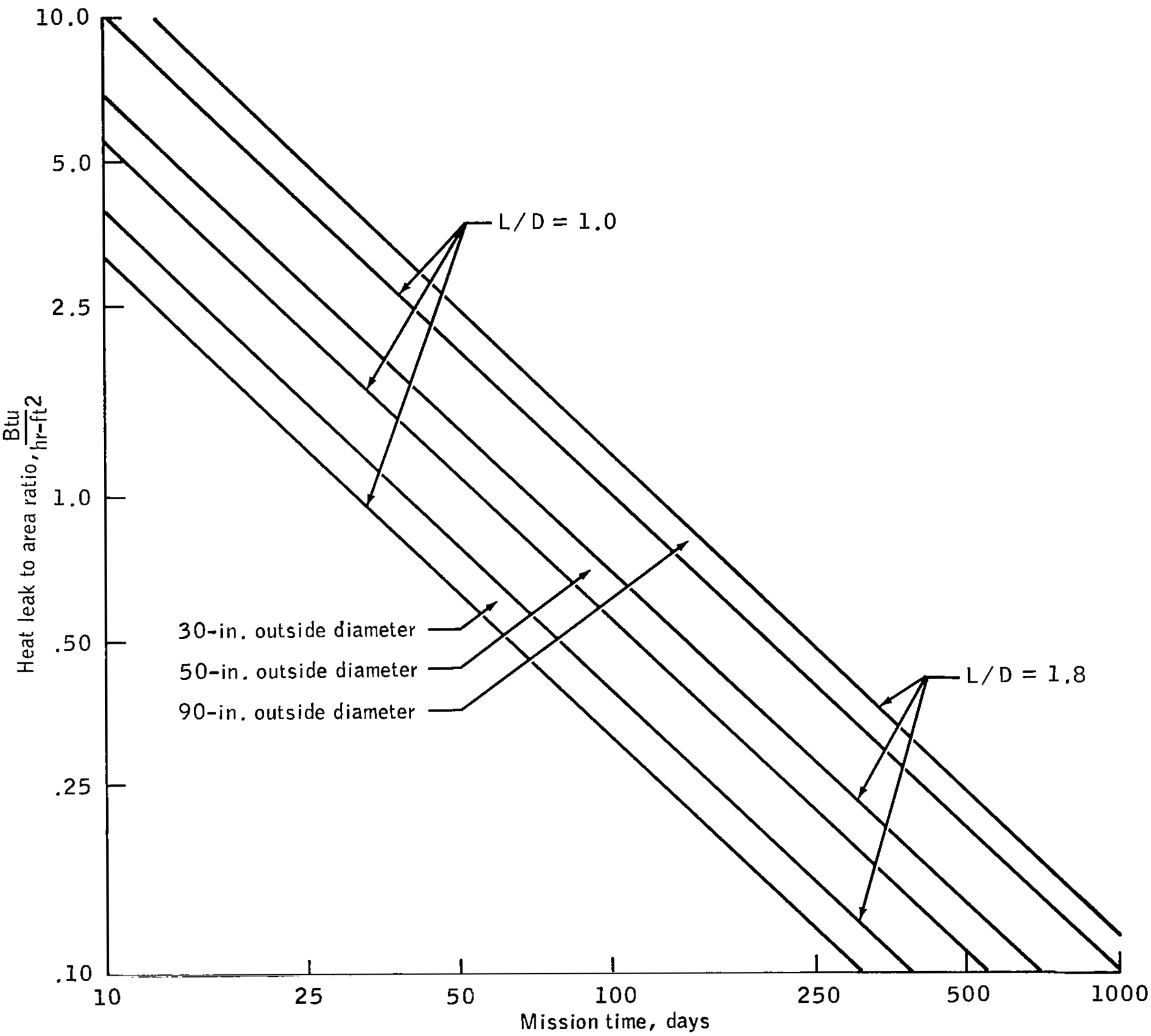

Figure 14. - Heat-leak-to-area ratio as a function of mission time for a range of length-to-diameter ratios L/D (150-psia neon).

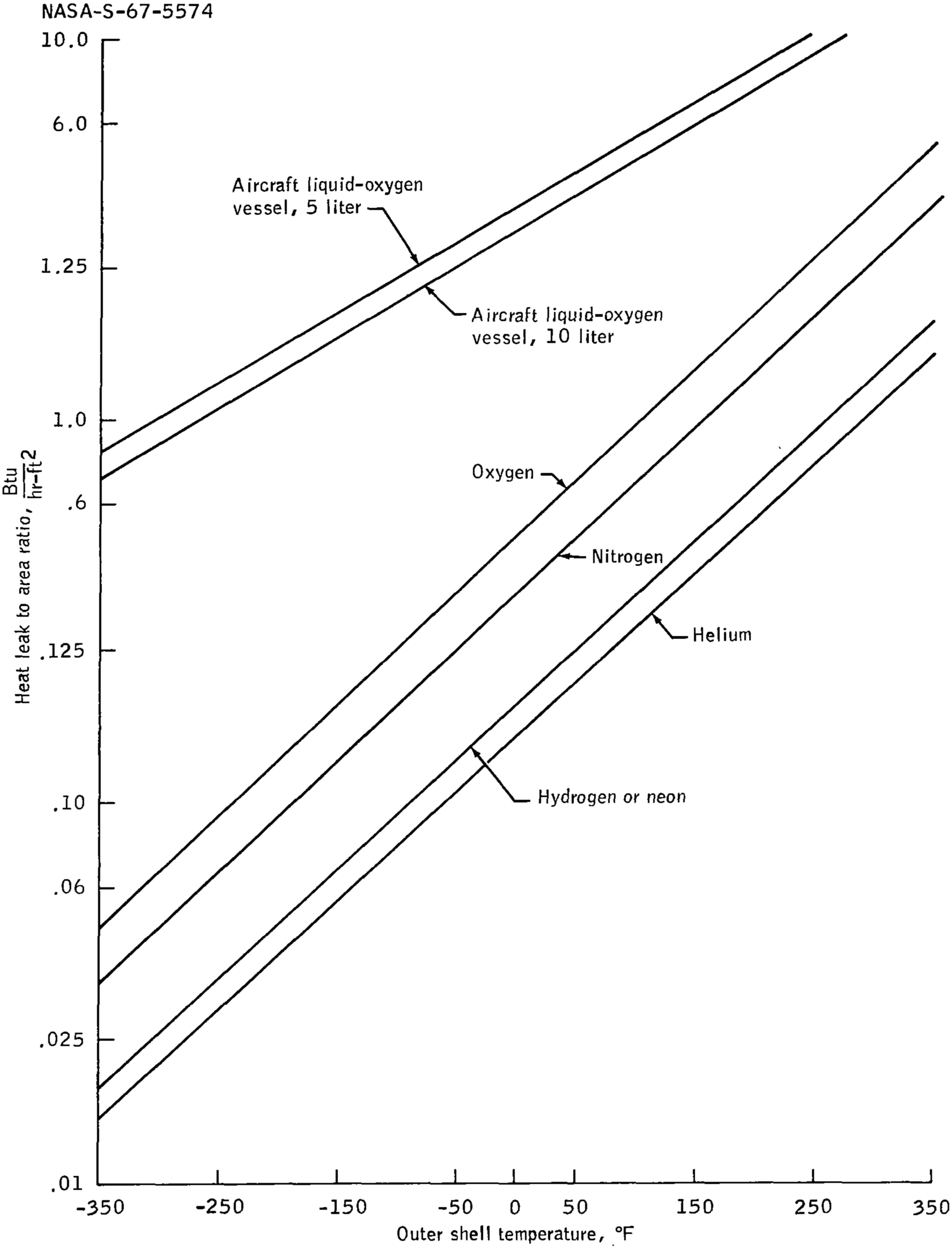

Figure 15. - Heat-leak-to-area ratio as a function of outer shell temperature.

NASA-S-67-5569

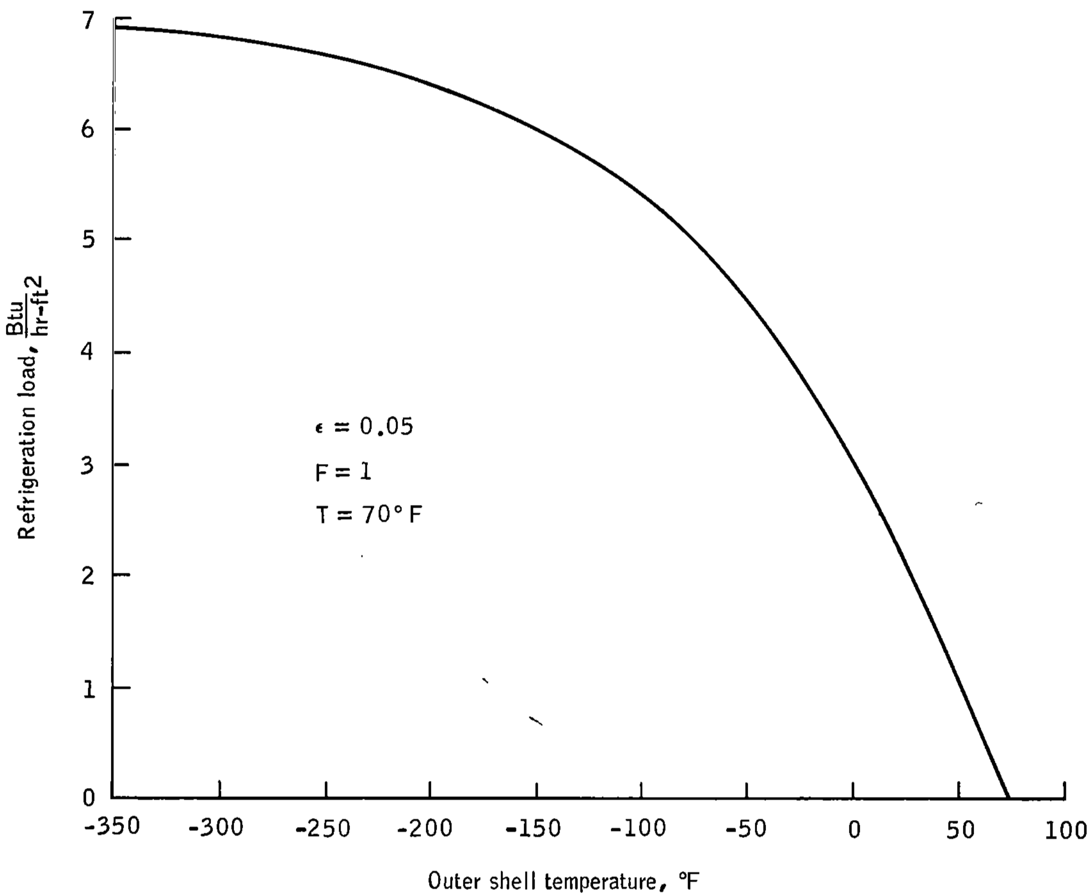

Figure 16. - Refrigeration load as a function of outer shell temperature.

NASA-S-67-5572

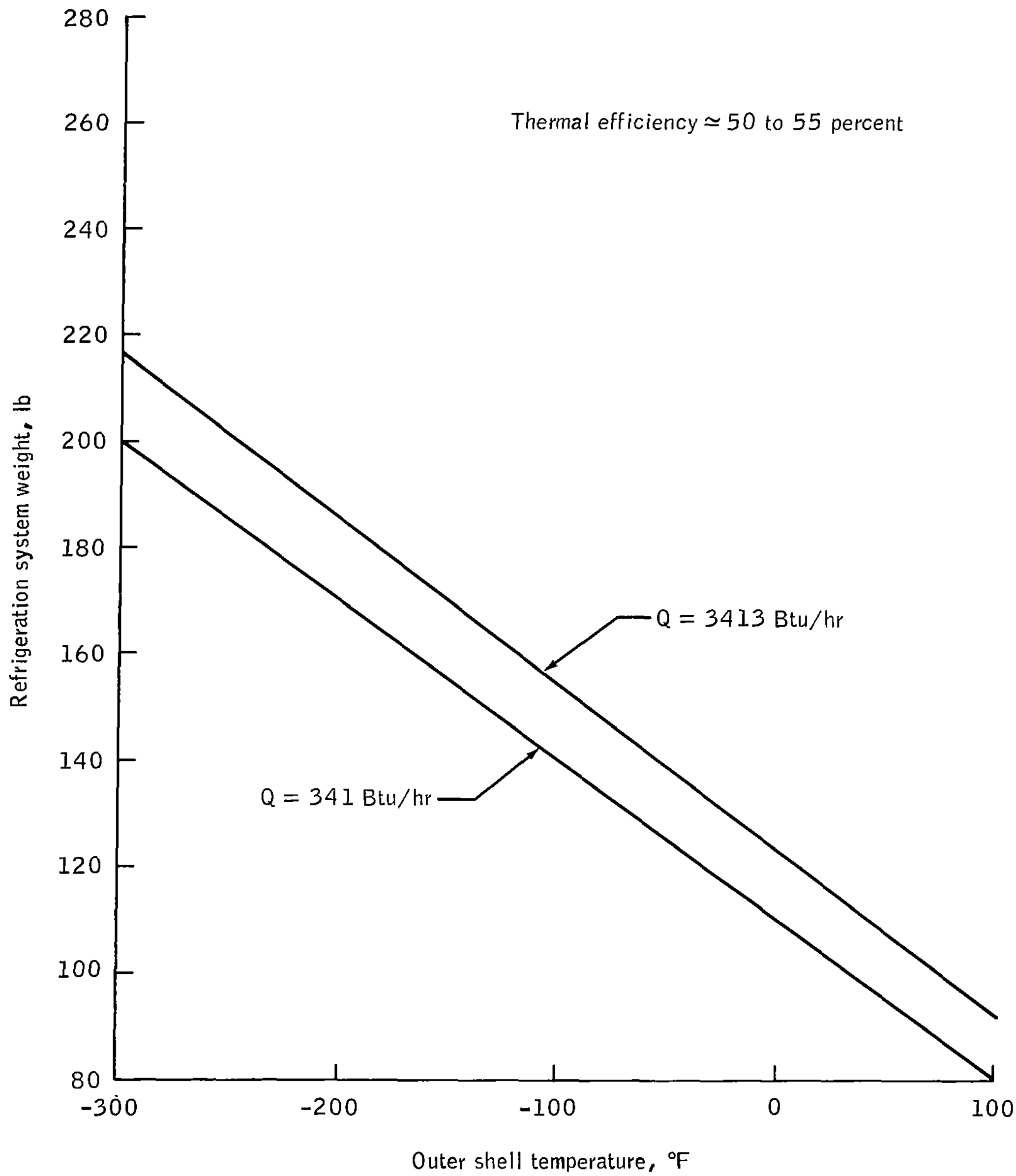

Figure 17. - Refrigeration system weight as a function of outer shell temperature and refrigeration heat Q.

NASA-S-67-5573

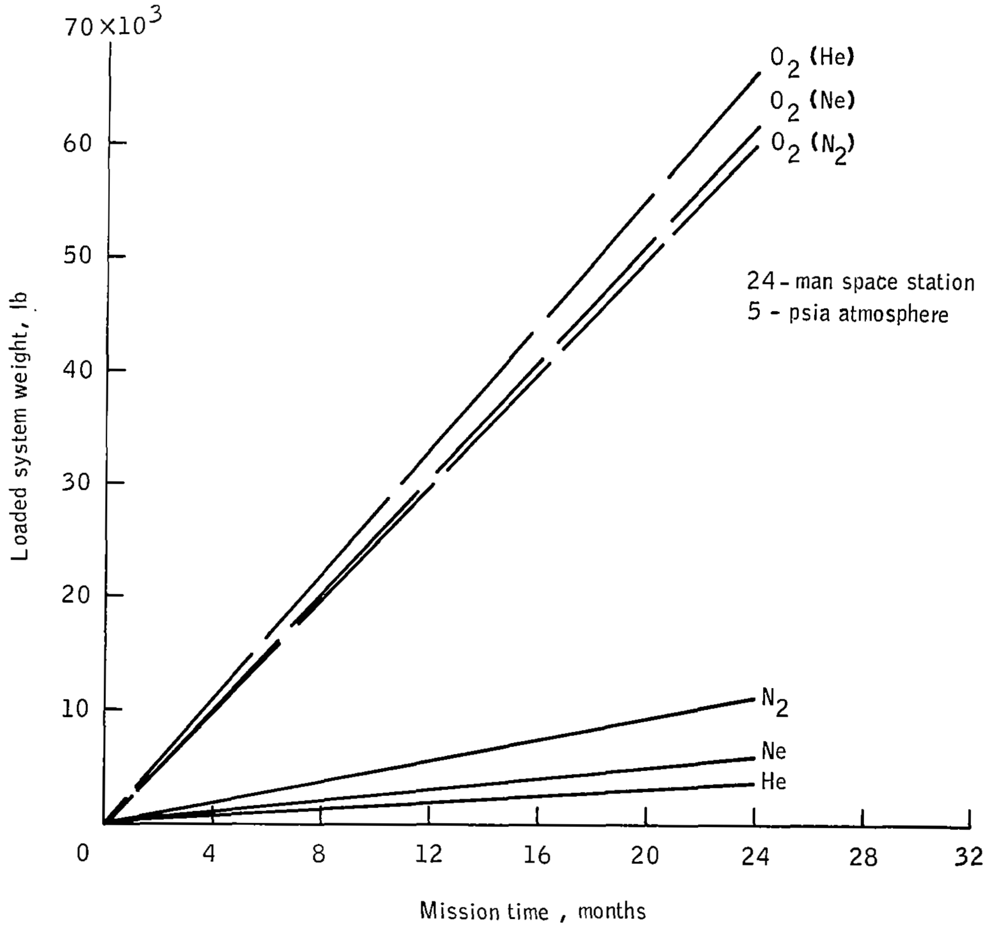

Figure 18. - Loaded system weight for reference mission I (length-to-diameter ratio L/D equals 1.0).

NASA-S-67-5561

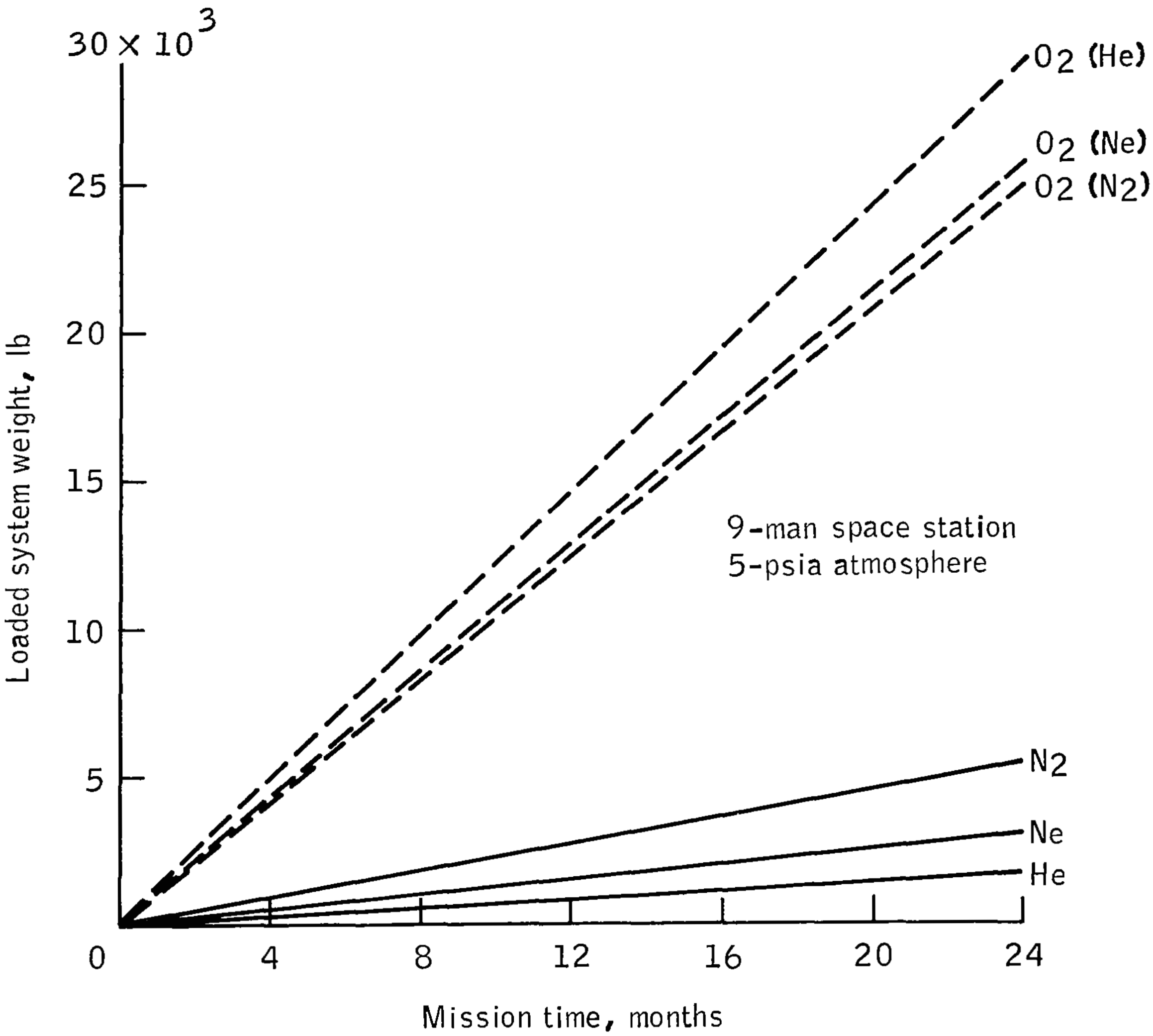

Figure 19. - Loaded system weight for reference mission II (length-to-diameter ratio L/D equals 1.0).

NASA-S-67-5565

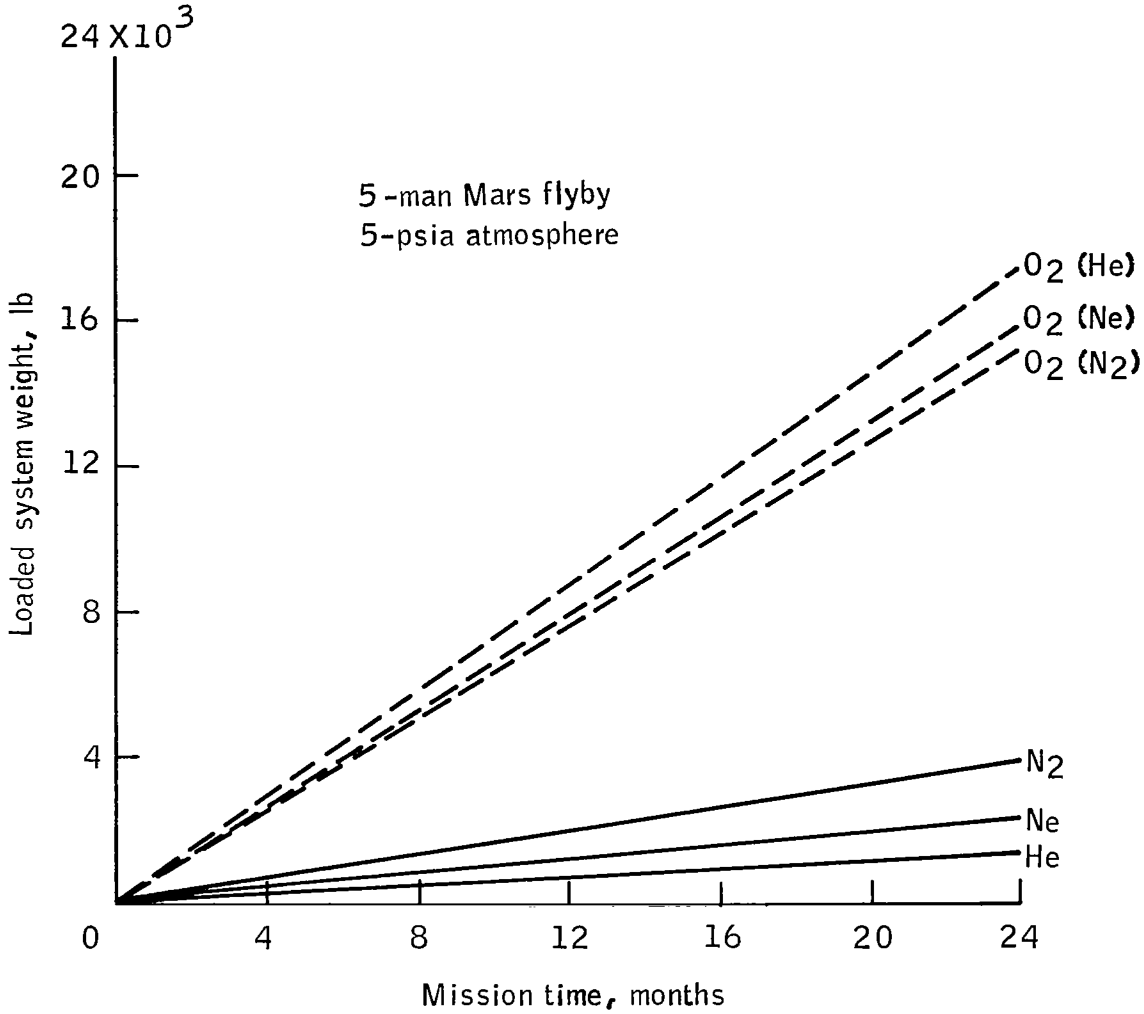

Figure 20. - Loaded system weight for reference mission III (length-to-diameter ratio L/D equals 1.0).

NASA-S-67-5579

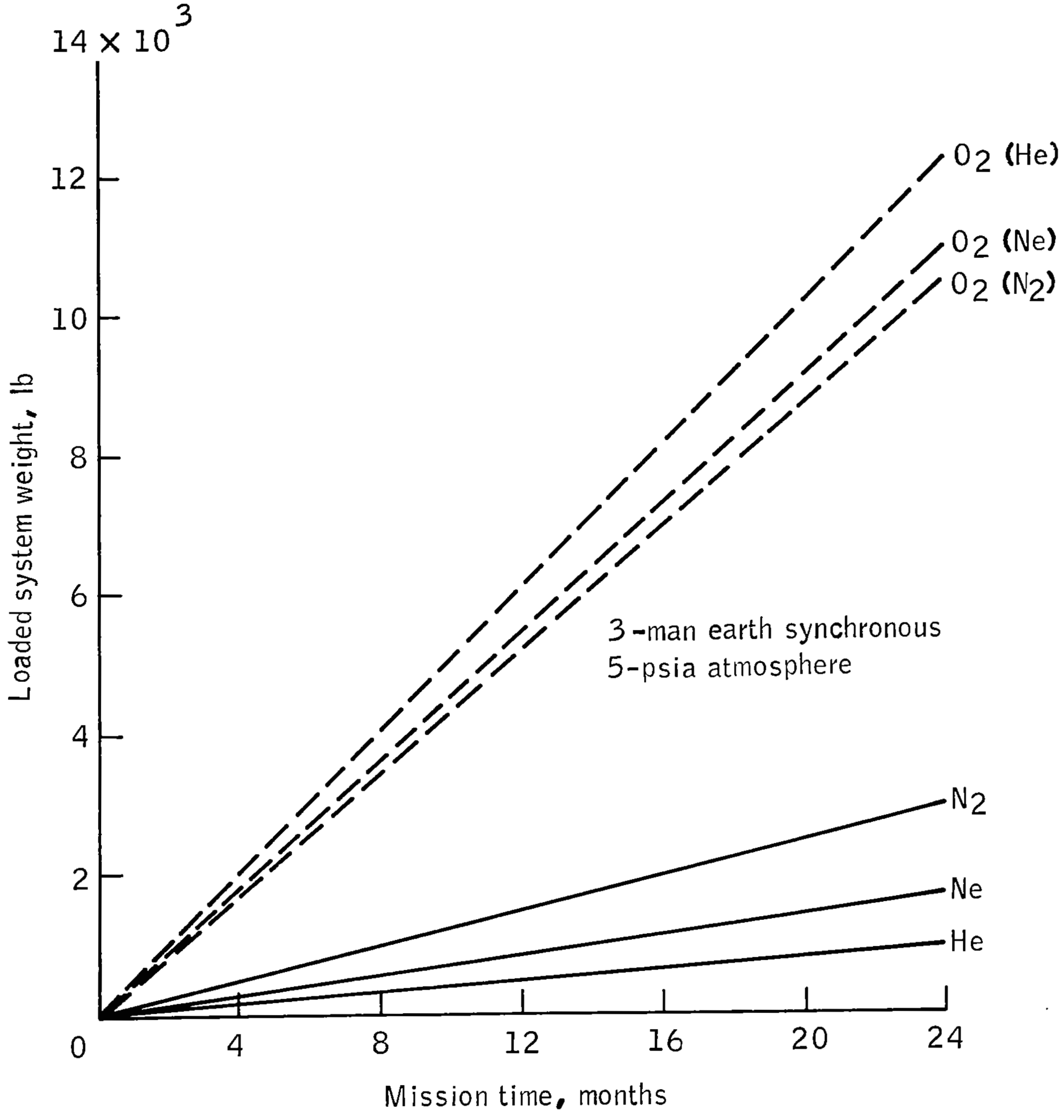

Figure 21. - Loaded system weight for reference mission IV (length-to-diameter ratio L/D equals 1.0).

NASA-S-67-5559

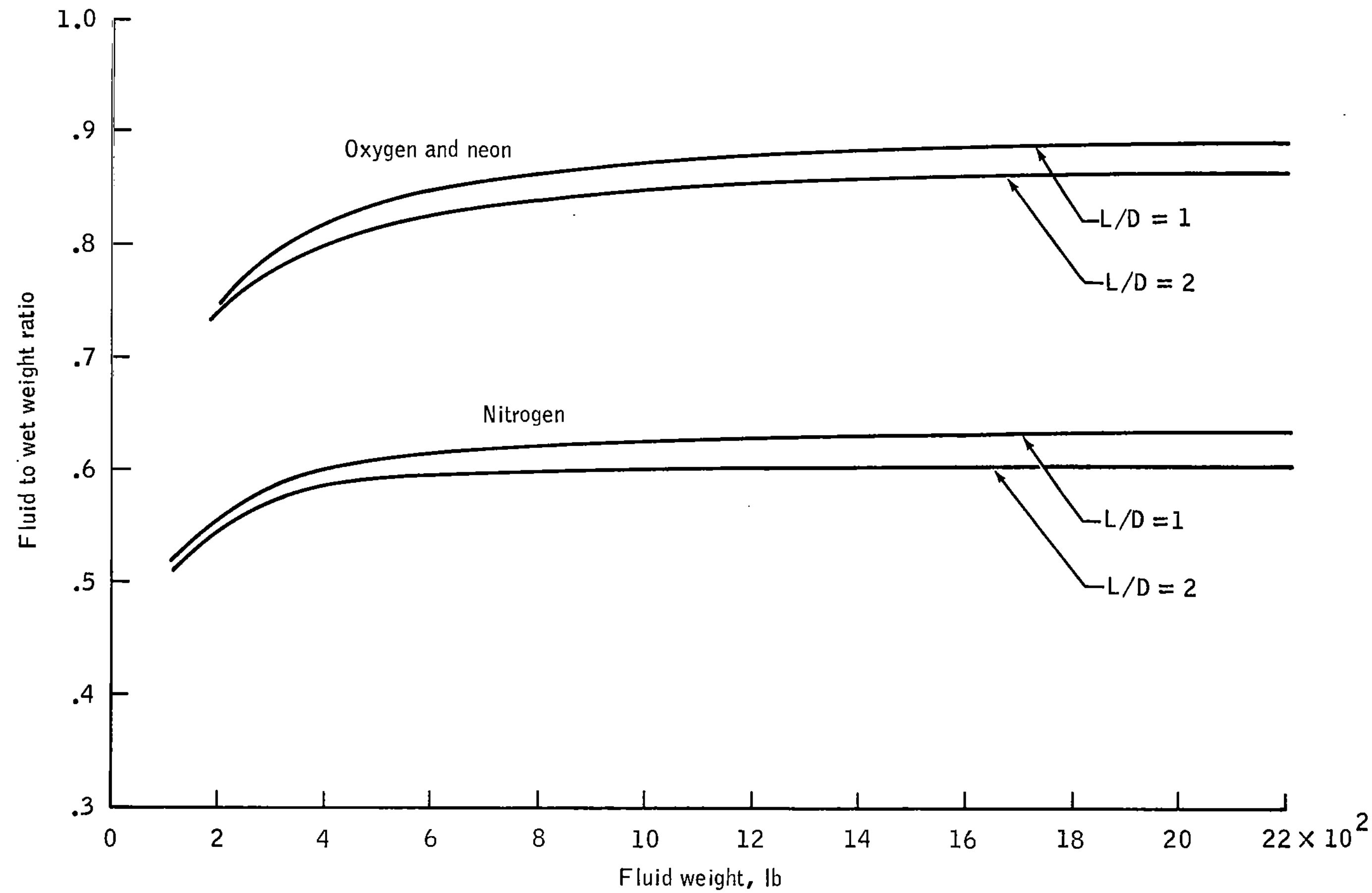

Figure 22. - Fluid-to-system-loaded-weight ratio as a function of the fluid weights of oxygen, neon, and nitrogen (fluids are subcritical at 150 psia; length-to-diameter ratios L/D are for Dewar configurations).

NASA-S-67-5568

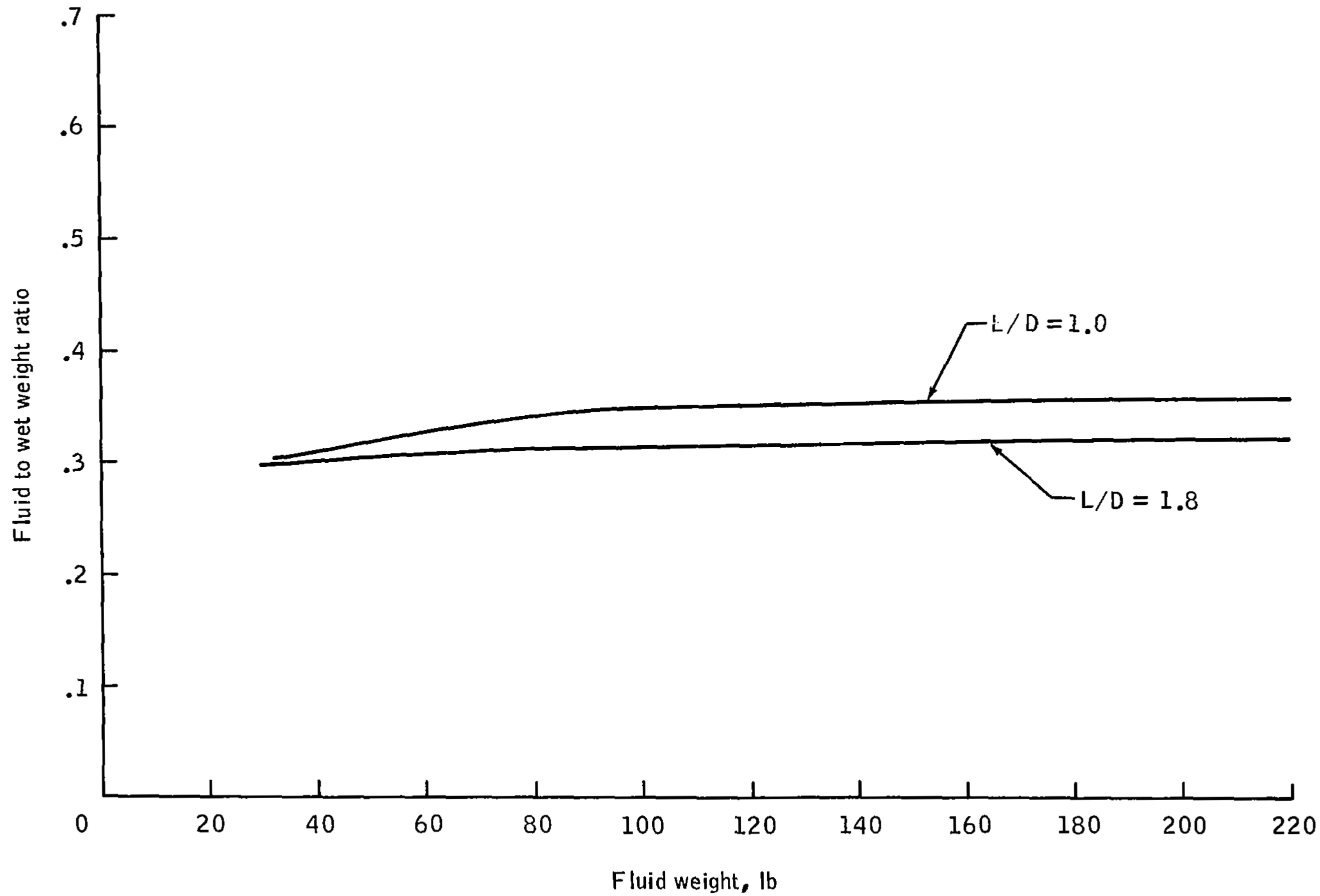

Figure 23. - Fluid-to-system-loaded-weight ratio as a function of the fluid weights of hydrogen and helium for a range of length-to-diameter ratios L/D (hydrogen at 660 psia and helium at 1000 psia share the same plot).

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