AEDC-TR-76-3

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A SUPERCONDUCTING MAGNET DEWAR MISSILE FOR LAUNCHING IN BALLISTIC RANGES

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March 1976

Final Report for Period July 1 — October 1, 1975

Prepared for

DIRECTORATE OF TECHNOLOGY (DY)
ARNOLD ENGINEERING DEVELOPMENT CENTER
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APPROVAL STATEMENT

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

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1 REPORT NUMBER: AEDC-TR-76-3	2 GOVT ACCESSION NO.
3 RECIPIENT'S CATALOG NUMBER	
4 TITLE (and Subtitle): A SUPERCONDUCTING MAGNET DEWAR MISSILE FOR LAUNCHING IN BALLISTIC RANGES	5 TYPE OF REPORT & PERIOD COVERED: Final Report - July 1 - October 1, 1975
	6 PERFORMING ORG. REPORT NUMBER
7 AUTHOR(s): E. E. Erickson - ARO, Inc.	8 CONTRACT OR GRANT NUMBER(s)
9 PERFORMING ORGANIZATION NAME AND ADDRESS: Arnold Engineering Development Center (DY) Air Force Systems Command Arnold Air Force Station, Tennessee 37389	10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Program Element 65807F
11 CONTROLLING OFFICE NAME AND ADDRESS: Arnold Engineering Development Center (DYFS) Air Force Systems Command Arnold Air Force Station, Tennessee 37389	12 REPORT DATE: March 1976
	13 NUMBER OF PAGES: 21
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15 SECURITY CLASS. (of this report): UNCLASSIFIED
	15a DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

Available in DDC

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

electromagnets	ballistics
superconductors	ranges
missiles	cryogenics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

One concept for magnetic guidance of projectiles in hypervelocity ballistic ranges is the use of a superconducting magnet within the projectile. The magnet must survive the large launch loads (250,000 g's) necessary to achieve test velocities (20,000 ft/sec). This report describes a conceptual design of a dewar which contains a superconducting magnet and its performance limitations. Thermal holding time for the proposed dewar would be in excess of 90 min. Structural strength aspects of the dewar

20. ABSTRACT (Continued)

components limit the launch load to 15,000 g's. Consequently, the current launcher at AEDC (50 ft long) would be limited to velocities of about 5,000 ft/sec or alternatively, an 830-ft-long launcher would be required to produce the desired velocity (20,000 ft/sec). The use of new launch techniques or magnet configurations could affect these results.

PREFACE

The research reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was done under ARO Project No. V31S-04A. The author of this report was E. E. Erickson, ARO, Inc. The manuscript (ARO Control No. ARO-VKF-TR-75-153) was submitted for publication on October 16, 1975.

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ILLUSTRATIONS

1.0 INTRODUCTION

This report evaluates the cryogenic, structural strength and performance aspects of a liquid-helium dewar missile which would house a superconducting magnet for guidance of the missile in a ballistic range. The dewar is based on a configuration suggested by Dr. H. J. Fink of the University of California (consultant to ARO, Inc., under ARO subcontract 75-12-VKF). The dewar missile would be fitted with various nose configurations for ballistic testing. The testing procedure would be to cool and fill the dewar with liquid helium, energize the magnet, and place the missile in a launch tube. The missile would be launched down a test range by a two-stage, light-gas launcher. Missile velocity in the range would be determined by the launch tube pressure level and length. The magnet in the missile would interact with a guide track in the range to provide guidance into a deceleration and recovery system.

The chief purpose of this analysis is to define in an approximate way the feasible operating regime of a dewar and magnet containing missile if it were to be launched from a large, two-stage, light-gas gun such as the 2.5-in. GO-4 launcher at the AEDC.

2.0 DEWAR MISSILE CONCEPT

2.1 DEWAR CRITERIA

The dewar should be compatible with the following criteria:

1. Dewar size = 2.5 in. OD by 5.0 in. long
2. Time to hold the magnet at 8°R = 1.0 hr
3. Typical launch tube = 2.5 in. ID by 50 ft long
4. Missile velocity = 20,000 ft/sec
5. Missile weight = 0.88 lb
6. Magnet size, 1.0 in. OD by 0.5 in. ID by 3.0 in. long

A preliminary concept of the missile as suggested by Dr. Fink is shown in Fig. 1. This concept was refined during the thermal, pressure, and acceleration strength evaluations. It was recognized when the magnet structural strength was investigated that the dewar could not meet the criteria of attaining a 20,000-ft/sec velocity in a 50-ft launch length, but the effort was continued to determine the dewar concept limitations and to lay the groundwork for future studies.

2.2 DEWAR DESCRIPTION

The dewar consists of an outer vessel, inner vessel, support structure, and fill and vent tubes. The inner vessel houses the superconducting magnet and the liquid-helium cooling medium. The liquid-helium requires isolation from ambient heat which dictates the use of super insulation between the inner and outer dewar vessels and a minimum support and fill and vent tube structure. Super insulation consists of multiple, alternating layers of reflective aluminum-coated polyester film separated by a fine glass fiber cloth spacer in a vacuum, and its heat infiltration is limited to radiation heat transfer since there is only minimal point contact between the reflector and spacer material. All metallic dewar components are type 304 stainless steel to keep conductive heat transfer to a minimum and to be compatible with the cold helium temperatures.

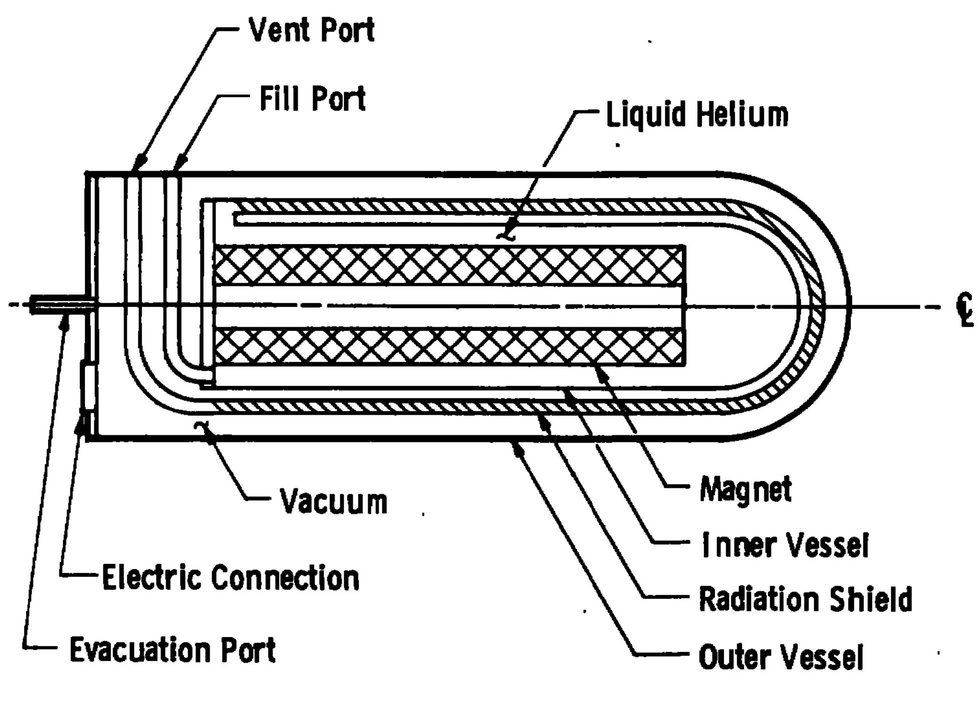

Figure 1. Preliminary dewar missile concept.

2.3 DEWAR THERMAL CONSIDERATIONS

Dewar heat leak and heat capacity determine the capability of the dewar of meeting the one-hour holding time requirement at 8°R. The time can be expressed as follows:

$$\tau = \frac{Q}{q_r + q_c} \tag{1}$$

where

τ = time, hr

Q = heat capacity, Btu

q_r = radiation heat transfer, Btu/hr

q_c = conduction heat transfer, Btu/hr

The heat-transfer values must be kept low and heat capacity high to obtain the longest holding times.

2.3.1 Radiation Heat Transfer

Radiation heat transfer is controlled by the number of layers of super insulation installed in the vacuum space between the inner and outer vessels. Each layer of insulation consists of a radiation shield, thermally isolated by a glass fiber cloth spacer from adjoining layers. Twenty-five shields with twenty-five spacers can be fitted in a one centimeter wide space (Ref. 1). The equation for radiation heat transfer is (Ref. 2):

$$q_r = \frac{A_{s_1}\sigma\epsilon\left(T_1^4 - T_2^4\right)}{(n+1)\left(1 + \frac{A_{s_1}}{A_{s_2}}\right)} \tag{2}$$

where

σ = Stefan-Boltzmann constant = 1.189×10^{-11} Btu/hr in.^{2} °R^4

A_{s_1} = outer vessel outside surface area, in.^{2}

A_{s_2} = inner vessel outside surface area, in.^{2}

T_1 = ambient temperature, 540°R

T_2 = inner vessel temperature, 8°R

ϵ = average emissivity

n = number of radiation shields

An emissivity value of 0.05 was used for both the stainless steel and aluminum-coated polyester film surfaces (Ref. 2). Trial calculations indicated that 20 layers of insulation would be adequate for a nominal radiation heat transfer. The vacuum space was sized for 20 layers of super insulation, and this space determined the inner vessel outer diameter, 1.96 in., and surface area, 30.4 in.^{2}. Radiation heat transfer (q_r) was calculated to be 0.074 Btu/hr.

2.3.2 Conduction Heat Transfer

Conduction heat transfer occurs through supports, fill, and vent lines and any direct path into the inner vessel. Conduction is calculated from the equation:

$$q_c = \frac{kA(T_1 - T_2)}{\ell} \tag{3}$$

where

k = thermal conductivity, Btu in./in.^{2} °R hr

A = cross-sectional area, in.^{2}

T_1 = warm end temperature, °R

T_2 = cold end temperature, °R

ℓ = length, in.

The conductive path should be as long as possible, have a minimal cross-sectional area, and have a low thermal conductivity to keep the heat transfer small. The dewar utilizes thin wall stainless steel tubing for the fill and vent lines. The original concept was changed to incorporate a coiled tube in the vacuum space at each end of the dewar. The coiled tube provides a long conductive path and also prevents liquid helium from flowing out of the dewar when it is moved or placed horizontally since the tubes are open to the atmosphere. To further reduce conduction heat leak, the coiled tubes also serve as the inner vessel supports when the dewar is at rest. The fill tube is 0.0937 in. OD by 0.005 in. wall by 4.25 in. long, and the vent tube is 0.0937 in. OD by 0.005 in. wall by 3.25 in. long. The tube diameters are as small as practical to pass liquid helium and the length as long as possible to fit the end space. The thermal conductivity of type 304 stainless steel is 0.354 Btu in./in.^{2}°R. From Eq. (3), the total conduction heat transfer (q_c) is the sum of the fill and vent tube transfer, 0.062 and 0.081 Btu/hr, respectively, or 0.143 Btu/hr. Heat transfer through the magnet lead-in wires was neglected because the wire length is relatively long and the cross-sectional area small when compared with the fill and vent tubes.

2.3.3 Heat Capacity

Heat capacity in the cold part of the dewar system depends mainly on the quantity of liquid helium present since the specific heats of the magnet and dewar structure are near zero at 8°R. Heat capacity is calculated from the equation:

$$Q = (V_2 - V_m)\rho_\ell h_{fg} \tag{4}$$

where

V_2 = inside volume of inner vessel, in.^{3}

V_m = volume of magnet, in.^{3}

ρ_ℓ = density of liquid helium, lb/in.^{3}

h_{fg} = latent heat of liquid helium, Btu/lb

The density and latent heat of liquid helium at atmospheric pressure are 0.00451 lb/in.^{3} and 8.63 Btu/lb, respectively (Ref. 3). The inner vessel and magnet volumes are 10.9 and 1.8 in.^{3}, respectively. For these conditions the heat capacity is 0.354 Btu.

2.3.4 Holding Time

The holding time at 8°R from Eq. (1) is 98 min. This is well above the criteria time of one hour, indicating that the insulation design and liquid helium capacity are adequate.

Typical cylindrical dewar diameter-length relationships based on the surface areas of Eq. (1) are shown in Fig. 2. Insulation and fill and vent tubes are the same as in the final dewar concept. Radiation heat leak is proportional to the inner and outer dewar vessel surface areas and conduction heat leak is constant for all dewar sizes. Figure 2 may be used to determine the dewar size which will house a known magnet volume (V_m) and maintain a temperature of 8°R for one hour.

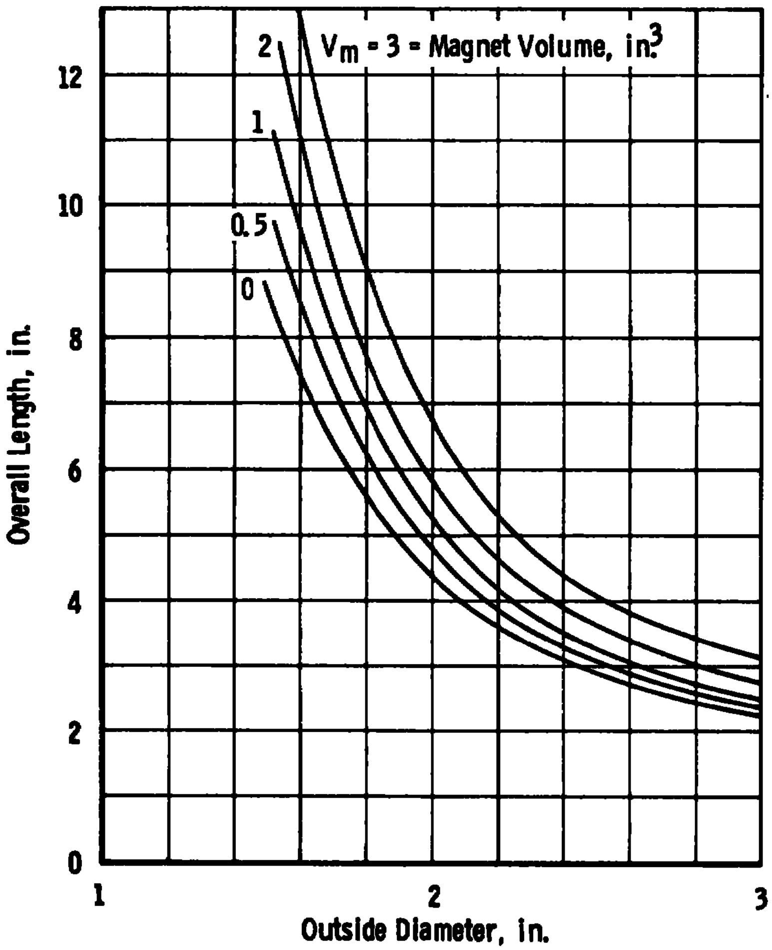

Figure 2. Typical dewar sizes for one hour holding time.

2.4 VELOCITY AND ACCELERATION

The velocity attainable by the dewar missile depends on the launch tube length and the acceleration loads the dewar can withstand. The uniform acceleration of a body from rest to a final velocity can be calculated from the equation:

$$a = \frac{U^2}{2s} \tag{5}$$

where a is uniform acceleration, ft/sec^2, U is the velocity ft/sec, and s is the launch tube length, ft. The acceleration in a launch tube typically is not uniform, and experience has shown that the maximum acceleration of a package in the launch tube of a two-stage, light-gas gun is approximately twice the minimum uniform acceleration.

Thus,

$$a_m = \frac{U^2}{s} \tag{6}$$

where a_m is the maximum acceleration, ft/sec^2. The maximum acceleration for a 50-ft launch tube and 20,000-ft/sec velocity is 8 million ft/sec^2. The acceleration can be expressed as a g-load factor:

$$g_f = \frac{a_m}{g} \tag{7}$$

where g_f is the g-load weight increase factor and g is the acceleration of gravity, 32.16 ft/sec^2. The g-load factor for the 8 million ft/sec^2 acceleration is 249,000. Equations (6) and (7) are combined and plotted in Fig. 3 which shows the velocity, g-load relationship for various launch tube lengths and how increasing the launch tube length reduces the g loads or increases the velocity. Different launch techniques, where the maximum acceleration is less than twice the uniform acceleration, would also decrease launch tube lengths.

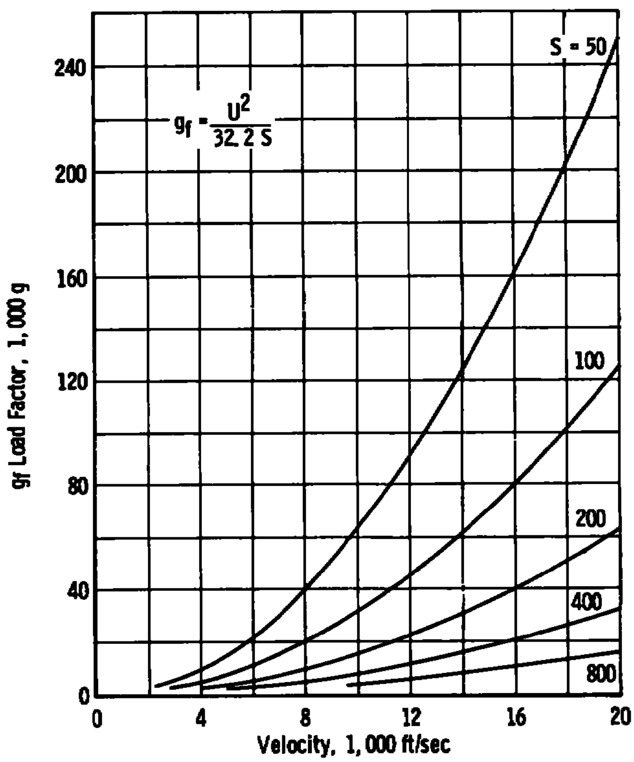

Figure 3. Missile launch factors assuming maximum acceleration is twice the minimum uniform acceleration.

2.5 ACCELERATION LOAD

The acceleration g loads multiply the weight of the dewar components and are parallel to the line of flight. Consequently, the axial length of the components and the material density determine the compressive stress caused by acceleration. The acceleration stress for a constant cross-sectional area can be expressed as

$$S_c = \ell \rho_m g_f \tag{8}$$

where S_c is the compressive stress, psi and ρ_m is the metal density, lb/in.^{3}.

The ultimate compressive stress is considered equal to the ultimate tensile stress for most metals (Ref. 4). However, there is an inherent safety factor in this assumption in that the tensile stress is based on the breaking point of a round test specimen. Elongation of the test specimen occurs before the breaking point, reducing the cross-sectional area, in effect weakening the test specimen. This area reduction does not take place during compression loading. Any yielding of the material actually increases the cross-sectional area, thus increasing the material load carrying capabilities. The ultimate compressive stress is thus larger than the ultimate tensile stress by a factor equivalent to the ratio of the test specimen original to reduced cross-sectional area. Ultimate compressive stress values equal to the ultimate tensile stress, with its inherent safety factor, will be used since the g loads are momentary and do not endanger personnel.

The compressive strength of the dewar stainless steel is 84,000 psi. The compressive strengths of niobium-tin and copper, the super conducting magnet materials, are, respectively, 24,000 and 32,000 psi. The low strengths of the niobium-tin and copper indicate the magnet to be the g-load limiting factor. The g-load factor as a function of material strength, length, and density is shown in Fig. 4. The maximum g load for a 3-in.-long magnet based on the strength of niobium-tin is 24,000. However, an allowable g-load value of 15,000 was selected since the magnet is not homogeneous and to allow a safety factor for nonuniformity and discontinuity in the magnet structure. Figure 3 indicates that this corresponds to a 5,000-ft/sec velocity in a 50-ft launch tube. Conversely, an 830-ft-long launch tube would be required to attain a 20,000 ft/sec velocity.

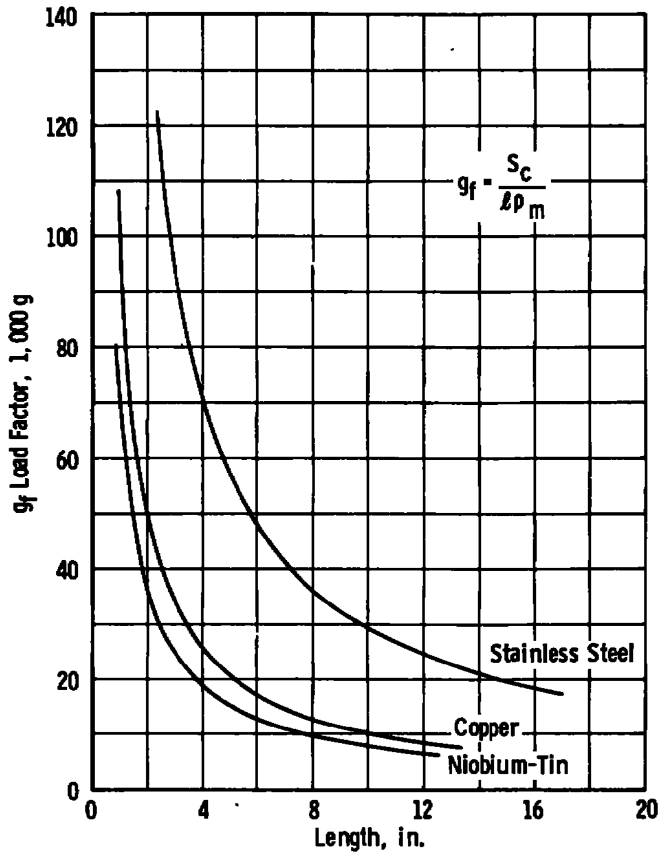

Figure 4. Material g-load resistance.

2.6 PRESSURE STRENGTH

The dewar cylindrical walls must withstand the pressure stress resulting from the evacuated insulation space as well as the g loads. The outer vessel shell must withstand an external pressure of one atmosphere. The equation used to approximate the outer shell wall thickness required for the external pressure is (Ref. 4):

$$t = \left[\frac{4(1-\nu^2)\,pr^3}{E}\right]^{0.33} \tag{9}$$

where

t = wall thickness, in.

ν = Poisson's ratio, 0.26

p = external pressure, psi

r = radius, in.

E = modulus of elasticity, 28 million psi

The wall thickness for stainless steel must be a minimum of 0.015 in. for one atmosphere external pressure, and a wall thickness of 0.020 in. is specified to facilitate fabrication.

The inner vessel wall thickness must withstand one atmosphere internal pressure. The equation for the wall thickness is (Ref. 5):

$$t = \frac{pr}{S_t} \tag{10}$$

where S_t is the allowable tensile stress, psi. An allowable tensile stress value equal to one-quarter of the ultimate tensile stress is used for the pressure stress as a safety factor.

The wall thickness must be a minimum of 0.001 in. for a one-atmosphere internal pressure and stainless steel allowable stress of 21,000 psi. Nominal thickness is specified to be 0.020 in. to provide a thickness suitable for fabrication and to allow extra material for g-load support.

The dewar ends must also withstand a one-atmosphere pressure.* The equation for the thickness of a flat circular end is (Ref. 5):

$$t = d\left(\frac{pC}{S_t}\right)^{1/2} \tag{11}$$

where d is the diameter, in., and C is a coefficient depending on the edge restraint, in this case 0.25. For the outer vessel, 2.5-in.-OD, the minimum end thickness is 0.033 in. For the inner vessel, 1.96-in.-OD, the minimum end thickness is 0.026 in.

*The external pressure of launch will be offset by the internal g forces on the rear end plate; however, final design should consider limiting pressures to the sides by suitable seals.

2.7 COMBINED ACCELERATION AND PRESSURE STRENGTH

Stresses due to the g load are next combined with the pressure stress to determine the final strength requirements. For the dewar walls, the pressure and g-load stress act at right angles to each other, and the maximum stress value is the maximum principal stress (Ref. 4). Therefore, the wall strength is adequate if it will separately withstand the pressure stress or the g load. From Fig. 4, it is apparent that the stainless steel shell can be up to 20 in. long and still withstand a 15,000 g load. The shell is, therefore, strong enough to support the pressure load, g load, and a nose and end plate weight equivalent to the weight of 20 minus 5 or 15 in. of shell length, 0.68 lb. The outer vessel front end plate g load acts in the same direction as the pressure load, and the pressure load must be added to the pressure equivalent g load. The pressure equivalent g load is

$$p_g = \rho_m \, t \, g_f \tag{12}$$

where p_g is in psi.

The required end plate thickness for the combined pressure loads can be determined from Eq. (11) by adding the pressure equivalent, pg, to the pressure, p. A head thickness of 0.080 in. will have a stress level of 84,000 psi for a 15,000 g load. The inner vessel front end plate thickness is calculated from the difference between pg and p since the forces act in opposite directions. The inner vessel end plate minimum thickness is 0.056 in. for an 84,000-psi stress.

2.8 INNER VESSEL SUPPORT

The inner vessel support system must withstand the high g loads. An adequate fixed support through the vacuum space would introduce a large heat leak into the inner vessel. To eliminate the fixed support a stainless steel bumper-type support was placed on the inner vessel with an 0.06-in. gap between the bumper and rear end plate. The inner vessel is free to move axially on the coiled fill and vent tube supports, and during launch, the g loads force the inner vessel and bumper against the end plate providing a direct, solid support. A hard rubber pad in the end plate absorbs some of the initial shock.

The launch force lasts only for a fraction of a second so that heat leak into the inner vessel is insignificant.

The bumper must be strong enough to support its own weight plus the weight of the inner vessel, insulation, magnet, and liquid helium. Weight of these components is estimated to be:

Inner vessel,	0.30 lb
Insulation,	0.03 lb
Magnet,	0.54 lb
Liquid helium,	0.04 lb

The equation for the cross-sectional area of the support is

$$A = \frac{W g_f}{S_c - \ell \rho_m g_f} \tag{13}$$

where W is the total weight to be supported. The required bumper cross-sectional area is 0.16 in.^{2} for a 15,000 g load.

3.0 FINAL DEWAR CONCEPT

3.1 SPECIFICATIONS

The development procedure culminated in the dewar shown in Fig. 5, for which specifications follow:

Material, type 304 stainless steel
ultimate tensile stress = 84,000 psi
density = 0.29 lb/in.^{3}

Maximum g Load = 15,000 limited by magnet

Weight, less nose and liquid helium = 1.42 lb

Outer Vessel, 2.5-in. OD by 5.0-in. long
shell thickness = 0.020 in.
front end plate thickness = 0.080 in.
rear end plate thickness = 0.125 in.
weight = 0.55 lb

Inner Vessel, 1.96-in. OD by 3.95-in. long
shell thickness = 0.020 in.
front end plate thickness = 0.060 in.

rear end plate thickness = 0.090 in.
bumper size = 1.0-in. OD by 0.875-in. ID by 0.31 in. long
weight = 0.30 lb

Fill Tube, 0.0937-in. OD by 0.005-in. wall by 4.25-in. long
weight = 0.002 lb

Vent Tube, 0.0937-in. OD by 0.005-in. wall by 3.25-in. long
weight = 0.001 lb

Super Insulation, 20 layers aluminum coated polyester plastic with glass fiber cloth separator
weight = 0.03 lb

Magnet, 1.0-in. OD by 0.5-in. ID by 3.0-in. long
weight = 0.54 lb

Nose Weight, limited by outer vessel shell strength = 0.5 lb

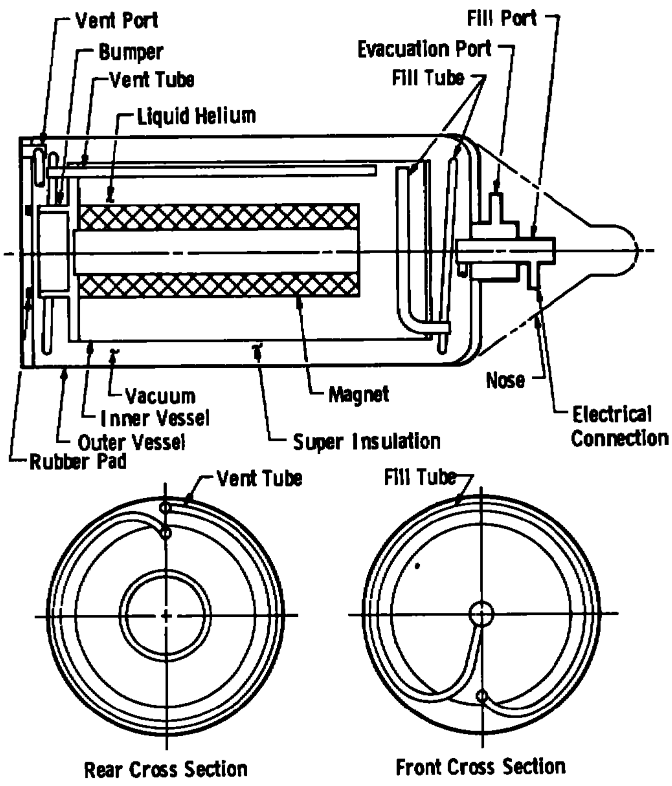

Figure 5. Final dewar missile concept.

3.2 DEWAR FEATURES

Significant features of the dewar are:

1. The liquid helium fill and vent tubes also support the inner vessel, eliminating extraneous supports.
2. The supports allow axial movement of the inner vessel so that launch g forces are opposed with a solid bumper support.
3. The super conducting magnet electric supply wires run inside the fill tube to eliminate vacuum tight electrical connections.
4. The fill and vent tube configurations minimize loss of liquid helium when the dewar is placed horizontally and during launch.
5. A helium boiloff gas shield, which is sometimes used on larger dewars, was not required and the layers of super insulation were kept to a minimum since the major heat transfer in a small dewar is due to conduction.

4.0 DISCUSSION OF RESULTS

The dewar can hold a 3-in.-long superconducting magnet at 8°R for 1 hr 38 min and can withstand a 15,000 g load. At this g load, it is estimated that the dewar could reach a velocity of approximately 5,000 ft/sec with a 50-ft launch tube or a velocity of 20,000 ft/sec with an 830-ft launch tube. Increasing the acceptable g loads will reduce the launch tube length for any given velocity.

The magnet mechanical strength is the limiting g-load factor. Magnet ultimate g loading can best be determined by test since construction variables such as the configuration and tightness of windings can not be evaluated analytically. Future development would be needed to determine the best balance between magnet design and launch tube length and to investigate different launch techniques.

It must be kept in mind that the launch process of a typical two-stage, light-gas gun entails transient effects of undoubted significance in the problem addressed herein. Therefore, the actual application, if this development were to be carried forward, could be expected to reveal problems not fully dealt with in this exploratory analysis. In any case, it is apparent that the concept of a dewar and magnet carrying missile is beset by severe limitations on allowable launch velocity when guns of practical size are considered.

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NOMENCLATURE

A	Cross-sectional area, in.^{2}
A_s	Surface area, in.^{2}
a	Uniform acceleration, ft/sec^2
a_m	Maximum acceleration, ft/sec^2
C	Coefficient, dimensionless
d	Diameter, in.
E	Modulus of elasticity, psi
g	Acceleration of gravity, 32.16 ft/sec^2
g_f	g-load factor, dimensionless
h_{fg}	Latent heat, Btu/lb
k	Thermal conductivity, Btu in./in.^{2} °F hr
ℓ	Length, in.
n	Number of radiation shields, dimensionless
p	Pressure, psi
p_g	Pressure equivalent, psi
Q	Heat capacity, Btu
q_c	Heat conduction, Btu/hr
q_r	Heat radiation, Btu/hr
r	Radius, in.
S_c	Compressive stress, psi
S_t	Tensile stress, psi
s	Distance, ft
T	Temperature, °R
t	Thickness, in.
U	Velocity, ft/sec
V	Volume, in.^{3}
V_m	Magnet volume, in.^{3}

W	Weight, lb
ϵ	Emissivity, dimensionless
ν	Poisson's ratio, dimensionless
ρ_{ℓ}	Liquid-helium density, lb/in.^{3}
ρ_m	Metal density, lb/in.^{3}
σ	Stefan-Boltzmann constant, Btu/in.^{2} hr °R^4
τ	Time, hr

SUBSCRIPTS

1	Outer vessel conditions
2	Inner vessel conditions