Optimum Design of Dewar Supports

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A number of struts or straps support a rigid, delicate mass (dewar) which must be successfully launched and maintained in orbit for a long time at a very low temperature. The support system must be designed so that the heat flow into the mass is minimized subject to constraints on minimum allowable natural frequency of the mass during launch, minimum natural frequency of the mass in orbit, maximum allowable stress in any support member during launch, and no buckling or slackening of any support member during launch. Optimum designs are obtained via the CONMIN program for a support system consisting of simple tension straps and support systems with passive thermal disconnect features by means of which the thermal conductance is greatly reduced during the transition from the launch condition to the orbital condition. The theory indicates that either of the optimized thermal disconnect support systems will allow the mass to stay cold far longer than the optimized tension strap support system.

Nomenclature

A = strut cross-sectional area
e = axial strain in support member
E = Young's modulus
I = mass moment of inertia, except Eqs. (24-27), where it denotes area moment of inertia for cross section of a support member
K = conductivity
L = strut length
L_s = spacing of support members (Fig. 2b)
M = mass supported by struts
N = number of support members (12 in Fig. 2; 6 in Fig. 3)
Q = acceleration in units of gravity, g
R = radius of supported mass, M
R_s = radius of spacecraft on which M is supported
t = thickness of support tube
T = tension on strut
ΔT = temperature rise [Eq. (13)]
u = displacement along the axis of a support member
u_{c_i} = displacement component of centroid of supported mass
U = strain energy in support member
X = vector of decision variables (Fig. 6)
α = coefficient of thermal expansion
α_{c_i} = rotation component of supported mass about its centroid
γ = orientation angle of strut measured in axial plane (Fig. 3)
θ = orientation angle of strut measured in horizontal plane (Fig. 3)
σ = stress
Ω = natural frequency, rad/s

Introduction

MANY instruments sent into orbit around the Earth must be maintained at cryogenic temperatures. Cooling is provided by a system called a dewar, the cold parts of which must be attached to a structure that is not cold. The lifetime of the dewar is limited by the flow of heat into it through support struts or straps, insulation, plumbing, and wire leads. Experience has shown[1] that a major source of parasitic heat flow is the support system. Therefore, it is important to design the support system so as to minimize its thermal conductance while meeting constraints on minimum frequency, maximum stress, and buckling.

The dewar support system must be designed for two very different environments: launch and orbit. During launch the support system experiences static and dynamic loads far in excess of those experienced in orbit. This environment is imposed for a short time compared to the time in orbit. In orbit the loads are very low. However, because of the presence of certain vibrating systems aboard the orbiting spacecraft of which the dewar is a part, its support system must still provide enough stiffness to maintain some minimum natural frequency.

The very different conditions present during launch as opposed to those present in orbit imply that it would be advantageous to have a support system the characteristics of which change radically as the environment changes. Two support concepts invented by Parmley[2] are based on the idea of a thermal disconnect: during launch the supports must be much stiffer than in orbit and they have a relatively high thermal conductance associated with structural cross-sectional areas that are required to keep stress low and buckling loads and natural frequencies high; in orbit parts of the structure disconnect in such a way as to lower the thermal conductance greatly and, to a lesser degree, lower the stiffness.

Three support systems are investigated here, one which may be called "standard" (has no disconnect feature), and two which have a disconnect feature.

Summary Statement of the Optimization Problem

Figure 1 shows schematically a rigid mass M supported by three pin-ended struts of axial stiffness EA, length L, and pretension T. The mass M is supported from a spacecraft S by elastic, massless members. The objective of the design process is to minimize the heat flow from S to M subject to the following constraints:

1) The minimum modal vibration frequency shall be larger than a specified value.
2) The support members shall not buckle or become slack during launch.
3) The stress in any member shall not exceed a specified value.

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Actual Configuration Investigated

In the analysis the dewar and the structure (vacuum shell) to which it is attached are assumed to be rigid. The configuration investigated here is shown in Figs. 2 and 3. The name "dewar" denotes everything supported by the 12 struts: the vapor-cooled shields and insulation, the tank and cryogen, and the payload. The axisymmetric dewar is supported by 12 struts or straps; 6 at a location $L_s/2$ forward of the overall center of gravity (c.g.) and 6 aft of the c.g. by the same distance. A plan view of the supports is displayed in Fig. 3. In general, both the support aximuthal angle θ and the declination angle γ, indicated in Fig. 3, may be decision variables in the optimization process. The support members are elastic and massless and carry loads only along their axes. At each of their ends they are pinned to rigid rings.

The supported mass consists of three bodies, treated here as rigid in themselves and rigidly connected to each other: 1) the tank and cryogen, 2) the vapor-cooled shields and insulation, and 3) the payload (instrument, such as a heavy telescope mirror). This movable mass is supported by the vacuum shell, which is assumed to be rigid and immovable.

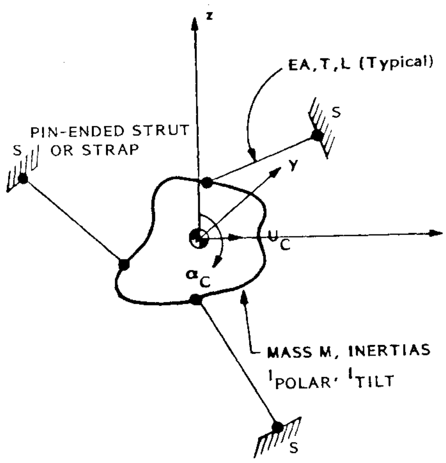


Fig. 1 Mass supported by pinned, massless members with length L, stiffness EA, tension T.

Three Types of Support Members

Optimization studies are carried out for three types of support members:

1) The Passive Orbital Disconnect Strut (PODS) concept (Fig. 4).
2) The "folded-tube" concept (Fig. 5).
3) The standard tension strap concept.

In the "PODS" and "folded-tube" concepts, the effective axial stiffness $(EA)_{\text{eff}}$ and heat flow parameter $(KA/L)_{\text{eff}}$ change abruptly from the launch condition to the orbital condition due to certain "disconnect" features within each strut.[2] Therefore, the design of each of these support systems involves the solution of two optimization problems, one corresponding to the launch phase and the other to the orbital phase.

The tension strap concept involves solution of one optimization problem, corresponding to the launch condition only, since the nature of this support system does not change for the orbital phase and the launch phase represents the more severe environment.

Optimization Analysis

Optimization studies are conducted with the use of a computer program originally written for weight minimization of composite cylindrical panels subjected to destabilizing loads.[3] For application to the problem of dewar support design, this program was modified by replacement of the expression for weight by an expression for heat flow and replacement of the expressions for local and general buckling loads by expressions for vibration frequencies.

Optimization is carried out by a nonlinear programming algorithm called CONMIN.[4,5] This routine, written by Vanderplaats in the early 1970's, is based on a nonlinear constrained search algorithm due to Zoutendijk.[6] The basic analytic technique used in CONMIN is to minimize an objective function (heat flow, for example) until one or more constraints, in this case, vibration frequencies, buckling loads, maximum stress or strain, and upper and lower bounds on design variables, become active. The minimization process then continues by following the constraint boundaries in design variable space in a direction such that the value of the objective function continues to decrease. When a point is

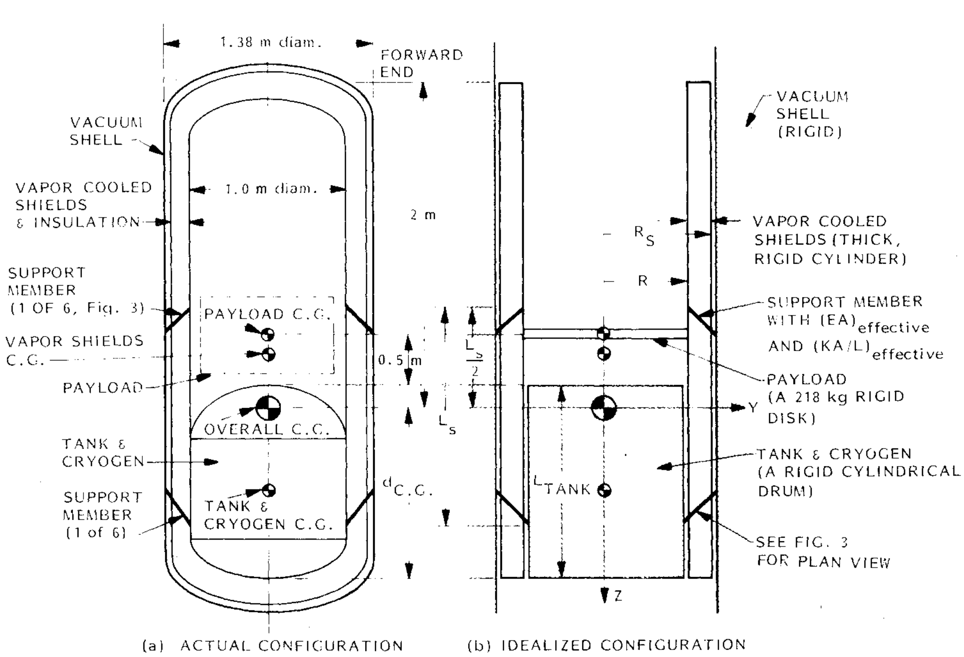


Fig. 2 Mass M consisting of rigid tank and cryogen, rigid vapor-cooled shields and insulation, and rigid payload supported from rigid vacuum shell by means of 12 elastic struts or straps, 6 forward and 6 aft.

reached such that no further decrease in the objective function is obtained, the process is terminated.

Tables 1 and 2 list the design parameters and constraint conditions for the three support concepts. A flowchart of the optimization process is shown in Fig. 6.

Analysis Details

General Case

The kinetic energy of the body shown in Fig. 1 is

$$\text{K.E.} = \frac{1}{2} M \sum_{i=1}^{3} \dot{u}_{c_i}^2 + \frac{1}{2} \sum_{i=1}^{3} I_i \dot{\alpha}_{c_i} \tag{1}$$

in which M is the mass; I_i $(i=1,2,3)$ the principal moments of inertia; $\dot{u}_{c_i}$ the velocity components along the principal axes;

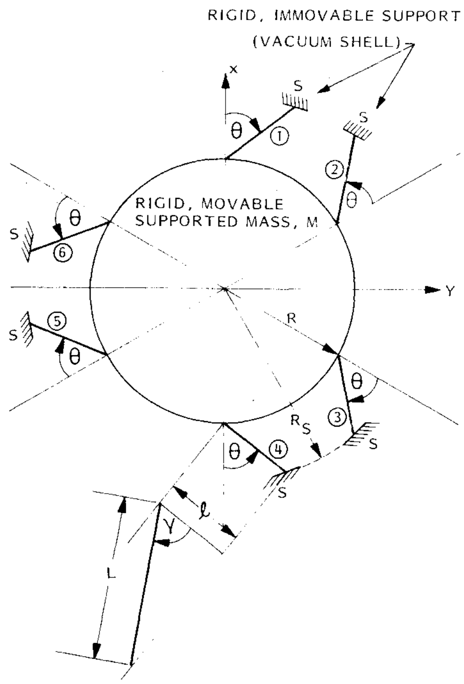


Fig. 3 Plan view of arrangement of six forward support members. The six aft members are arranged with the same θ, but with γ of opposite sign.

and $\dot{\alpha}_{c_i}$ the angular velocity components about the principal axes.

If the N identical *pinned* structural members supporting the body are under initial tension, the strain energy in all of the members (or straps) due to modal vibrations or further loading from the prestressed state is

$$\text{Strain energy} = \frac{1}{2} (EA)_{\text{eff}} L \sum_{j=1}^{N} (e_j^2 - e_{j0}^2) \tag{2}$$

in which $(EA)_{\text{eff}}$ is the effective axial stiffness of each strut, and e_{j0} are the initial axial strains associated with the initial tension (prestress) in the members.

The total axial strain e in any member can be written as

$$e = u'_{\text{tot}} + \tfrac{1}{2} u'^2_{\text{tot}} \tag{3}$$

in which u_{tot} is the total displacement along the axis of the member

$$u_{\text{tot}} = u_0 + u \tag{4}$$

with u_0 being the displacement associated with the initial tension and u the displacement associated with infinitesimal modal vibration or static loading. The superscript $(\ )'$ represents the derivative of u_{tot} with respect to the coordinate along the axis of the member. The total strain e can, with Eq. (4), be written in the form

$$e = u'_0 + u' + (u'_0 + u')^2/2 = e_0 + u'(1 + u'_0) + (u')^2/2 \tag{5}$$

The strain energy U in Eq. (2) can then be expressed in the form

$$U = \frac{1}{2} (EA)_{\text{eff}} L \sum_{j=1}^{N} [e_{j0}^2 + 2e_{j0} u'_j (1 + u'_{j0}) + e_{j0} u_j'^2 + u_j'^2 (1 + u'_{j0})^2 + \text{h.o.t.} - e_{j0}^2] \tag{6}$$

The second term on the right-hand side of Eq. (6) drops out when the work done to provide the initial tension is considered to be part of the total energy of the system. This term is equal and opposite in sign to the work done on the system to provide the initial tension. (It is assumed, of course, that the initially

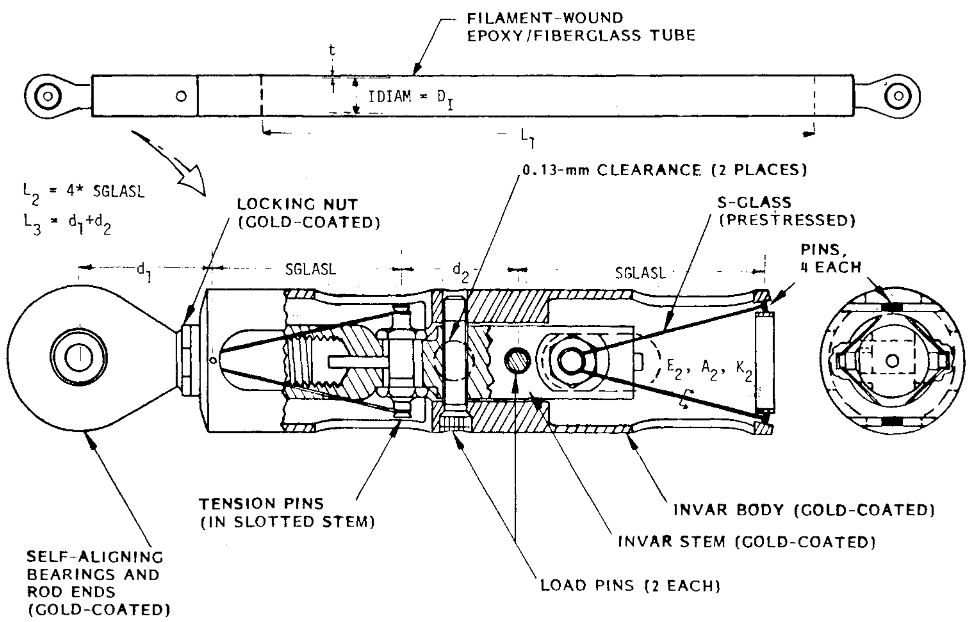


Fig. 4 PODS concept.

Table 1 Design parameters (decision variables) in the optimization process for the three dewar support concepts

PODS concept (Fig. 4)		Folded-tube concept (Fig. 5)		Tension-strap concept both launch and orbital conditions
Launch condition	Orbital condition	Launch condition	Orbital condition	
L_s = axial spacing of supports on dewar (Fig. 2)	A_2 = cross-sectional area of S-glass strands (Fig. 4)	Same as for PODS concept	A_2 = cross-sectional area of tube 2 (Fig. 5)	Same as for PODS concept
θ = azimuthal angle of strut (Fig. 3)	SGLAS*L* = axial length of S-glass strands (Fig. 4)	Same as for PODS concept	A_3 = cross-sectional area of tube 3 (Fig. 5)	Same as for PODS concept
γ = declination angle of strut (Fig. 3)		Same as for PODS concept	FOLD*L* = length of tubes 2 and 3 as percentage of length of tube 1 (Fig. 5)	Same as for PODS concept
t = thickness of fiberglass tube (Fig. 4)		t = thickness of tube 1 (Fig. 5)		A = cross-sectional area of strap
D_I = inner diameter of fiberglass tube (Fig. 4)		D_I = inner diameter of tube 1 (Fig. 5)		TENSN = tension in strap

Table 2 Constraint conditions on the optimization process for the three dewar support concepts

PODS concept (Fig. 4)	Folded-tube concept (Fig. 5)	Tension-strap concept
Maximum stress in fiberglass tube due to launch loads (10 *g* axial + 10 *g* lateral)	Same as for PODS concept, tube 1	Maximum stress in strap due to launch loads, as in PODS concept
Buckling of fiberglass tube as a column	Buckling of tube 1 as a column	Tension strap must not go slack during launch
Buckling of fiberglass tube as a thin shell	Buckling of tube 1 as a thin shell	Not applicable
Stress in tube due to differential expansion of dewar and vacuum shell during filling with cryogen	Same as for PODS concept, applied to tube 1	Same as for PODS concept, applied to tension strap
Minimum thickness of fiberglass tube = 0.038 cm (0.015 in.)	Minimum thickness of tube 1 = 0.038 cm (0.015 in.)	Not applicable
Maximum inner diameter of fiberglass tube = 3.8 cm (1.5 in.)	Maximum inner diameter of tube 1 = 5.08 cm (2 in.)	Not applicable
Maximum values for strut angles θ and γ = 90 deg	Same as for PODS concept	Same as for PODS concept
Minimum vibration frequency = 35 Hz	Same as for PODS concept	Same as for PODS concept
Minimum cross-sectional area of S-glass members 1.3×10^{-4} cm^2 (0.00002 in^2)	Minimum thickness of tubes 2 and 3 = 0.025 cm (0.01 in.)	Not applicable
Maximum axial length of S-glass members = 3.8 cm (1.5 in.)	Maximum length of tubes 2 and 3 = 95% of length of tube 1; length of tube 2 equals that of tube 3	Not applicable
Minimum axial length of S-glass members = 1.5 cm (0.6 in.)	Not applicable	Not applicable
Minimum vibration frequency = 20 Hz	Same as for PODS concept	Same as for PODS concept

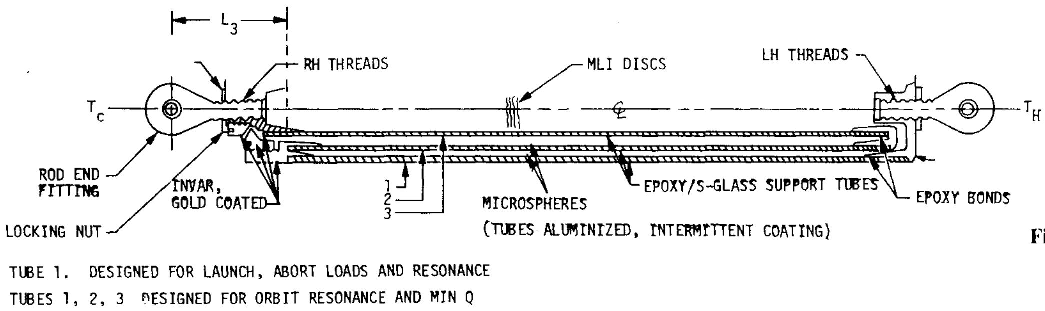


Fig. 5 Folded-tube strut concept.

tensioned system is in equilibrium!) The "h.o.t." represents cubic and quartic terms in u', which can be dropped if we consider vibrations or static deflections of infinitesimal amplitude. With use of the approximation $u_0' \approx e_0$, Eq. (6) can be expressed in the form

$$U = \frac{1}{2}(EA)_{\text{eff}} L \sum_{j=1}^{N} [u_j'^2 (1+3e_{j_0})] \tag{7}$$

or, with use of the stress-strain relation,

$$(EA)_{\text{eff}} e_{j_0} = T_j \tag{8}$$

in which T_j is the tension in the jth member, Eq. (7) becomes

$$U = \frac{1}{2} L \sum_{j=1}^{N} [(EA)_{\text{eff}} + 3T_j] u_j'^2 \tag{9}$$

With equal tension in all members, we have

$$U = \frac{1}{2} L[(EA)_{\text{eff}} + 3T] \sum_{j=1}^{N} u_j'^2 \tag{10}$$

The expressions for kinetic energy [Eq. (1)] and strain energy [Eq. (10)] are used to obtain natural frequencies [Eqs. (11) and (12)]

Special Case: Axisymmetric Dewar with 12 Support Struts or Straps

Configuration and Mass Properties

Figure 2a shows an axisymmetric tank supported by 12 struts or straps; 6 at a location $L_s/2$ forward of the overall center of gravity (c.g.) and 6 aft of the c.g. by the same distance. A plan view of the supports is displayed in Fig. 3.

In general, both the support azimuthal angle θ and the declination angle γ, shown in Fig. 3, may be decision variables in the optimization process. However, several computer runs have demonstrated that the optimal value of θ usually corresponds to a case in which the struts pass through one another, e.g., $\theta = 90$ deg. It, therefore, was judged practical in the optimization computer runs to express θ as a function of γ such that pairs of struts meet at the vacuum shell. In this derivation, however, θ is maintained independent of γ.

The supported mass consists of three bodies, treated here as rigid in themselves and rigidly connected to each other: 1) the tank and cryogen, 2) the vapor-cooled shields and insulation, and 3) the payload. Figure 2b shows an idealization for the purpose of analysis. The vacuum shell is treated as if it were rigid and immovable.

Optimization Strategy

The objective function of the optimization analysis, i.e., the quantity to be minimized, is an effective heat flow factor or "conductance," $N(KA/L)_{\text{eff}}$, in which N is the number of supports, K the strut or strap conductivity, A the cross-sectional area, and L the length. This factor is to be minimized by variation of the design variables (decision variables) listed in Table 1 subject to the constraint conditions listed in Table 2.

In the PODS and folded-tube concepts the decision variables listed under the heading "Launch condition" are first allowed to vary as the heat flow factor $(KA/L)_{\text{launch}}$ is minimized. The variables listed under "Orbital condition" are not part of this problem. They have no influence at all, since the nature of the PODS and folded-tube designs are such as to render them inactive during launch. After optimum values of L_s, θ, γ, t, and D_I (Figs. 2-4) have been found, they are held fixed and the decision variables listed under the heading "Orbital condition" are allowed to vary as the heat flow factor $(KA/L)_{\text{orbital}}$ is minimized.

Variation of Dewar Geometry with Weight

It is of interest to ascertain optimum supports for a range of weight of supported mass from 360 to 909 kg. In this parameter study the inner diameter of the vacuum shell is held constant at 1.38 m (54.37 in.) and the outer diameters of the tank and payload are held constant at 1.0 m (39.37 in.). The vapor-cooled shields and insulation project forward from the forward end of the cryogen tank by a constant 2 m (78.74 in.), and the payload center of gravity is located a constant 0.5 m (19.69 in.) forward of the forward end of the cryogen tank. Further details of mass distribution and expressions for mass moments of inertia appear in Ref. 7.

Natural Frequencies

There are six natural frequencies for the system shown in Fig. 2 which correspond to rigid-body motion of the supported mass. Four of these are distinct, corresponding to translation of the mass M: 1) along the axis of revolution (axial) and 2) normal to the axis of revolution (lateral); and rotation of the mass M: 3) about the axis of revolution (torsional or rolling) and 4) rotation of M about an axis through the c.g. normal to the axis of revolution (tilting or pitching). The natural frequencies are calculated from

$$\Omega_i^2 = L[(EA)_{\text{eff}} + 3T)] \sum_{j=1}^{N} u_j'^2 \Big/ M u_{c_i}^2 \qquad i = 1,2 \tag{11}$$

for axial or lateral modes and

$$\Omega_i^2 = L[(EA)_{\text{eff}} + 3T)] \sum_{j=1}^{N} u_j'^2 \Big/ I_i \alpha_{c_i}^2 \qquad i = 1,2 \tag{12}$$

for torsional (roll) or tilt (pitch) modes. The lateral and pitching modes are decoupled because it is assumed that the rigid mass M is supported symmetrically with respect to the axial coordinate on either side of the mass centroid (Fig. 2). For these four modes of vibration it is required to calculate u_j', $j = 1,2,\ldots,12$ given unit values of u_{c_i}, $i = 1,2$ (corresponding to axial and lateral components of translation) and given unit values of α_{c_i}, $i = 1,2$ (corresponding to unit values of rotation about the axis of revolution and rotation about an axis through the mass centroid normal to the axis of revolution.

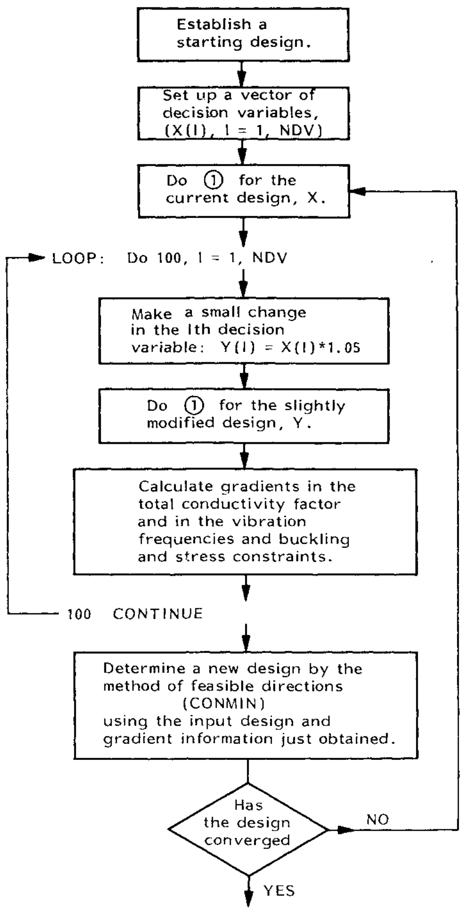


Fig. 6a Strategy used in optimization process.

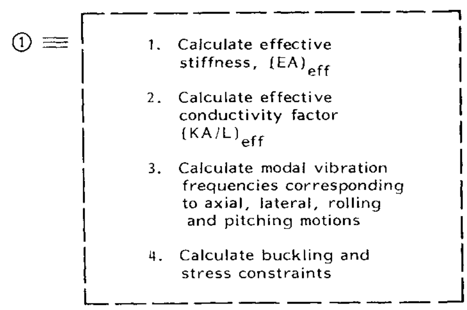


Fig. 6b Analysis module in PANDA-DEWAR.

Details of these calculations appear in Ref. 7. The natural frequencies were checked by a finite element model analyzed with the use of the STAGSC-1 computer program.[8] A figure showing the finite element model and a table comparing predictions of natural frequencies from that model and from the present closed-form analysis appear in Ref. 7.

Stress and Buckling Constraints

In the prelaunch state and at launch the dewar support system is subjected to thermal and mechanical loading that may cause failure of the support material or buckling of one or more of the struts. If the dewar is supported by tension straps the tension in the straps must be sufficient at launch so that the g-loading does not cause any strap to go slack.

In general there are four conditions, any combination of which might constrain the optimum design.

1) The prestress required (tensile if the supports are arranged as shown in Figs. 2 and 3) in struts or straps before the tank is filled with the cryogen, so that this prestress vanishes after the tank has been filled and it, the vapor-cooled shields, and the vacuum shell have reached their prelaunch equilibrium temperatures.

2) The maximum tensile or compressive stress experienced by any support member during the launch, when peak accelerations of 10 g axial combined with 10 g lateral are seen by the dewar.

3) The possibility that any support member may buckle as a column (Euler buckling) or, in the case of the tension strap concept, that a strap may go slack due to dynamic launch loads.

4) The possibility, in the cases of the PODS or the folded-tube concept, that any strut tube may buckle as a thin shell.

Prestress Due to Differential Thermal Expansion of the Dewar upon Filling with Cryogen

Figure 7 shows the geometry of the problem. The configuration indicated by dotted lines represents that for which the optimization analyses for launch and orbital conditions are carried out. That is, it is assumed in the optimization analyses that there is no prestress in the support members, except for the tension in the case of the tension strap concept required to keep any strap from going slack during launch. If the dewar is assembled at ambient temperature prior to being filled with cyrogen, the support members must be prestrained at this time according to the formula

$$e_{\text{thermal}} = \alpha\Delta T[L_s \sin\gamma/2 - R\cos\gamma\cos\theta]/L \tag{13}$$

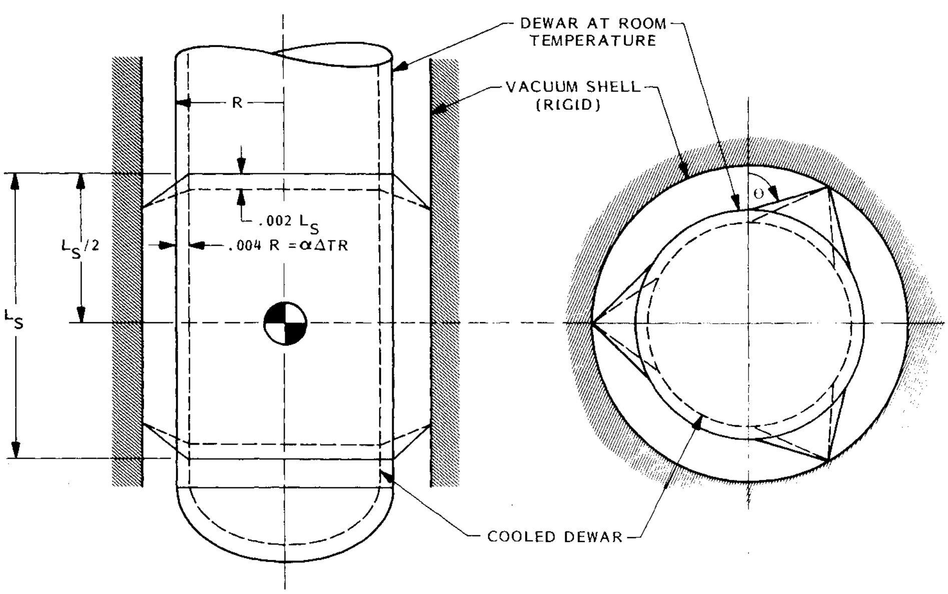


Fig. 7 Change in configuration due to differential contraction of the dewar and the vacuum shell after filling with the cryogen.

in which $\alpha\Delta T$ represents the differential thermal expansion (0.004 in Fig. 7) between the vacuum shell and the supported mass after the tank has been filled with cryogen and everything has reached its prelaunch equilibrium state. Use of Eq. (13) to formulate a constraint condition in the optimization analysis is based on the assumptions that the supporting members themselves suffer no change in dimension due to cooling down and that the supported mass and vacuum shell are rigid.

The total prestress in each support member required at the time of assembly is

$$\sigma_{\text{pre}} = E e_{\text{thermal}} (L/L_{\text{eff}}) + T/A \tag{14}$$

in which L_{eff} is the effective length of the support member that is strained (less than the length L shown in Fig. 3 because of "rigid" end fittings), and T is the tension in the support member (tension strap concept only) in the prelaunch (filled) state.

The constraint condition to be used in the optimization analysis is

$$\sigma_{\text{pre}}/\sigma_{\max} \leq 1.0 \tag{15}$$

Stress Due to Launch Accelerations

During launch the dewar is subjected to peak accelerations with a 10-g axial component and a 10-g lateral component. The maximum stress seen by any support member due to the inertial reaction of the supported mass to the sum of these acceleration components must not exceed a specified value.

The strain in each support member due to either an axial or a lateral acceleration component can be computed in two steps:

1) Compute the amount u_c the c.g. of the supported mass moves relative to the vacuum shell due to its inertial reaction to the 10-g acceleration.

2) With this value of u_c, compute the maximum strain and hence stress in any support member.

The strain energy of the supports is

$$U = \frac{1}{2} L[(EA)_{\text{eff}} + 3T] \sum_{j=1}^{N} e_j^2 \tag{16}$$

in which e_j is the strain in the jth support and N the number of supports. Corresponding to axial and lateral motions the strain energy components are

$$U_{\text{axial}} = u_{c_{\text{axial}}}^2 6[(EA)_{\text{eff}} + 3T]\sin^2\gamma/L \tag{17}$$

$$U_{\text{lateral}} = u_{c_{\text{lateral}}}^2 3[(EA)_{\text{eff}} + 3T]\cos^2\gamma/L \tag{18}$$

in which Eq. (24) of Ref. 7 has been used to derive Eq. (17), and Table 3 of Ref. 7 has been used to derive Eq. (18). The c.g. displacements u_c and $u_{c_{\text{axial}}}$ and $u_{c_{\text{lateral}}}$ can be computed from the following equations:

$$F_{\text{inertial}}^{\text{axial}} = MQ_{\text{axial}} g = \frac{\mathrm{d}U_{\text{axial}}}{\mathrm{d}u_{c_{\text{axial}}}}$$

$$= 12 u_{c_{\text{axial}}} [(EA)_{\text{eff}} + 3T]\sin^2\gamma/L$$

$$F_{\text{inertial}}^{\text{lateral}} = MQ_{\text{lateral}} g = \frac{\mathrm{d}U_{\text{lateral}}}{\mathrm{d}u_{c_{\text{lateral}}}}$$

$$= 6 u_{c_{\text{lateral}}} [(EA)_{\text{eff}} + 3T]\cos^2\gamma/L \tag{19}$$

in which Q_{axial} and Q_{lateral} are the numbers of g's seen by the dewar during launch ($Q_{\text{axial}} = Q_{\text{lateral}} = 10$).

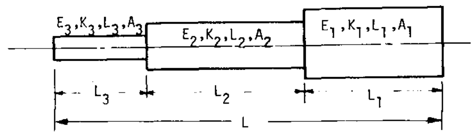


Fig. 8 Schematic of a compound strut.

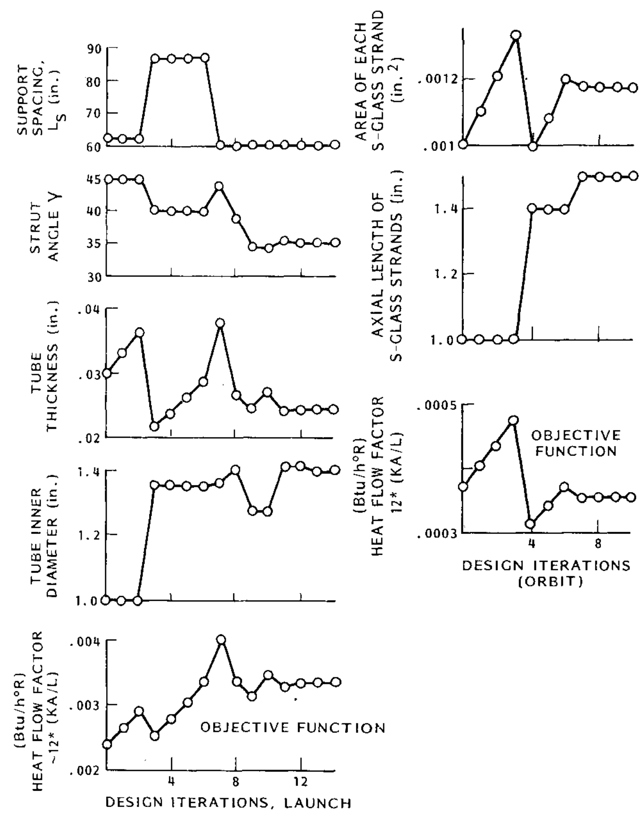


Fig. 9 PANDA-DEWAR design iterations for the PODS support concept.

The maximum axial and lateral strains corresponding to $u_{c_{\text{axial}}}$ and $u_{c_{\text{lateral}}}$ from Eqs. (19) are, from Eq. (24) and Table 3 of Ref. 7 respectively,

$$e_{\text{axial}} = u_{c_{\text{axial}}} \sin\gamma/L = \frac{MQ_{\text{axial}} g}{12[(EA)_{\text{eff}} + 3T]\sin\gamma}$$

$$e_{\text{lateral}} = u_{c_{\text{lateral}}} \cos\gamma/L = \frac{MQ_{\text{lateral}} g}{6[(EA)_{\text{eff}} + 3T]\cos\gamma} \tag{20}$$

The total strain in the most highly loaded support member is

$$e_{\text{launch}} = |e_{\text{axial}}| + |e_{\text{lateral}}| + T/(EA) \tag{21}$$

and the associated stress is

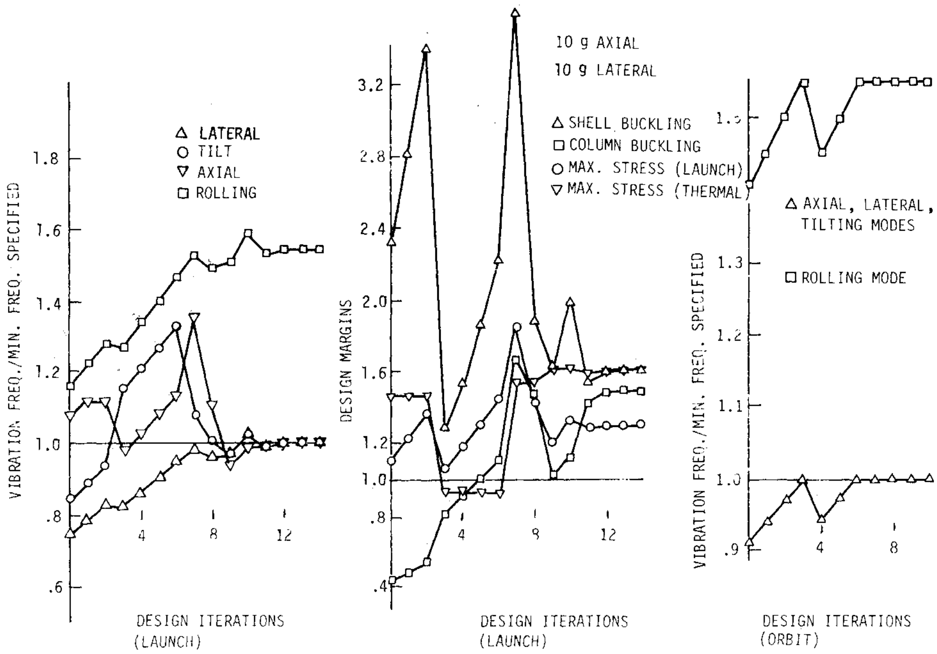
$$\sigma_{\text{launch}} = E e_{\text{launch}} \tag{22}$$

As in the case of the thermal prestress [Eq. (15)] the constraint condition to be used in the optimization analysis is

$$\sigma_{\text{launch}}/\sigma_{\max} \leq 1.0 \tag{23}$$

Note that Eqs. (17-20) are valid only if the support members are arranged symmetrically with respect to the mass c.g. as shown in Fig. 2. Hence, the lateral component of acceleration

Fig. 10 Value of constraint conditions during iterations.



produces only lateral displacement of the supported mass relative to the vacuum shell. In a nonsymmetrical arrangement of the supports the lateral component of acceleration would of course produce a combination of lateral and pitching displacements of the supported mass M.

Column Buckling

For struts pinned at both ends (PODS and folded-tube concepts) we have

$$\text{Critical load} = \pi^2 EI/L^2 = EAe_{\text{crit}} \tag{24}$$

in which I is the area moment of inertia of the strut cross section about a diameter and L is the length of the strut between pinned ends (Fig. 3). The maximum compressive strain is

$$e_{\text{crit}} = T/EA - |e_{\text{axial}}| - |e_{\text{lateral}}| \tag{25}$$

in which the strain components e_{axial} and e_{lateral} are given by Eqs. (20). The constraint condition to be used in the optimization analysis is

$$|e_{\text{axial}}| + |e_{\text{lateral}}| \leq \pi^2 I/AL^2 + T/EA \tag{26}$$

or

$$\frac{|e_{\text{axial}}| + |e_{\text{lateral}}|}{\pi^2 I/AL^2 + T/EA} \leq 1.0 \tag{27}$$

In the case of tension straps, the bending rigidity is zero ($I=0$). The buckling criterion [Eq. (27)] must be replaced by a criterion that e_{crit} in Eq. (25) remains positive during launch. Thus, the buckling criterion [Eq. (27)] can be used for tension straps if the area moment of inertia I is set equal to zero.

Buckling of Strut as a Thin Shell

In the PODS and folded-tube concepts each support member consists of a cylindrical shell during the launch phase which may be compressed axially according to Eq. (25). The buckling stress is given by

$$\sigma_{\text{crit}} = K^* [0.6Et/R_{\text{ave}}] \tag{28}$$

in which K^* is a knockdown factor to account for the deleterious effect of initial imperfections in the shape or material of the strut, t the thickness of the tube wall, and R_{ave} the average radius of the tube. In this analysis K^* is taken as 0.5, which previous experiments have demonstrated to be appropriate for axially compressed cylindrical shells with $R_{\text{ave}}/t \leq 100$.

The corresponding constraint condition for application in the optimization analysis is

$$\frac{E(|e_{\text{axial}}| + |e_{\text{lateral}}|)}{(K^* 0.6Et/R_{\text{ave}})} \leq 1.0 \tag{29}$$

Effective Stiffness and Conductance

In the PODS and folded-tube concepts each support member is a compound strut with an "effective" stiffness $(EA)_{\text{eff}}$ and an "effective" conductance $(KA/L)_{\text{eff}}$. In Fig. 8 is shown a schematic of a compound strut with three different sections, each with its own properties E_i, K_i, L_i, A_i, $i=1,2,3$. The proper overall stiffness and conductance are obtained from the following mixture formulas:

$$1/(EA)_{\text{eff}} = [L_1/(E_1A_1) + L_2/(E_2A_2) + L_3/(E_3A_3)]/L \tag{30}$$

and

$$[L/(KA)]_{\text{eff}} = L_1/(K_1A_1) + L_2/(K_2A_2) + L_3/(K_3A_3) \tag{31}$$

PODS Concept

Figure 4 shows the geometry of the PODS concept. In this case (L_1, E_1, A_1, K_1) can be associated with the fiberglass tube; (L_2, E_2, A_2, K_2) can be associated with the S-glass strands; and (L_3, E_3, A_3, K_3) can be associated with the rest of the length of the strut, that is, calculated from the dimensions of the end fittings and the distances at each end between each of the two sets of S-glass strands.

The S-glass strands run at angles to the axis of the strut, and there are eight strands (a "group") at each end of the strut (one "group" = two bundles of four each) that connect the fiberglass tube to the thermally "isolated" body. It can be shown that the effective axial stiffness of each group of 8 S-glass strands is

$$(EA)_{\text{eff}}^{\text{S-glass}} = 8E_sA_s(\text{SGLASL})^3/[(\text{SGLASL})^2 + D_f^2/2]^{3/2} \tag{32}$$

in which SGLASL is the axial projection of the length of one set of four S-glass strands and D_I is the inner diameter of the fiberglass tube.

In the launch condition the effective stiffness and conductance for each support member in the PODS concept are

$$(EA)_{\text{eff}}^{\text{launch}} = E_I A_I L (L - 2L_3)$$

$$(KA/L)_{\text{eff}}^{\text{launch}} = K_I A_I / (L - 2L_3) \qquad (33)$$

in which L_3 is equal to the sum of the distance from the center of the rod end bearing to the first attachment point of the first set of S-glass strands (d_I) and the distance between the two sets of S-glass strands (d_2). (See Fig. 4.)

In the orbital condition the effective stiffness and conductance for each support member in the PODS concept are

$$(EA)_{\text{eff}}^{\text{orbital}} = L / \{ 0.25 [(\text{SGLAS}L)^2 + D_I^2/2]^{3/2} / [(\text{SGLAS}L)^2 E_s A_s] + (L - 2L_3)/(E_I A_I) \}$$

$$(KA/L)_{\text{eff}}^{\text{orbital}} = 1 / \{ [(1/K_{\text{hot}}) + (1/K_{\text{cold}})] [(\text{SGLAS}L)^2 + D_I^2/2]^{1/2} / (8A_s) + (L - 2L_3 - 4\text{SGLAS}L)/(K_I A_I) \} \qquad (34)$$

in which K_{hot} and K_{cold} are the conductivities of the S-glass strands at the "hot" and "cold" ends of each strut.

Folded-Tube Concept

Figure 5 shows the geometry of the folded-tube concept. In this case (L_i, E_i, A_i, K_i) in Eqs. (30) and (31) can be associated with tube i.

In the launch condition the effective stiffness and conductivity factors for each support member in the folded-tube concept are given, as in the PODS concept, by Eqs. (33), with L_3 being the length of one of the end fittings. In the orbital condition, we have

$$(KA/L)_{\text{stiffness}}^{\text{orbital}} = 1 / [(L - 2L_3)/(K_I A_I) + L_{\text{fold}}/(K_2 A_2) + L_{\text{fold}}/(K_3 A_3)] \qquad (35)$$

in which L_{fold} is the length of tubes 2 and 3.

Tension-Strap Concept

The effective stiffness and conductance are given by Eqs. (33) with $L_3 = 0$.

Optimization

The objective of the optimization analysis for each support-member concept is to derive values of the design parameters listed in Table 1, such as to minimize the flow of heat into the supported mass from the vacuum shell, to which it is attached, while maintaining enough structural rigidity to keep the lowest frequencies at launch and during orbital conditions above certain specified values, and stresses due to assembly and launch loads below those that would cause buckling or material failure of the support system.

A computer program called PANDA-DEWAR was written to solve this problem. Optimum designs were obtained for several dewar weights for four support concepts, including two "PODS" concepts, a "folded-tube" concept, and a simple tension-strap concept. The first three concepts involve support struts the nature of which changes in a way that greatly decreases their effective conductance for orbital conditions. Optimization of the dewar support systems involving each of these concepts requires solution of two optimization problems, the first corresponding to launch conditions and the second to orbital conditions. In the case of the

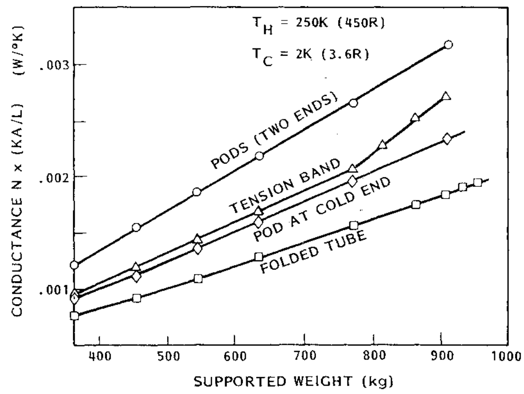


Fig. 11 Conductance at launch for a range of dewar weight.

tension-strap concept the support systems need be optimized only for launch conditions.

Optimization is carried out by a nonlinear programming algorithm based on the method of feasible directions.[4] The computer program for the dewar support design was generated by modification of a program called PANDA[3] for the minimum weight design of stiffened composite cylindrical panels. Application to the dewar support problem was accomplished by replacement of the expression for panel weight in PANDA with an appropriate expression for the heat conductance $N(KA/L)_{\text{eff}}$ through the support system, and by replacement of certain expressions for general and local shell buckling by the appropriate expressions for frequency, stress, and buckling of the supported mass and the supports derived in the previous sections.

Figure 6 shows the strategy used to obtain optimum designs in PANDA-DEWAR. The starting design does not have to be close to an optimum, nor does it have to be a feasible design. For the PODS and folded-tube concepts the strategy outlined in Fig. 6 is applied twice; first for the launch condition, during which parameters relative to the orbital phase (Table 1) have no role, and then for the orbital phase during which the parameters varied in the launch phase are held constant.

Numerical Results

Design Iterations

Figures 9 and 10 show results of design iterations for one of the "PODS" support concepts. Values of the decision variables and objective function for launch and orbital conditions are plotted in Fig. 9, and values of the constraint conditions for launch and orbit are plotted in Fig. 10. Active constraints at the optimum design include vibration frequencies corresponding to lateral motion, axial motion, and tilt (pitching).

Parameter Study

The results of the optimization analysis over a wide range of dewar weights are displayed in Figs. 11 and 12. Two sets of results corresponding to the PODS concept are shown, one in which it is assumed that disconnect PODS exist at both ends of each strut and the other in which there is a disconnect POD only at the end of the strut which is attached to the tank. The latter concept is superior for the orbital condition because the conductance of the S-Glass strands decreases from 0.052 to 0.00722 Btu/(h-in.°F) over the temperature range represented by the states at the "hot" and "cold" ends of each strut. In Figs. 11 and 12 the heat flow factors represent the sum over all 12 support members. The folded-tube concept appears to be the best for launch conditions. However, it should be emphasized that the results do not account for the heat flow due to radiation from the outer tubes toward the inner tubes.

The folded-tube concept under orbital conditions is less advantageous than it appears from the present analysis

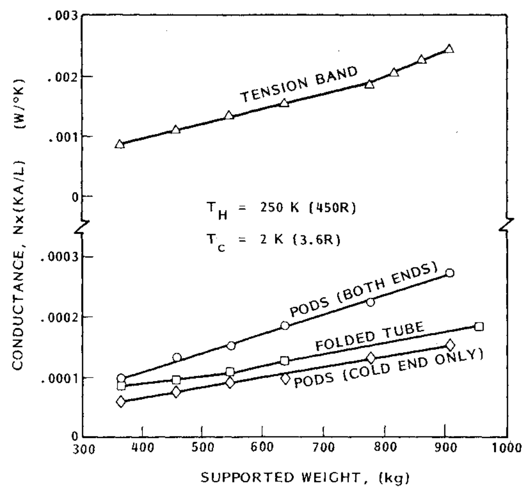


Fig. 12 Conductance in orbit for a range of dewar weight.

because the axial stiffness computed from Eq. (30) is an upper bound to the actual axial stiffness. The major factor omitted from the simplified analysis is the eccentricity of the tube connections. The tubes will bend locally in the neighborhoods of these connections. This bending, coupled with the radial eccentricities between adjacent tubes, gives rise to rotation of the junctions with a resultant increase in axial deflection for a given axial force.

It must also be emphasized that the results displayed here are doubtless quite optimistic because flexibility of the structures to which the support members are attached is neglected. Inclusion of this flexibility, of course, would lower the natural frequencies of the system, thereby leading to the requirement of stiffer and hence more conductive support members in order to compensate for the tank and vacuum shell flexibilities. These factors should be accounted for in post-optimization checks of designs obtained from the simplified treatment just described.

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