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by Irving E. Sumner and James R. Barber
Lewis Research Center
Cleveland, Ohio 44135

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Irving E. Sumner and James R. Barber
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Abstract

Three reusable insulation systems concepts have been developed for use with cryogenic tanks of earth-based space vehicles. Two concepts utilized double-goldized Kapton (DGK) or double-aluminized Mylar (DAM) multilayer insulation (MLI), while the third utilized a hollow-glass-microsphere, load-bearing insulation (LBI). All three insulation systems have recently undergone experimental testing and evaluation under NASA-sponsored programs. Thermal performance measurements were made under space-hold (vacuum) conditions for insulation warm boundary temperatures of approximately 291 K (524 $^{\circ}$R). The resulting effective thermal conductively was approximately 8×10^{-5} W/m-K (4.6×10^{-5} Btu/hr-ft-$^{\circ}$R) for the MLI systems (liquid hydrogen test results) and 5.4×10^{-4} W/m-K (3.1×10^{-4} Btu/hr-ft-$^{\circ}$R) for the LBI system (liquid nitrogen test results corrected to liquid hydrogen temperature). The DGK MLI system experienced a maximum thermal degradation of 38 percent, the DAM MLI system 14 percent, and the LBI system 6.7 percent due to repeated thermal cycling representing typical space flight conditions. Repeated exposure of the DAM MLI system to a high humidity environment for periods as long as 8 weeks provided a maximum degradation of only 24 percent. The MLI systems provided the lowest total system weights (including liquid hydrogen boiloff), assuming modifications could be made to the fiberglass fairings and purge bag configurations, when the insulation systems were optimized for a typical 163-hour space mission.

Introduction

With the advent of a reusable Space Transportation System (STS), considerable interest has been shown toward upper-stage propulsion vehicles and liquid propellant tanker (or resupply) vehicles that are themselves reusable for some specified number of space flights. Some concepts for these vehicles would require them to be tanked on the ground prior to launch. The vehicles might then typically be flown in both low and high earth orbits for periods of time ranging from several hours to several hundred hours depending on the requirements for each specific space flight. After each space flight, the vehicles would be returned to the ground for refurbishment prior to the next space flight. Among the candidates for such vehicles are those that utilize cryogenic propellants. For these vehicles to effectively utilize the maximum energy available from the cryogenic propellants and also be cost effective, the insulation systems that limit the heat input to the propellant tanks must have high thermal performance and be reusable.

NASA has been supporting efforts that will provide needed technology on reusable, high-performance cryogenic insulation systems. This technology will allow future space vehicle designers to make the necessary decisions that are required to select a reusable cryogenic insulation system suitable for a particular application. Three such reusable cryogenic insulation system projects are summarized, and the results are compared herein. These insulation systems are: (1) Evacuated Load-Bearing High-Performance Insulation[1], (2) Helium-Purged Double-Goldized Kapton/Dacron Tuft Multilayer Insulation[2], and (3) Helium-Purged Double-Aluminized Mylar/Silk Net Multilayer Insulation[3]. These insulation systems as designed, fabricated and tested, represent a wide range of differing approaches to achieve a common objective; that of providing a high-performance, reusable insulation system capable of withstanding ground-hold and space-hold thermal cycling.

It should be noted that although comparisons of the various insulation system performance parameters are made herein for one specific space vehicle and mission, the actual advantages of one system over another may be determined only when the desired mission or use is chosen to form the basis for making a more detailed comparison. For example, the Load-Bearing Insulation system, which was relatively heavy and has a relatively high thermal conductivity under space conditions, may have no advantages for long-term space missions. However, it may be advantageously used on short-term space missions where the better ground-hold thermal performance provides mission trade-off benefits that overcome its relatively poorer space-hold thermal performance, or it may be advantageously used in the earth's atmosphere for cryogenically fueled aircraft, for example. Also, it might be desirable to incorporate features of both of the multilayer insulation (MLI) systems tested to arrive at an optimum or lower cost insulation system for certain types of space missions.

Symbols

A	area, m^2
C_i	insulation system thermal performance - weight parameter based on insulation surface area, Q_iW_i/A_i^2, W-kg/m^4
C_t	insulation system thermal performance - weight parameter based on tank surface area, Q_iW_i/A_t^2, W-kg/m^4
K_e	insulation effective thermal conductivity, $(Q_i/A_i)\left[t_i/(T_H - T_C)\right]$, W/m-K
Q	heat input, W
$\dot{q}$	heat flux, W/m^2
T	temperature, K
t	thickness, m
W	weight, kg

Subscripts:

C	cold
H	hot
i	insulation
m	measured
t	tank

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Description of Insulation Systems

Load-Bearing Insulation

The Load-Bearing Insulation (LBI) concept represented a unique approach to the problem of providing a high-performance insulation system for cryogenic propellant tanks. This insulation concept was developed and tested by the Lockheed Missiles and Space Company, Palo Alto Research Laboratory under Lockheed Independent Technology Programs and a NASA Lewis Research Center contract NAS3-17817. The results of the contractual effort were reported in Ref. 1. This concept, shown in Fig. 1, utilized uncoated hollow glass spheres approximately 0.08 mm (0.003 in.) in diameter with a bulk density of 0.069 g/cc (4.3 lb/ft^3) to provide the required barrier to thermal radiation and also to provide a poor solid conduction heat transfer path from the hot boundary to the tank wall. The hollow glass spheres were contained within a lightweight vacuum jacket formed from 0.08 mm (0.003 in.) thick 321 alloy stainless steel. A wedge design was formed into the vacuum jacket to allow the jacket to move elastically as the tank wall contracted due to chilldown from a cryogenic fluid or expanded from the subsequent warmup. The jacket was also stiffened locally within the pattern of wedges to increase its load-bearing capability without sustaining permanent deformation and to maintain a more uniform insulation thickness. The annular space between the tank wall and the vacuum jacket containing the glass spheres was evacuated, backfilled with carbon dioxide, and reevacuated to less than 1.3 pascal (1×10^{-2} torr) to reduce the gaseous conduction mode of heat transfer through the insulation. The hollow glass spheres themselves were subjected to a high-temperature vacuum bakeout to reduce the internal gas pressure to near zero. The tank wall and the inside surface of the vacuum jacket were gold-coated to provide low emissivity surfaces to further reduce the radiation mode of heat transfer. The spacing between the tank wall and the vacuum jacket was maintained by a large number of spring assemblies which consisted of a slightly compressed stainless steel spring and three Kevlar strands to limit the maximum extension of the spring. The spring assemblies aided in preventing the migration of glass spheres to any preferential areas while initially filling the annular space and during any vibration or high, sustained acceleration environments which the insulated tank might be subjected to.

During normal operations under ground-hold conditions and within the earth's atmosphere, the atmospheric pressure loading on the outside surface of the vacuum jacket was sustained primarily by the hollow glass spheres, and solid conduction was the primary mode of heat transfer through the insulation. When the ambient pressure surrounding the insulated test tank was reduced to near zero (vacuum conditions), the compressive loading on the glass spheres was reduced considerably, and thermal radiation became the dominant mode of heat transfer.

The LBI system was installed and tested on a 1.17-meter (3.84-ft) diameter spherical tank using liquid nitrogen as the cryogenic test fluid. A photograph of the insulated tank, ready for testing, is shown in Fig. 2. A summary of the physical characteristics of the insulation system is shown in Table I. The insulation system weighed a total of 15.00 kg (33.07 lb). Of this weight, 5.06 kg (11.16 lb) was included for the insulation of the tank support struts. The strut insulation was not optimized for the test program conducted and should not be charged against the basic insulation system weight. The resulting basic insulation weight per unit tank wall area was 2.31 kg/m^2 (0.474 lb/ft^2).

Double-Goldized Kapton/Dacron Tuft Multilayer Insulation System

The Double-Goldized Kapton/Dacron Tuft (DGK/DT) Multilayer Insulation system was designed to (1) provide rapid purging of the insulation prior to loading the tank with a cryogenic propellant on the ground, (2) withstand temperatures as high as 450 K (810 ^{o}R), and (3) be reusable over a total of 100 flight cycles. This insulation system design was developed and tested by Convair Division of General Dynamics under contract to NASA Marshall Space Flight Center (Contract NAS8-27419). The results of this contractual effort were reported in Ref. 2. This insulation system concept, as shown in Fig. 3, incorporated two blankets of multilayer insulation (MLI), each containing 22 double-goldized Kapton radiation shields separated by Dacron tuft spacers (a proprietary MLI concept known as Superfloc). The insulation was installed over fiberglass-reinforced-plastic (FRP) fairings located at the top and bottom, as well as around the girth near the equator, of the 2.23 meter (7.3 ft) diameter test tank. The fairings facilitated the fabrication and installation of the MLI blankets. Both the gore blankets and the flat, circular blankets at the top and bottom of the tank were held in place by means of support pins located on the conical fairings (as noted in Detail A) and the girth fairing. The fairings also acted as plenum chambers for the helium purge system. The helium purge gas was distributed into the MLI blankets at discrete points by means of plastic purge pins attached to the fairings and penetrating the insulation blankets. The insulated tank was enclosed within a close fitting, FRP purge bag to limit the volume which had to be purged and to reduce the possibility of the insulation being contaminated with dust, water vapor, etc.

The MLI blankets for the sides of the tank were fabricated in 30 degree gore panels as shown in Fig. 4. The edges of adjacent gore panels were butted and held together with plastic twin-pin fasteners (Detail A). The butt joints between the gore panels in the inner and outer MLI blankets were offset approximately 2.5 cm (1.0 in.) to reduce the possibility of gaps between MLI panels providing a direct path for thermal radiation to reach the tank wall.

The helium purge gas distribution system is shown in Fig. 5. Purge gas feed lines were routed to each of the plenum cavities provided by the fiberglass fairings. Orifices in the feed lines metered the gaseous helium flow into each cavity. The plastic purge pins distributed the purge gas into the MLI panels at discrete points. Each purge pin was slotted to distribute the purge gas evenly between all of the radiation shields. This purge gas distribution system allowed for a relatively high purge gas flow rate (up to 55 purge volumes/hr) to simply displace the initial interstitial gas within the MLI blankets within a relatively short period of time (approximately 5 min).

The overall insulation system and purge bag configuration is shown in Fig. 6. The fiberglass purge bag was fabricated from two layers of 181 style glass cloth preimpregnated with epoxy resin and was coated on each side by a layer of FEP Teflon. The purge bag was fabricated in two halves and joined by means of a flanged joint around the equator of the tank. A summary of the physical characteristics of this insulation system is noted in Table I. Most of the weight of this system was for the fiberglass purge bag (43.2 kg (95.3 lb)) and the fairings (29.5 kg (65.0 lb)) while the multilayer insulation weighed only 14.9 kg (30.8 lb). The resulting total insulation system weight per unit tank wall area was 6.21 kg/m^2 (1.27 lb/ft^2) with the purge bag and 3.14 kg/m^2 (0.64 lb/ft^2) without the purge bag.

Double-Aluminized Mylar/Silk Net Multilayer Insulation System

The Double-Aluminized Mylar/Silk Net (DAM/SN) MLI system tested and reported in Ref. 3 was modeled after a similar insulation system designed to be used in conjunction with shadow shields acting as the primary means of thermal protection during deep-space missions lasting as long as 1200 days.[4,5] As such, the DAM/SN insulation system concept (Fig. 7) was simplified somewhat and did not provide the most effective means of thermal protection from a 300 K (540 °R) temperature environment that was imposed during the test program. The simplified portions of the insulation system design included: (1) installation of MLI around the tank support brackets and struts, (2) the "Y"-type joint configuration between some of the MLI panels, and (3) use of nylon positioning pins to attach the MLI panels to the tank wall. This insulation system was tested at the Lewis Research Center to determine (1) the helium purge characteristics of a MLI system where the initial interstitial gas within the panels was replaced with helium primarily by means of gas diffusion, (2) the degradation in thermal performance due to simulated flight cycles, and (3) the degradation in thermal performance due to exposure to a high humidity environment.

The DAM/SN insulation system concept, as shown in Fig. 7, incorporated two blankets of multilayer insulation, each containing 15 double-aluminized Mylar radiation shields separated by double silk net spacers. Fiberglass fairings or cones were used at the top and bottom of the 1.39-meter (4.57-ft) diameter test tank to facilitate installation of the MLI blankets. The MLI panels for the top and bottom of the tank were fabricated in the shape of truncated cones without any seams between the circular and conical portions of the panels. Nylon positioning pins adhesively bonded directly to the tank wall were used to properly locate and help support the MLI gore panels on the sides of the test tank. Small five-layer MLI panels were used to cover the ends of the positioning pins around the equator of the tank.

The details of the joints between the MLI gore panels and the conical MLI panels at the top and bottom of the tank are shown in Fig. 8(a). The MLI panels in the outer blanket were joined with a standard butt joint in which the cover sheets overlapped the joint to reduce the thermal radiation penetrating the joint. The MLI panels in the inner blanket were joined in a "Y"-type joint which is not as efficient thermally as a butt joint due to the physical contact between warmer and colder layers of insulation. However, the use of this joint configuration allowed the MLI panels to be installed on the tank more easily. The details of the butt joint between adjacent MLI gore panels is shown in Fig. 8(b). The butt joints were again overlapped with the cover sheets on each side of the MLI blanket. The butt joints between the inner and outer blankets were offset 6 degrees to again reduce the thermal radiation penetrating the joints.

The helium purge gas distribution system is shown in Fig. 9. Helium purge gas was distributed underneath the MLI gore panels through two purge rings located adjacent to the tank wall above and below the equator of the tank. The volumes underneath the upper and lower fiberglass cones were purged separately through two purge tubes. Purge gas flow to each purge ring and tube was controlled by a separate orifice. Volumetric purge flow rates up to approximately 37 purge volumes per hour were used. Approximately 3 hours were required for the initial interstitial gas concentration to be reduced and for greater than 99 percent helium concentration to be achieved everywhere within the MLI blankets. Also shown in Fig. 9 are the approximate locations of the nylon positioning pins and the Velcro pile fastener adhesively bonded to the tank wall that were used to attach the MLI gore panels to the tank.

The overall insulation system configuration is shown in Fig. 10. In this MLI system, 60-degree gore panels were used for the sides of the test tank. The areas where the tank support brackets penetrated the MLI gore panels were also covered by the same five-layer MLI panel which covered the positioning pins. A summary of the physical characteristics of this insulation system is noted in Table I. On the basis of weight per unit tank wall area, the DAM/SN MLI system had the lowest value of 1.92 kg/m^2 (0.393 lb/ft^2). This was due to the minimal use of fiberglass for fairings and the elimination of a purge bag as a part of the overall insulation system.

One interesting aspect of the DAM/SN MLI system that was mentioned only briefly in Ref. 3 was that the insulation system was basically several years old prior to the start of the test program and had not always been handled with the extreme care normally thought to be required to provide a high-performance multilayer insulation system. Some brief highlights of the insulation system history were as follows:

1. The MLI gore panels used on the sides of the test tank had been fabricated, and then sealed in plastic bags and stored for approximately 30 months. They were shipped from the west coast to Cleveland, Ohio, and back to the west coast prior to being installed on the test tank. The materials used in fabricating the conical MLI panels for the top and bottom of the tank had been in storage for approximately 6 years.

2. The completely insulated tank, enclosed in a sealed plastic bag, was shipped from the west coast to Cleveland, Ohio, by truck.

3. The insulation system, mounted on the tank, was again stored for an additional 18 months, with the plastic shipping bag removed, in a relatively clean, relatively low-humidity (20-50 percent) environment.

4. The insulation system was in a shop-environment with no humidity control for approxi-

mately 5 months prior to the start of testing.

Despite the long storage time and the lack of any particular care in controlling the environmental conditions in the months immediately prior to testing, and despite the fact that no high-temperature vacuum bakeout procedure was used prior testing, the insulation system still provided good thermal performance that was close to the value predicted.

Thermal Performance Test Results

Ground-Hold Thermal Performance

A comparison of the ground-hold thermal performance of two of the three reusable insulation systems is noted in Table II. No ground-hold thermal performance measurements were made for the DGK/DT MLI system.

The measured heat input for the LBI system was 295 W (1007 Btu/hr) with the vacuum chamber pressure at 0.9 atmosphere pressure for safety considerations. The resulting heat flux, based on insulation surface area, was approximately 67 W/m^2 (21.3 Btu/hr-ft^2). Using the information presented in Ref. 1, this measured heat flux was corrected for (1) chamber pressure of 1 atmosphere pressure and (2) cold-side boundary temperature of 20 K (36 ^oR) for liquid hydrogen. The resulting calculated heat flux was 73 W/m^2 (23.2 Btu/hr-ft^2), and the thermal performance weight criteria (C_i) was 164 W-kg/m^4 (10.7 Btu-lb/hr-ft^4).

The measured heat input for the DAM/SN MLI system with 1 atmosphere vacuum chamber pressure and a liquid hydrogen cold-side boundary temperature was 3845 W (13,130 Btu/hr). The resulting insulation heat flux was 562 W/m^2 (178 Btu/hr-ft^2), and the thermal performance weight criteria (C_i) was 967 W-kg/m^4 (62.8 Btu-lb/hr-ft^4).

These values of heat flux and thermal performance weight criteria indicate that the LBI system does provide much better ground-hold thermal performance than a helium purged MLI system; the thermal performance weight criteria for the DAM/SN MLI system was 5.9 times that for the LBI system.

Space-Hold Thermal Performance

A comparison of the space-hold thermal performance test results for the three insulation systems is shown in Table III for the insulation system boundary temperatures as noted. The insulation system effective thermal conductivity (K_e) was calculated using the heat input (Q_i) attributed to only the insulation system (excluding that attributed to the penetrations and tank support struts). The effective thermal conductivities for the two MLI systems were relatively close ($\approx 8\times10^{-5}$ W/m-k (4.6×10^{-5} Btu/hr-ft-^oR)) while the conductivity for the LBI system was approximately eight times greater. The values of the thermal performance weight criteria, based on either insulation or tank surface area, indicated that one or the other of the MLI systems provided the lowest values depending on whether or not the purge bag weight was included for the DGK/DT MLI system.

A comparison of the expected space-hold thermal performance for common boundary temperatures (T_H = 291 K (524 ^oR) and T_C = 20 K (36 ^oR)) is shown in Table IV for the three insulation systems. The basic insulation heat input was corrected on the basis of solid conduction and thermal radiation heat transfer equations presented in Refs. 1 and 6 for the LBI and DAM/SN insulation systems, respectively. The seam heat input for the DAM/SN insulation system was corrected on the basis of information presented in Ref. 7. The other heat inputs were corrected from ratios of the temperature differences involved. No significant changes in the values of effective thermal conductivity from those presented in Table III were noted, and the relative ranking of the insulation systems on the basis of the thermal performance and weight criteria remained unchanged.

Reusability

All three insulation systems were subjected to a series of tests simulating the typical flight cycle environmental conditions expected during a space mission starting from launch from the surface of the earth and returning. The flight cycle included the initial ground-hold and propellant loading conditions, the launch pressure decay during chamber pumpdown to vacuum conditions, the space-hold (vacuum) conditions, and the repressurization of the vacuum chamber back to 1 atmosphere pressure. Space-hold thermal performance data was obtained periodically throughout the test series for each insulation system. The heat flux and the resulting change in the thermal performance (compared with the initial test) attributed to the insulation system (corrected for common boundary temperatures, T_H = 291 K (524 ^oR) and T_C = 20 K (36 ^oR)) are shown in Figs. 11(a) and (b), respectively. This comparison indicated that the LBI system would have the highest heat flux but exhibited a relatively stable thermal performance for seven flight cycles. There appeared to be a 6.7-percent degradation in the space-hold thermal performance through the first seven flight cycles, although this was attributed to experimental uncertainty rather than environmentally induced degradation of thermal performance.[1]

The DGK/DT MLI system provided the lowest heat flux of the three insulation systems. However, the heat input attributed to this MLI system suffered an initial thermal performance degradation of 37.5 percent through the 50^{th} flight cycle. This degredation was due primarily to structural failure of three twin-pin links allowing three seams between gore panels to separate slightly. After repair, the thermal performance improved but then degraded again prior to the end of the test program. A post-test examination of the MLI system revealed two more broken twin-pin links and some localized areas where the seams between adjacent MLI panels had opened up slightly.

The DAM/SN MLI system provided a somewhat higher heat flux than the DKG/DT MLI system but exhibited a maximum thermal performance degradation of less than 14 percent through the 12^{th} flight cycle. Repeated exposure of this MLI system to a 100-percent relative humidity environment for periods of time ranging from 2 hours to as long as 8 weeks resulted in a maximum increase of the heat flux of less than 24 percent. The thermal performance for the last space-hold thermal performance test was restored to within 13 percent of the initial thermal performance of the MLI system (Q_i/A_t = 1.24 W/m^2 (0.393 Btu/hr-ft^2)) following a 5-day vacuum soak at ambient room temperature. A post-test examination of the MLI system revealed that no structural damage had occurred, and measurement of the emissivity of the radiation shields indicated that no degradation from pretest measurements had occurred.

Overall, it appeared that a multilayer insulation system utilizing double-aluminized Mylar radiation shields with silk net spacers could be subjected to high-humidity environments without degrading the nominal thermal performance more than 24 percent. It must be assumed that the MLI system would be purged with helium for some time prior to loading cryogenic propellants on the ground, and that the MLI system is designed to allow adequate venting of the interstitial purge gas during the launch and insertion into earth orbit. And since it is generally accepted that aluminized Mylar and silk netting are insulation materials that are particularly susceptible to moisture (e.g., Ref. 6), the use of Kapton (either aluminized or goldized) radiation shields and some other spacer material (e.g., Dacron or Nylon) should provide an insulation system that would have even less degradation of its thermal performance after exposure to a high-humidity environment.

The LBI system avoids the problems of thermal degradation due to the presence of moisture. However, it does have unique problems of its own that must be recognized when assessing the reusability of the LBI system. These include: (1) maintenance of a low pressure (≈1 pascal) (1×10^{-2} torr) within the vacuum jacket under ambient temperature ground conditions with a residual gas that can be cryopumped on the tank wall when the cryogenic propellant is loaded, (2) complete filling of the vacuum jacket annulus with glass spheres so that voids do not occur at some later point in time, and (3) minimum breakage of the glass spheres during the life of the insulation system.

Comparison of Insulation Systems for a Common Space Mission

The three insulation systems, as tested, were not optimized for any common space mission, and it is, therefore, not proper to evaluate the weight and thermal performance of one system against another on that basis. Part of the required work effort in contract NAS3-17817 performed by the Lockheed Missiles and Space Company[1] was to optimize both the LBI and DGK/DT MLI systems for a 163-hour, multiburn space mission using the Option 2 Cryogenic Space Tug design requirements noted in Ref. 8. The stated performance goals for the liquid hydrogen tank, for example, along with the insulation system weights and resulting thermal performance as presented in Ref. 1 are summarized in Table V. The resulting LBI system was 2.0 cm (0.79 in.) thick and weighed 180.4 kg (397.7 lb). The total prorated weight (including the prorated liquid hydrogen boiloff) was 295.1 kg (650.6 lb). The optimized DGK/DT MLI system was 2.3 cm (0.91 in.) thick and weighed 339.8 kg (749.1 lb). The total prorated weight for this MLI system was 365.2 kg (805.1 lb). Although the LBI system was the lighter of the two insulation systems by a substantial margin (70.1 kg (154.5 lb)), both insulation system total prorated weight estimates greatly exceeded the performance goal of 127.1 kg (280.2 lb). However, two assumptions used in determining the optimized DGK/DT MLI system weight for the Option 2 Space Tug may be subjected to some question.

1. The fiberglass fairing weight was scaled up from that used in the test program primarily on the basis of the ratio of the tank surface areas. This appears to be unreasonable from the standpoint that (1) the top and bottom conical fairings would not be required to cover the entire ends of the Space Tug LH_2 tank as was done for the test tank and (2) the girth fairing (or fairings) could probably be fairly widely separated on the Space Tug LH_2 tank without influencing the time required to purge the insulation system drastically.

2. The insulation system configuration where the fiberglass purge bag completely encapsulated the LH_2 tank could be simplified by allowing the structural skin of the Space Tug to act as the purge enclosure around the cylindrical section of the tank. This concept would require only a fiberglass purge enclosure at the top and bottom of the tank as shown in Fig. 12. The purge enclosure would be used primarily to contain the purge gas within a specified volume and to keep the cold ground-hold environment away from electronic equipment, for example.

The revised weight estimates for the DGK/DT MLI system to account for these two modifications are noted in the fourth column of Table V. The total prorated weight estimate of 197.4 kg (435.2 lb) was considerably lighter than either of the two previous weight estimates and was also much closer to the performance goal of 127.1 kg (280.2 lb).

The weight estimates shown in Table V for the DAM/SN MLI system were not optimized in a manner similar to that for the LBI and DGK/DT MLI systems. The basic insulation weight was scaled up on a weight per unit tank area basis assuming the same insulation thickness as actually tested. The prorated liquid hydrogen boiloff rate was simply calculated on the basis of the measured thermal performance of the DAM/SN MLI system for both the ground-hold and space-hold orbital environmental conditions. The total prorated weight estimate for the DAM/SN MLI system of 243.4 kg (536.6 lb) still indicates, however, that it would be lighter than the LBI system but heavier than the modified DGK/DT MLI system.

Concluding Remarks

Three reusable insulation systems suitable for use on cryogenic propellant tanks of space vehicles were tested and evaluated in three separate NASA-sponsored programs. The space-hold (vacuum) thermal performance was experimentally measured during a series of cyclic tests simulating complete flight cycles that a reusable earth-based space vehicle would be subjected to.

The best insulation system on the basis of space-hold thermal performance was the multilayer insulation (MLI) system composed of double-goldized Kapton radiation shields with Dacron tuft spacers (DGK/DT MLI system). This insulation system also incorporated a rigid fiberglass-reinforced-plastic (FRP) purge bag to contain the helium purge gas and protect the insulation from any effects of moisture or other types of contamination that might be present in the ground environment. If the weight of the purge bag, and other FRP fairings installed on the tank wall, proposed in the original design could be substantially reduced, the DGK/DT MLI system would also have the lowest total weight (including the prorated liquid hydrogen boiloff). The goldized reflective surfaces on the radiation shields provided very low emissivity surfaces to reduce radiation heat transfer. The Kapton polymide film provided a high-temperature capability (up to 670 K (1206 °R)), and would also be likely to provide a relatively low moisture absorption capability. The Dacron tuft spacers provided for widely separated radiation shields for ease of purging and venting of the purge gas, and low solid conduction heat transfer. The disadvantages of this system were primarily the high cost of the basic materials and fabrication, and the difficulty of forming the radiation shields to conform to double-curved surfaces (if required).

The other multilayer insulation system tested that utilized double-aluminized Mylar radiation shields and double silk net spacers (DAM/SN) represented an insulation system configuration that was not designed to provide the most effective thermal protection from an ambient room temperature environment under vacuum conditions. In addition, this insulation was not always handled and stored with the extreme care normally thought to be required to provide a high-performance multilayer insulation system. And despite the fact that no long-duration, high-temperature vacuum bake-out procedure was used prior to testing, the DAM/SN insulation system still provided good space-hold thermal performance that was only slightly poorer than the DGK/DT MLI system. Repeated thermal cycling caused a degradation of less than 14 percent in the thermal performance. Deliberate, repeated exposure to a high-humidity environment for periods of time as long as 8 weeks resulted in a degradation in the thermal performance of less than 24 percent. The DAM/SN MLI system also offers many of the same advantages as the DGK/DT MLI system with the following exceptions: (1) lower maximum service temperature (420 K (756 ^{o}R)) and (2) higher weight per unit area due to the presence of the silk net spacer. However, the DAM/SN MLI can be formed more easily to the contour of double-curved surfaces, if required, and the material and fabrication costs are lower.

The load-bearing insulation (LBI) system utilizing the hollow glass spheres contained within a flexible stainless steel vacuum jacket provided better thermal performance/weight characteristics for a 163-hour space-mission than the MLI systems when the "as-tested" weights of the MLI systems were scaled up to a "full-sized" LH_2 tank. If the purge bag and fairing weights of the MLI systems could be reduced or eliminated, the MLI systems showed a weight advantage over the LBI system. However, the LBI system offers some unique potential advantages for cases where: (1) a relatively passive (no purging) insulation is desirable, (2) frequent excursions through the atmosphere or long durations of ground-hold conditions are required, and (3) high-temperature service is required.

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TABLE I. - COMPARISON OF INSULATION SYSTEM AREAS AND WEIGHTS AS TESTED

Insulation system			
Type	LBI	DGK/DT	DAM/SN
Insulation thickness (t_i), M	0.0133	0.038	0.019
Area (A_i), M^2	4.42	16.5	6.84
Test tank	Sphere	Oblate spheroid	Sphere
Diameter, m	1.17	2.23	1.39
Surface area, m^2	4.30	14.1	6.12
Insulation system weight, kg			
Fiberglass fairings or cones	-------	29.56	2.86
Vacuum jacket or purge bag	[a]9.11	43.23	------
Ion pumps or purge tubing	.36	.92	.41
Insulation (microspheres or MLI)	[b]5.53	13.97	8.51
Total weight, kg	15.00	87.57	11.78
Basic insulation system weight per unit area, kg/m^2			
W_i/A_i	2.25	[c]5.31 [d]2.69	1.72
W_i/A_t	2.31	[c]6.21 [d]3.14	1.92

[a]Includes 4.29 kg for non-optimized vacuum jackets enclosing tank support struts.
[b]Includes 0.77 kg for microsphere insulation for tank support struts.
[c]With purge bag.
[d]Without purge bag.

TABLE II. - COMPARISON OF GROUND-HOLD THERMAL PERFORMANCE

Insulation system	Boundary temperature, K		Chamber pressure, atm	Measured heat input, Q_m, W	Insulation system effective thermal conductivity, K_e, W/m-k	Calculated heat flux, $\dot{q}_i$, W/m^2	Thermal performance weight criteria, C_i, W-kg/m^4
	Hot side (T_H)	Cold side (T_C)					
LBI	278	78	0.9	[a]295	4.4×10^{-3}	67	---
	280	20	1.0	----	[b]3.7×10^{-3}	73	164
DGK/DT	(c)	(c)	(c)	(c)	(c)	(c)	(c)
DAM/SN	220	20	1.0	3845	5.3×10^{-2}	562	967

[a]Data directly from ref. 1.
[b]Calculated using information from ref. 1.
[c]No ground-hold thermal performance measurements made.

TABLE III. - COMPARISON OF SPACE-HOLD THERMAL PERFORMANCE AS TESTED

Insulation system	LBI	DGK/DT	DAM/SN
Boundary temperatures, K			
Hot side (T_H)	280	291	299
Cold side (T_C)	78	20	20
Heat inputs, W			
Basic insulation	38.41	3.26	2.78
Spring assemblies	3.14	------	-----
Support blocks	2.03	------	-----
Seams	------	2.76	2.30
Purge pins	------	2.43	-----
Positioning pins	------	------	1.03
Degradation of MLI at struts	------	------	2.42
Miscellaneous	------	.40	-----
Penetrations (fill and vent lines, instrumentation wiring, etc)	.02	3.25	.01
Tank support struts	.62	.50	.34
Total (q_m)	[a]44.22	[a]12.60	[b]8.88
Insulation system thermal conductivity, K_e, W/m-k	6.5×10^{-4}	7.5×10^{-5}	8.5×10^{-5}
Thermal performance-weight criteria, W-kg/m^4			
Insulation surface area (C_i)	22.2	[c]2.87 [d]1.45	2.15
Tank surface area (C_t)	23.4	[c]3.90 [d]1.97	2.68

[a]Data for initial test (zero previous flight cycles).
[b]Data for 11 previous flight cycles (test 13, ref. 3).
[c]With purge bag.
[d]Without purge bag.

TABLE IV. - COMPARISON OF INSULATION SYSTEM SPACE-HOLD THERMAL PERFORMANCE CORRECTED FOR COMMON BOUNDARY TEMPERATURES:

T_H = 291 K, T_C = 20 K

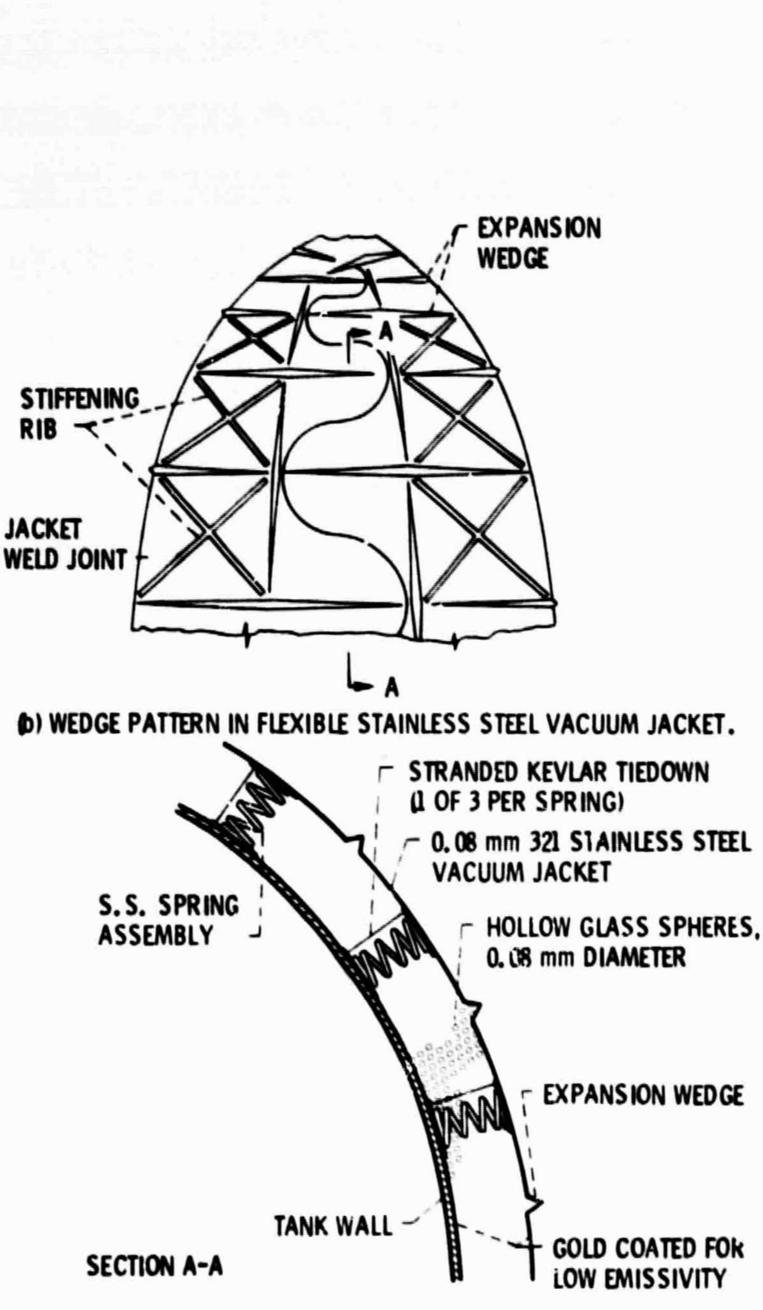
Insulation system	LBI	DGK/DT	DAM/SN
Heat input, W			
Basic insulation	41.63	3.26	2.53
Spring assemblies	3.88	----	----
Support blocks	2.70	----	----
Seams	-----	2.76	2.06
Purge pins	-----	2.43	----
Positioning pins	-----	----	1.00
Degradation of MLI at struts	-----	----	2.35
Miscellaneous	-----	.40	----
Total	48.21	8.85	7.94
Insulation system thermal conductivity, K_e, W/m-k	5.4×10^{-4}	7.5×10^{-5}	8.1×10^{-5}
Thermal performance-weight criteria, W-kg/m^4			
Insulation surface area (C_i)	24.5	[a]2.87 [b]1.45	2.00
Tank surface area (C_t)	25.9	[a]3.90 [b]1.97	2.49

[a]With purge bag.
[b]Without purge bag.

TABLE V. - COMPARISON OF REUSABLE INSULATION SYSTEMS FOR SPACE TUG LIQUID HYDROGEN TANK

LH_2 tank Diameter, m . . . . 4.166 Length, m . . . . 5.464 Cylindrical length, m 2.445	Bulkhead Radius/height ratio. . . . . 1.38 Volume, m^3 . . . . 60.75 Surface area, m^2 . . . . 76.84

	Performance goal (ref. 1)	LBI (ref. 1)	DGK/GT (ref. 1)	Modified DGK/DT	DAM/SN
Insulation system weight, kg					
Basic insulation	39.0	110.4	39.0	39.0	95.4
Vacuum jacket	-----	67.4	-----	-----	-----
Purge system	62.7	-----	-----	-----	-----
Fiberglass fairings	-----	-----	138.3	30.0	5.0
Fiberglass purge bag	-----	-----	129.5	70.0	70.0
Purge distribution hardware	-----	-----	5.0	5.0	10.0
Penetration panel	-----	-----	28.0	28.0	28.0
Miscellaneous	-----	2.6	-----	-----	-----
Total fixed weight	101.7	180.4	339.8	172.0	208.4
LH_2 boiloff [prorated (163-hr mission)]	25.4	114.7	25.4	25.4	35.0
Total prorated weight	127.1	295.1	365.2	197.4	243.4
Insulation thickness, m	-----	0.020	0.023	0.023	0.019
Orbital heat input, W					
Basic insulation (T_H = 222 K)	-----	214.7	41.2	41.2	54.2
Tank supports and plumbing	-----	5.1	5.1	5.1	5.1
Miscellaneous	-----	1.6	----	----	----
Total	46.4	221.4	46.3	46.3	59.3
Ground-hold heat input, W	27,020	3,690	64,700	64,700	68,750



(a) CROSS SECTION OF INSULATION SYSTEM.

Figure 1. - Load bearing insulation system concept.

Figure 2. - Load-bearing insulation system installed on 1.17 diameter spherical test tank.

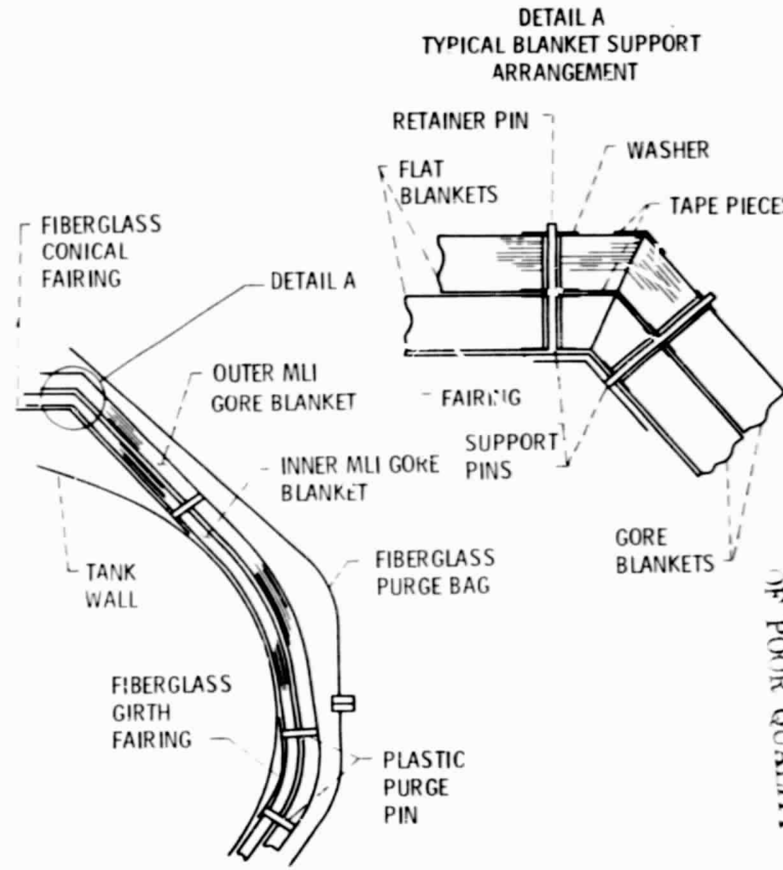


Figure 3. - DGK/Dacron tuft MLI system concept.

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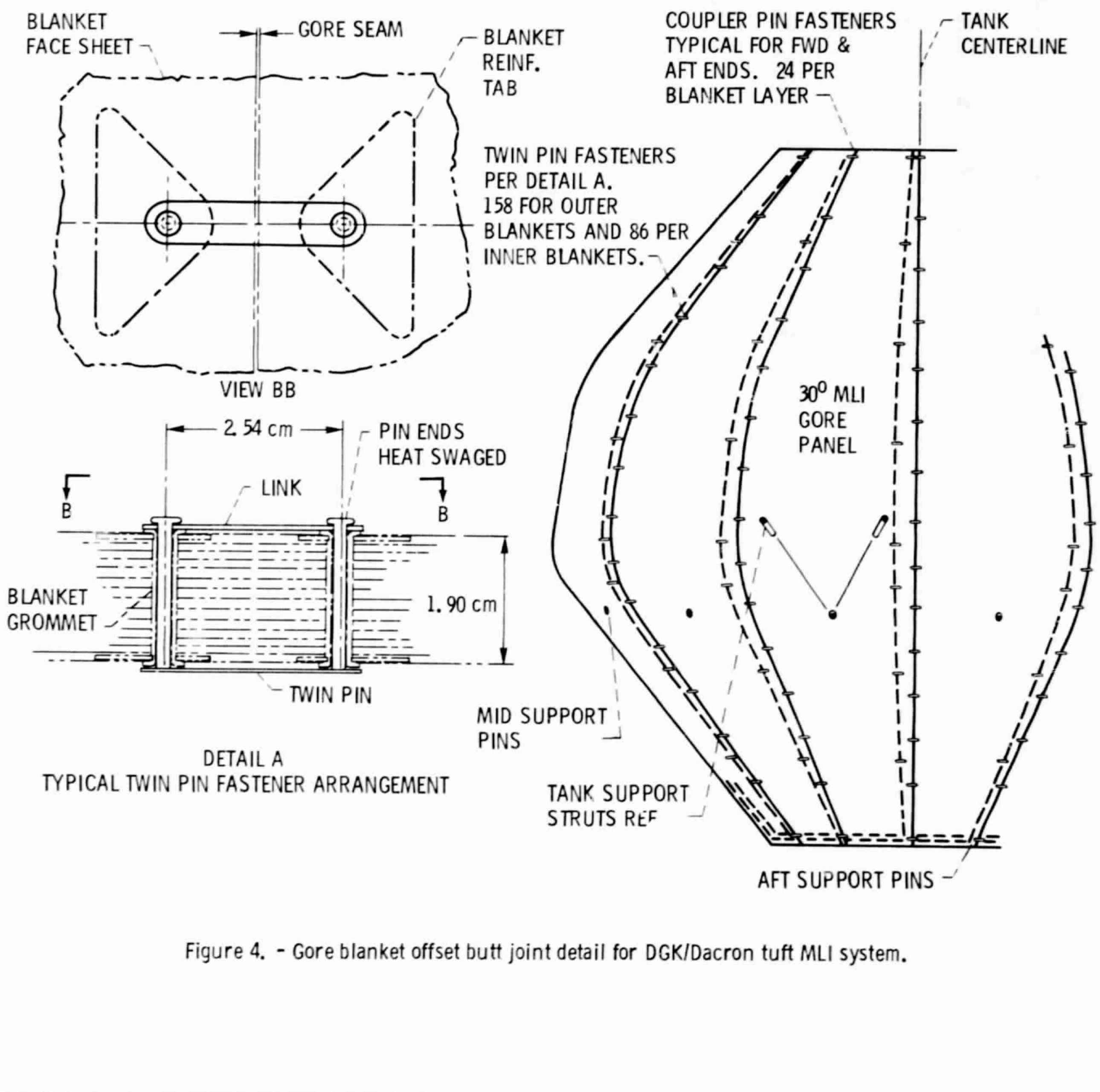


Figure 4. - Gore blanket offset butt joint detail for DGK/Dacron tuft MLI system.

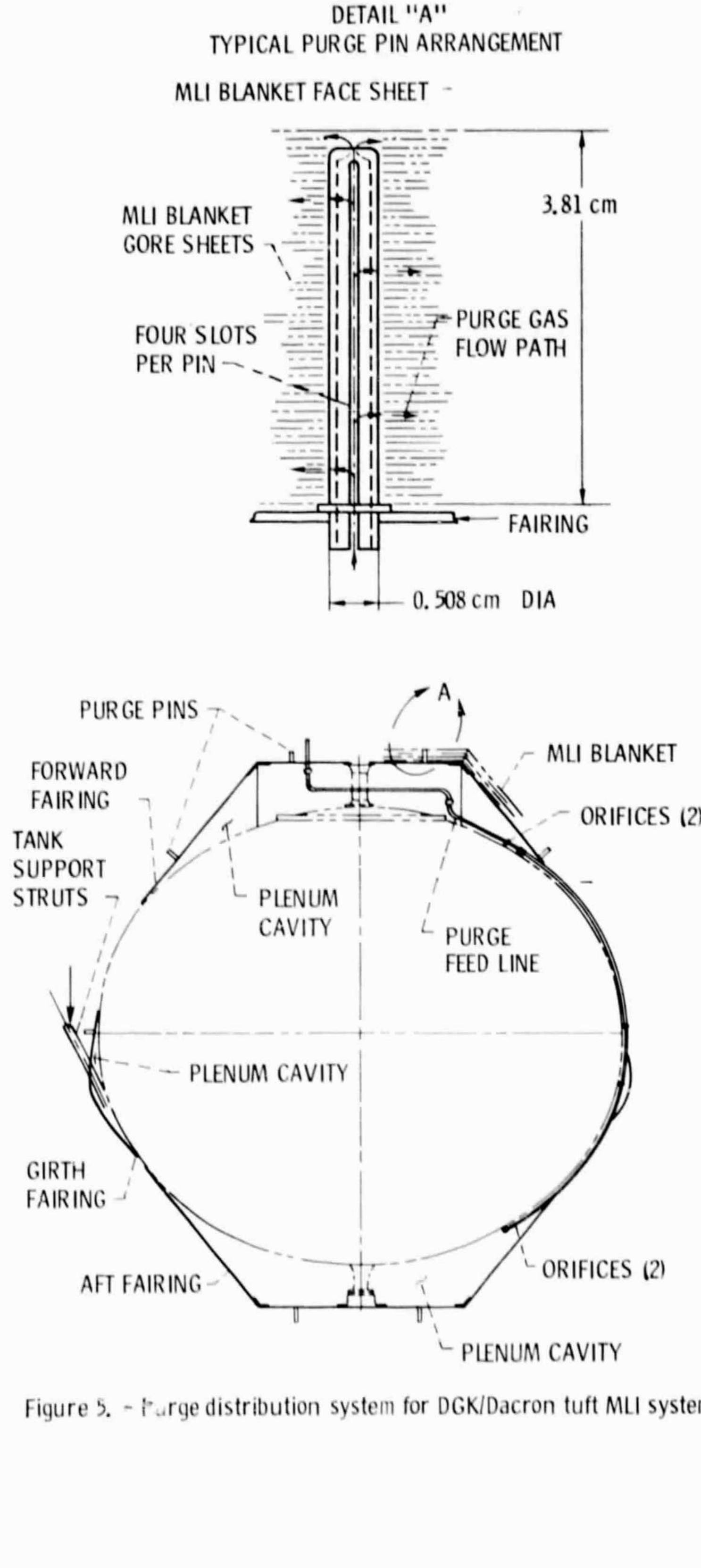


Figure 5. - Purge distribution system for DGK/Dacron tuft MLI system.

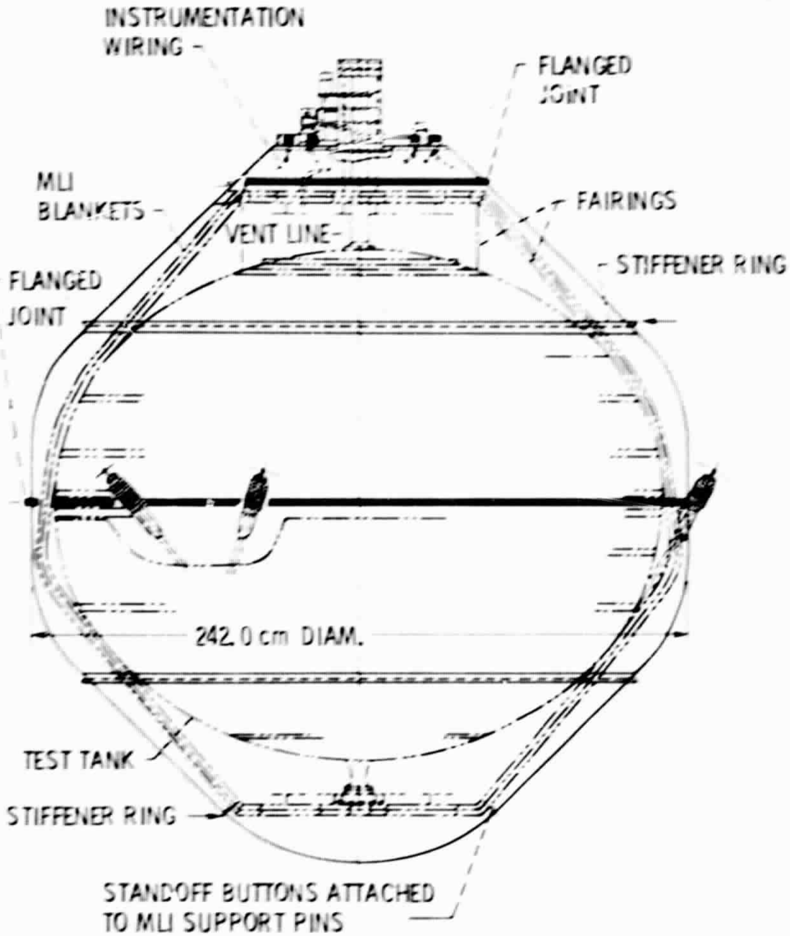


Figure 6. - DGK/Dacron tuft MLI system and purge bag configuration.

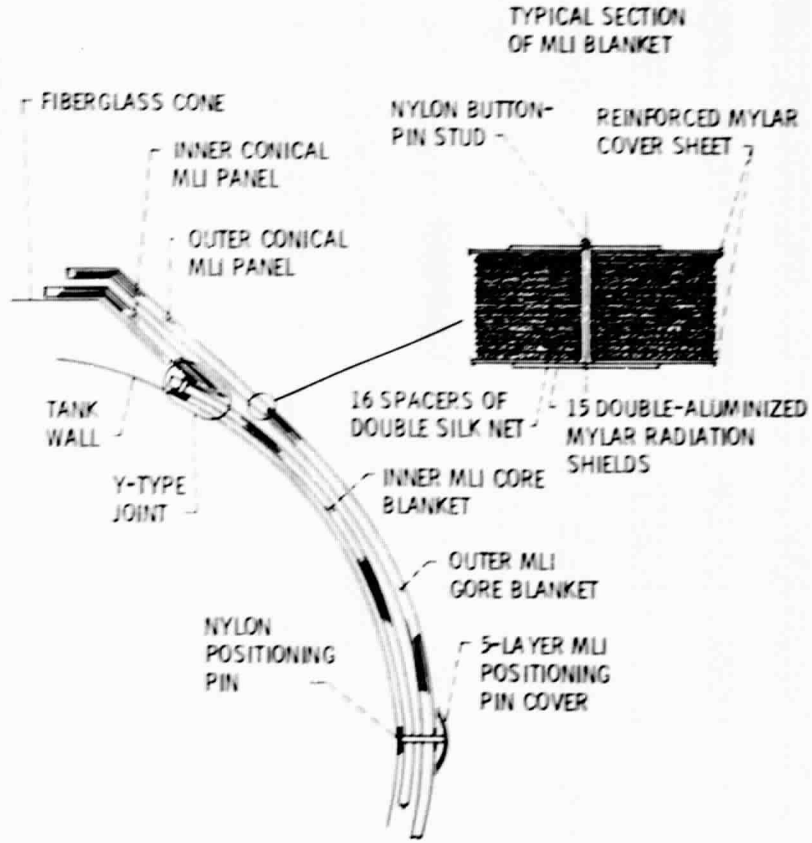
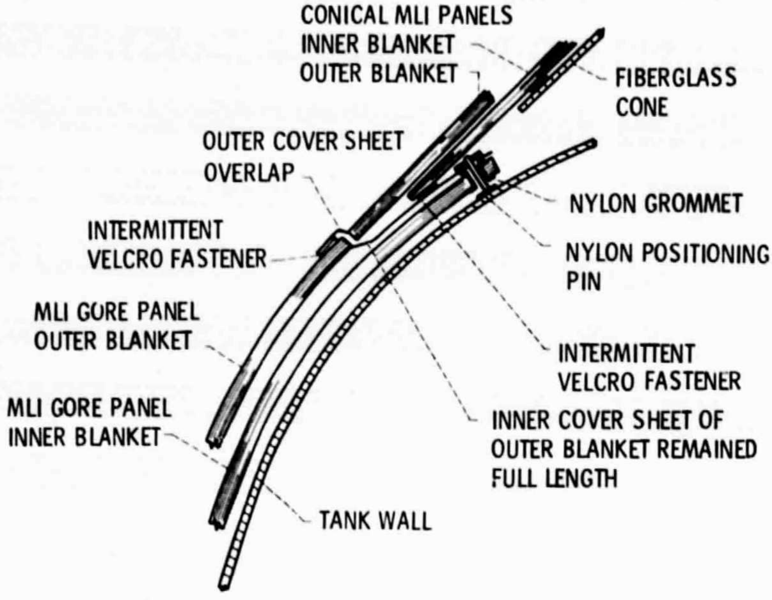
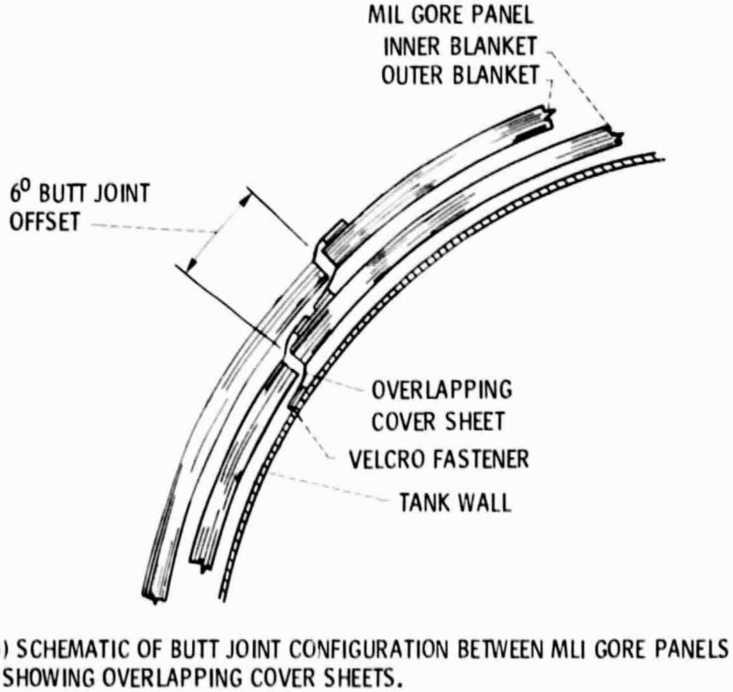


Figure 7. - DAM/Silk net MLI system concept.



(a) SCHEMATIC OF JOINTS BETWEEN MLI GORE PANELS AND CONICAL MLI PANELS AT TOP AND BOTTOM OF TANK.



(b) SCHEMATIC OF BUTT JOINT CONFIGURATION BETWEEN MLI GORE PANELS SHOWING OVERLAPPING COVER SHEETS.

Figure 8. - Butt joint detail for DAM/Silk net MLI system.

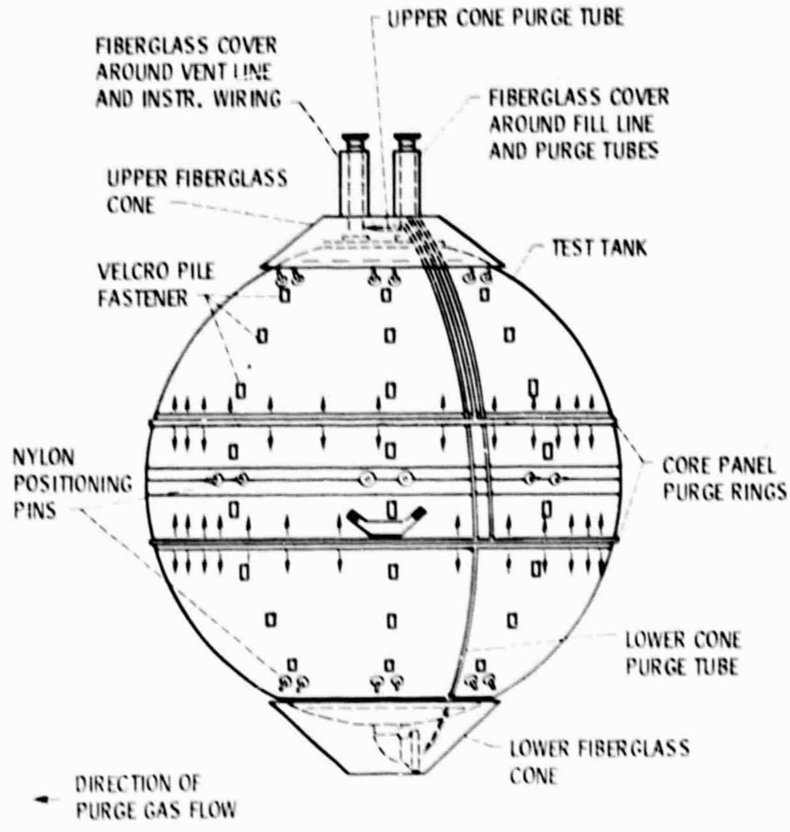


Figure 9. - Purge distribution system for DAM/silk net MLI system.

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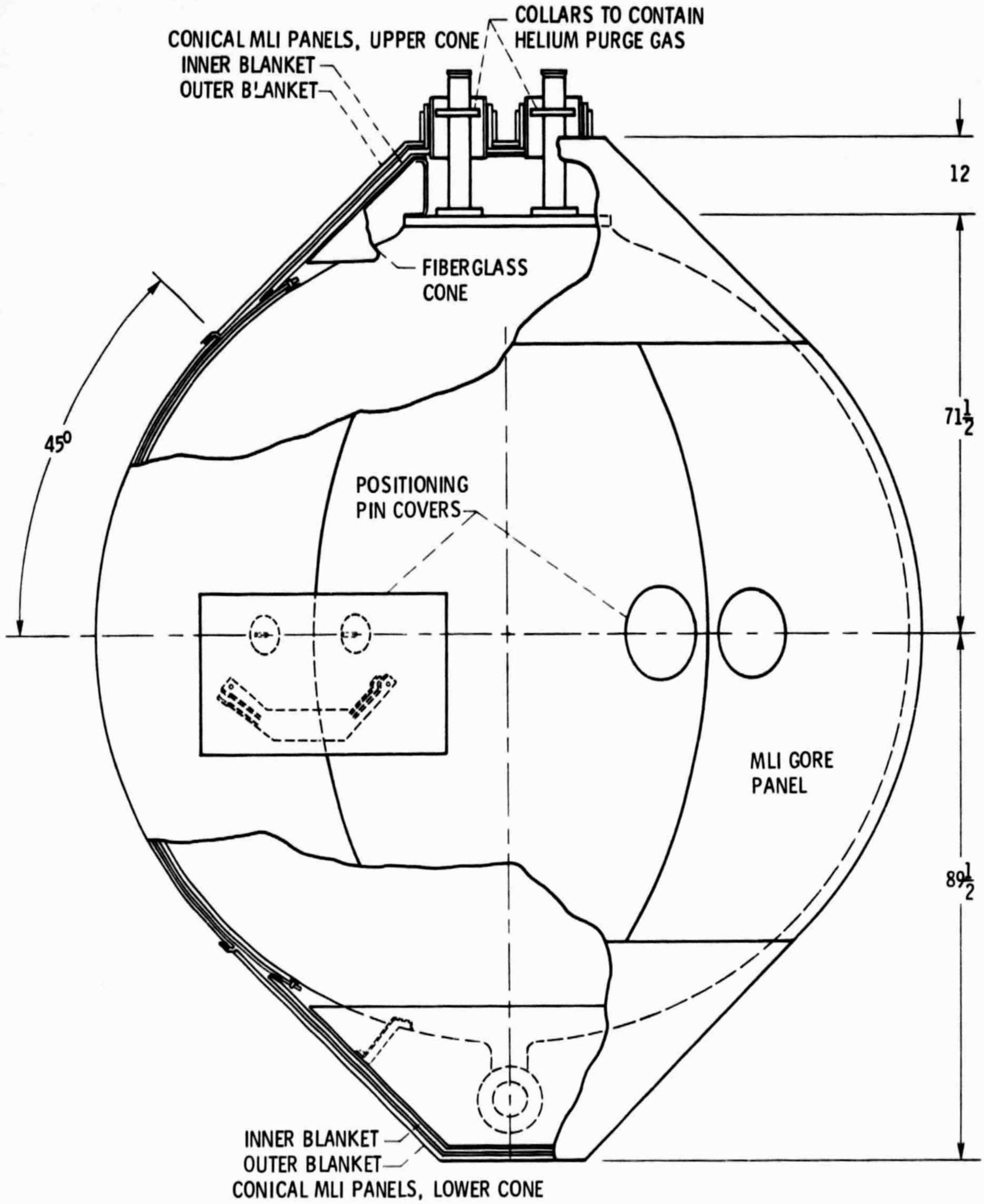
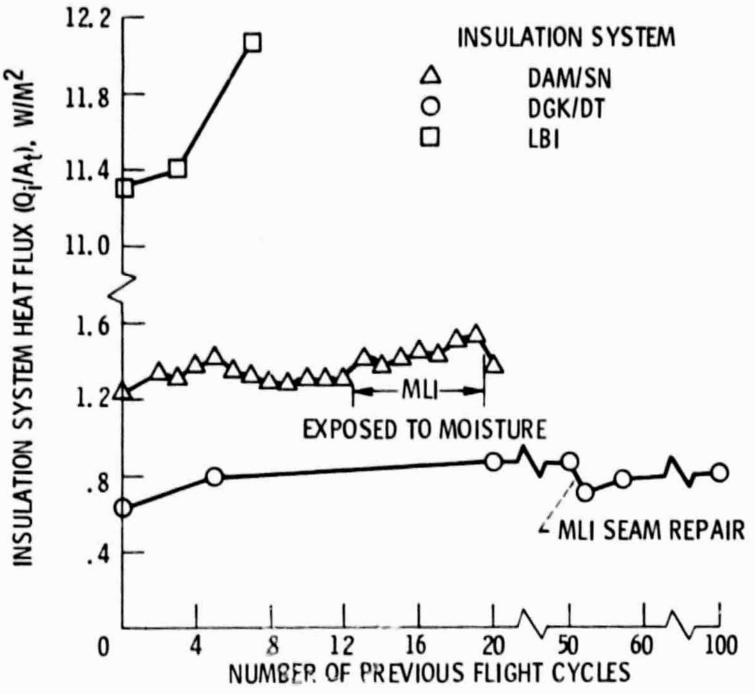
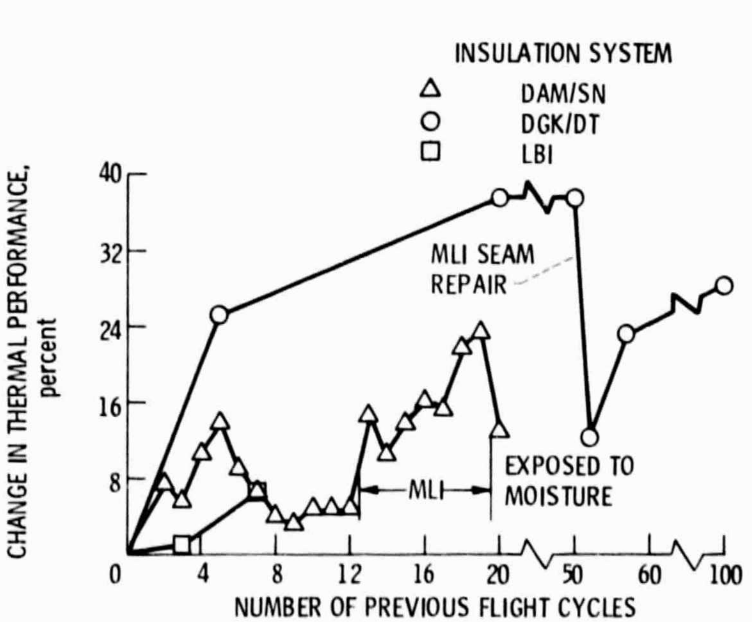


Figure 10. - DAM/SILK net MLI system configuration (all dimensions are in cm).



(a) INSULATION SYSTEM HEAT FLUX (Q_i/A_t).

Figure 11. - Thermal performance during space-hold vacuum conditions (data corrected for constant T_H = 291 K, T_C = 20 K).



(b) CHANGE IN THERMAL PERFORMANCE.

Figure 11. - Concluded.

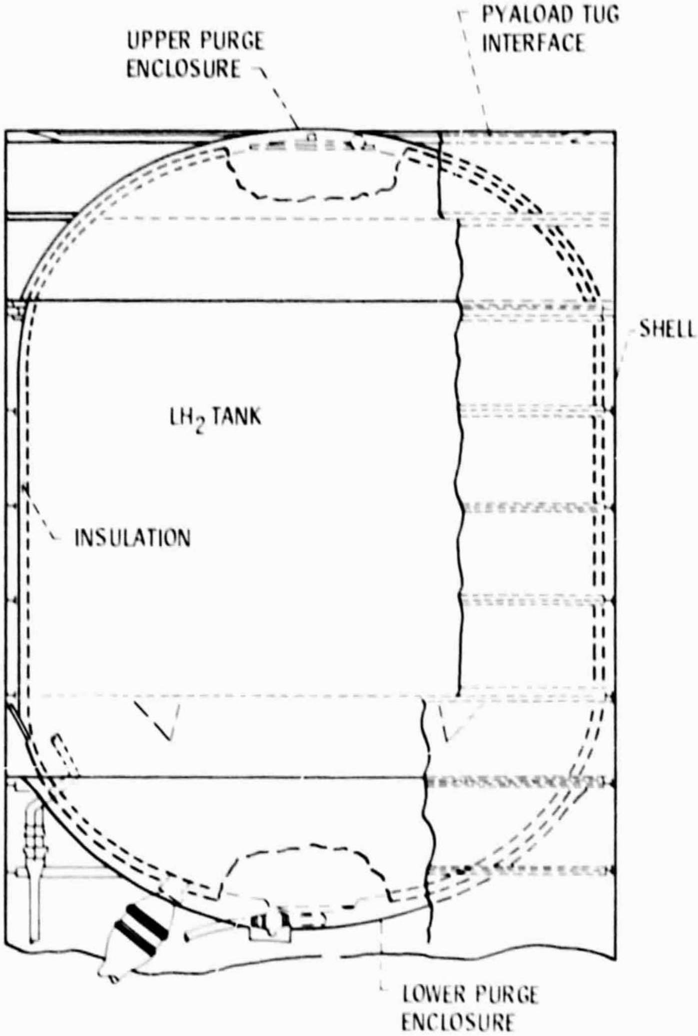


Figure 12. - Helium purge enclosure concept for space tug liquid hydrogen tank.