SESSION I

EXPANDABLE STRUCTURE CONCEPT OF CREW TRANSFER TUNNEL FOR SPACE VEHICLES

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SECTION I - INTRODUCTION

For several years the Air Force has been studying a number of future manned space station concepts that would use existing re-entry capsule hardware. These concepts have ranged from a simple re-entry module to sophisticated systems of long mission capability and rendezvous and docking facilities. During these studies it became apparent that a structural requirement would arise for crew transfer tunnels, air locks, and space maintenance hangars. To satisfy this requirement, the Air Force initiated both in-house and contractual research and technology programs. Throughout this effort, the Aerospace Corporation has served as an active consultant.

The development of a crew transfer tunnel that would connect a re-entry vehicle to a cylindrical crew module was selected as an initial objective. Once this objective was defined, a materials survey was conducted to tentatively select a structural system and materials best suited for this particular application. This survey indicated that a multi-ply elastic recovery structure should be used.

The in-house program was initiated by fabricating a wood mockup of a crew transfer tunnel, which was tested in a zero-g aircraft to provide human factors data. This effort was followed by a contract awarded to Goodyear Aerospace Corporation to design, fabricate, and test an expandable crew transfer tunnel. The tunnel configuration being developed under this contract is similar to the wood mockup. The contract effort also includes design studies of air locks, an alternate crew transfer tunnel configuration, and space maintenance hangars as possible experiments for future flight testing.

The purpose of this paper is to summarize the results of both Air Force and contractual initial development of the expandable crew transfer tunnel.

SECTION II - DESIGN CONSIDERATIONS

1. GENERAL

The general design of the expandable crew transfer tunnel was specifically derived under the major constraints imposed by human factors considerations. In addition, it was required that the tunnel design be consistent with mission requirements. Therefore, the design was oriented to provide crew transfer between currently planned spacecraft and orbital laboratories.

2. HUMAN FACTORS

The human factors design requirements were established by Air Force in-house programs. By a cooperative effort between the Aero Propulsion Laboratory, the Aero Medical Laboratory, and the Materials Laboratory, a wood mockup of the tunnel geometry was fabricated. This mockup was flown in the KC-135 zero-g aircraft and thoroughly evaluated relative to human factors requirements in zero-g transfer.

The tunnel mockup was attached to a mockup of the left half of a two-man spacecraft. Entry from the tunnel into the spacecraft was through a 17- by 30-in. elliptical hatch located in the main entry hatch of the spacecraft. Entry from the other end of the tunnel into a simulated orbital laboratory was through a 22-in.-diameter circular hatch. Two ropes were placed 21 in. apart to serve as handrails from one hatch to the other.

The subject wore a full-pressure suit. The critical dimensions of the suited subject were:

Weight, 171 lb (66 percentile)
Stature, 179 cm (74 percentile)
Chest breadth, 36 cm (99 percentile)
Chest depth, 24 cm (70 percentile)
Biacromium, 42 cm (85 percentile)
Cervical height, 153 cm (70 percentile)

The human factors flight evaluation consisted of:

1. Three unpressurized-suit transfers from the spacecraft to the laboratory
2. Two unpressurized-suit transfers from the laboratory to the spacecraft, one of which included a turnaround at the laboratory
3. Six pressurized-suit transfers from the laboratory to the spacecraft. One included a turnaround at the laboratory; another, the carrying of a specimen case; the last,

the transfer of a "completely disabled" shirt-sleeved astronaut

4. Four pressurized-suit transfers from the spacecraft to the laboratory. One included a turnaround at the laboratory; another, a turnaround at the spacecraft; the last, the carrying of a specimen case

Transfers in an unpressurized suit presented no difficulties. Transfers in a pressurized suit required more time and were more cumbersome but were completed with little difficulty. Figure 1 shows the typical mode of transfer in a pressurized unit. The results of these transfer tests can be summarized as follows:

1. No problems were encountered in passing through the 17- by 30-in. elliptical hatch.
2. A specific technique must be worked out for transferring packages and equipment through the hatches.
3. The two handrails were effective locomotion aids to crew transfer and should be incorporated in tunnel design.
4. The tunnel geometry, represented by the mockup, was entirely compatible with effective crew transfer. However, a final tunnel design should have no sharp protuberances that might snag the umbilicals or the space suit and should have a nonabrasive liner to avoid space suit damage.

There are other human factors requirements to be met in any tunnel design. Nontoxic materials must be used in tunnel construction to avoid contamination of the artificial environment. Interior tunnel lighting may be required. Low-intensity lighting would appear to be adequate but should be evaluated in actual transfer experiments.

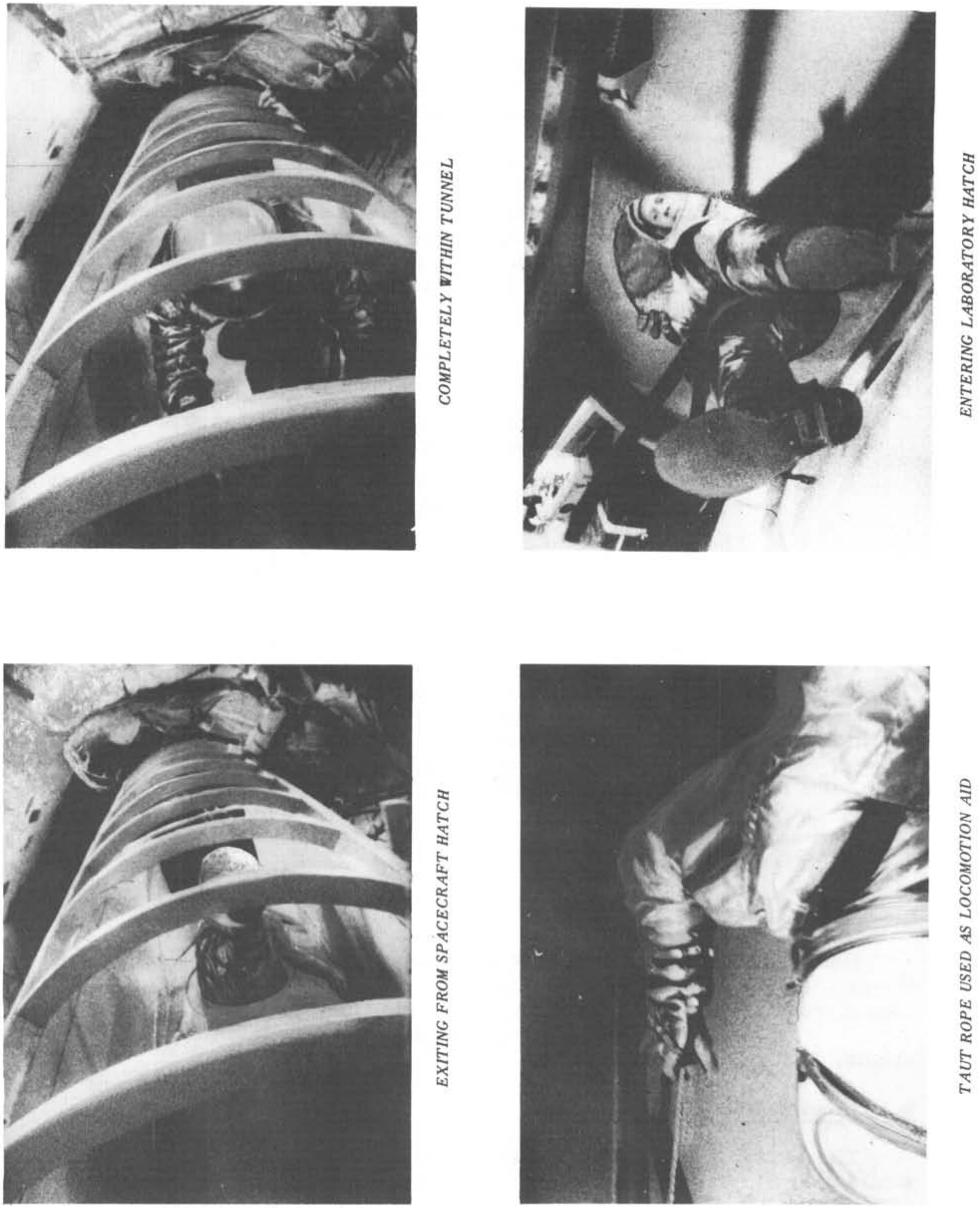
3. MISSION REQUIREMENTS

a. General

Human factors requirements were used largely to establish tunnel geometry and the locomotion aids required for effective crew transfer. Mission considerations were then used to evolve the final design of the tunnel. Mission aspects considered included launch pad and boost requirements, orbital operations, and mission termination.

b. Launch Pad Requirements

The tunnel should incorporate a modular design approach. This approach would permit, prior to mounting on the launch vehicle, (1) prepackaging of the tunnel, and (2) on-the-ground checkout and repair, if necessary. In addition, the packaged tunnel would be relatively easy to install on or remove from the spacecraft, and the canister would protect it during hold or countdown.



COMPLETELY WITHIN TUNNEL

ENTERING LABORATORY HATCH

EXITING FROM SPACECRAFT HATCH

TAUT ROPE USED AS LOCOMOTION AID

Figure 1 - Crew Transfer Experiment under Zero g

c. Boost Requirements

The packaged tunnel and packaging canister should impose a minimum effect on the aerodynamics of the launch vehicle. A flight canister would require sufficient insulation to prevent aerodynamic heating from damaging the packaged tunnel. During this critical phase of the mission, a malfunction may necessitate abort. Accordingly, for compatibility with mission abort requirements, the design should incorporate provisions to jettison the packaged tunnel and canister from the launch vehicle. In addition, the packaged tunnel must be qualified for the following environmental conditions encountered during the boost phase:

Noise, (see Table 1)
Vibration, (see Table 2)
Shock, 150 g, 2.5-millisecond sawtooth pulse
Acceleration, 5 g forward longitudinal, 2 g lateral

TABLE 1 - NOISE AT VEHICLE SURFACE

Sound level (db)	Frequency (cps)
136	18.75 to 37.5
137	37.5 to 75
138	75 to 150
139	150 to 300
140	300 to 600
141	600 to 1200
139	1200 to 2400
134	2400 to 4800
128	4800 to 9600

TABLE 2 - RANDOM VIBRATION SPECTRUM

Acceleration spectral density (g^2/cps)	Frequency (cps)
1.0	10 to 80
6.0	200 to 300
3.0	360 to 1000
0.1	2000

d. Orbital Flight

When an orbital path is achieved, the packaging canister will be ejected, and the packaged tunnel will deploy to its expanded volume automatically. To initiate crew transfers, the tunnel will be pressurized to its design pressure of 7-1/2 psi. The orbital mission lifetime will be 45 days at altitudes from 100 to 300 naut mi. To withstand conditions encountered in the orbital environment, the tunnel materials must meet the following requirements:

1. Provide a 0.995 probability of zero meteoroid penetrations
2. Maintain interior surface temperatures within 50 to 100 F
3. Be suitable for operations in hard vacuum of 10^{-6} to 10^{-7} torr
4. Absorb 10^6 rads of Van Allen electron radiation without serious degradation

e. Mission Termination

At mission termination, the re-entry vehicle will separate from the orbital module prior to re-entry. Accordingly, the design must incorporate provisions to jettison the transfer tunnel after the final transfer from the laboratory module to the re-entry vehicle.

4. DESIGN CONFIGURATION

A modular design of the expandable crew transfer tunnel was jointly derived by the Aero Propulsion Laboratory, the Aero Medical Laboratory, and Goodyear Aerospace. This design was evolved to combine the human factors requirements and the mission requirements into a single overall design objective.

Basically, the design incorporates an expandable tunnel geometry simulating that geometry used on the mockup for human factors evaluation. The expandable structure has a rigid floor, which in turn is integrated with the packaging canister. In essence, the tunnel floor forms the lower half of the packaging canister and is connected to the upper half of the canister by frangible bolts for canister ejection. The advantages of this design are:

1. No attachments are required between the packaging canister and the launch vehicle.
2. Mounting attachment points are required only at the hatch connections, thus simplifying installation and removal.
3. The ejection systems are simplified. Requirements for launch abort and mission termination are combined into a single system.

Figures 2, 3, 4, 5, and 6 show the operational sequence from prelaunch to mission termination. Figure 2 shows the prepackaged tunnel module attached to the spacecraft and laboratory hatches. Figure 3 shows design

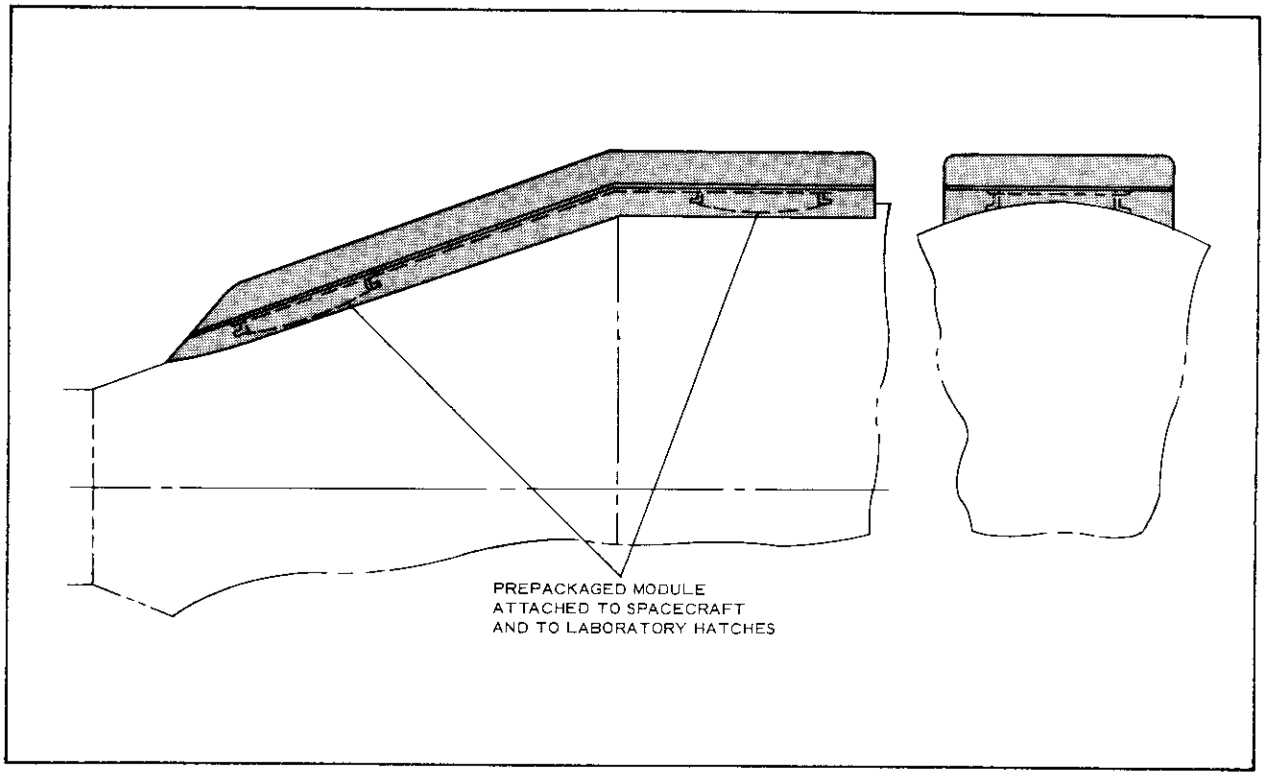


Figure 2 - Launch Configuration of Prepackaged Tunnel

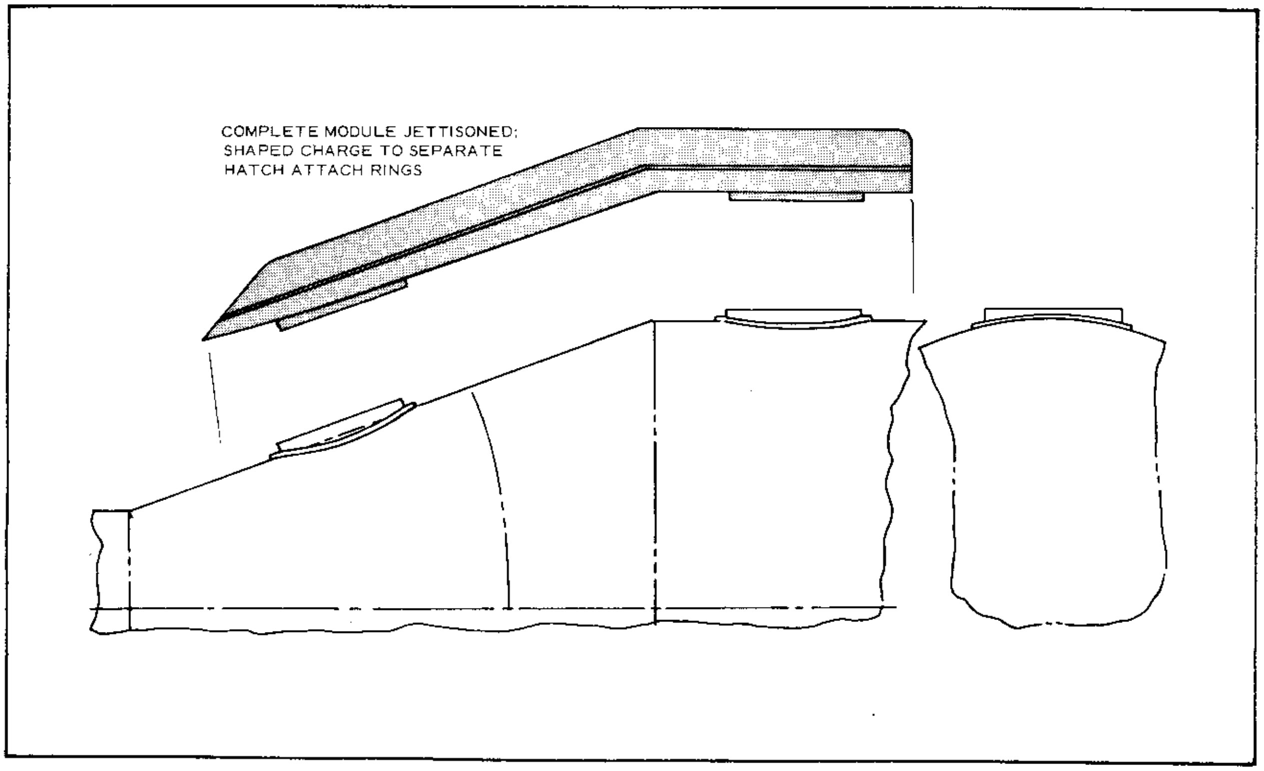


Figure 3 - Tunnel Ejection at Launch Abort

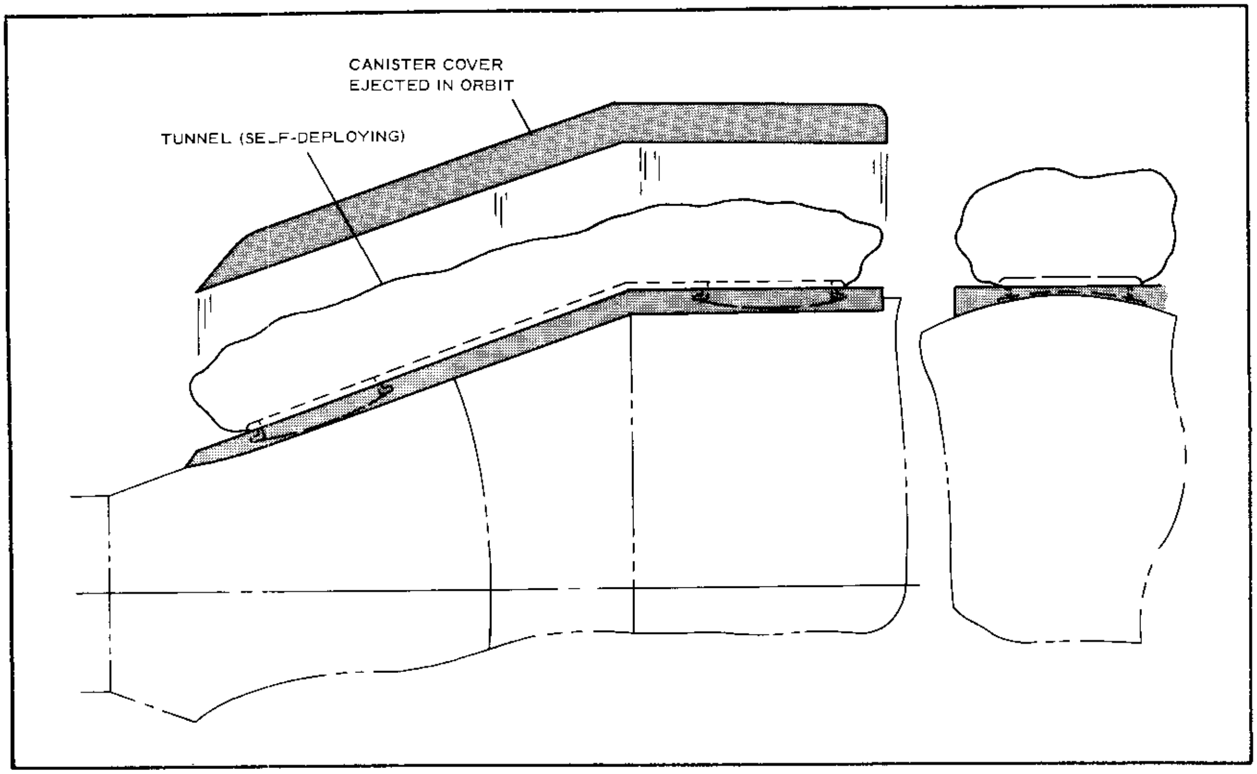


Figure 4 - Canister Ejection and Tunnel Deployment

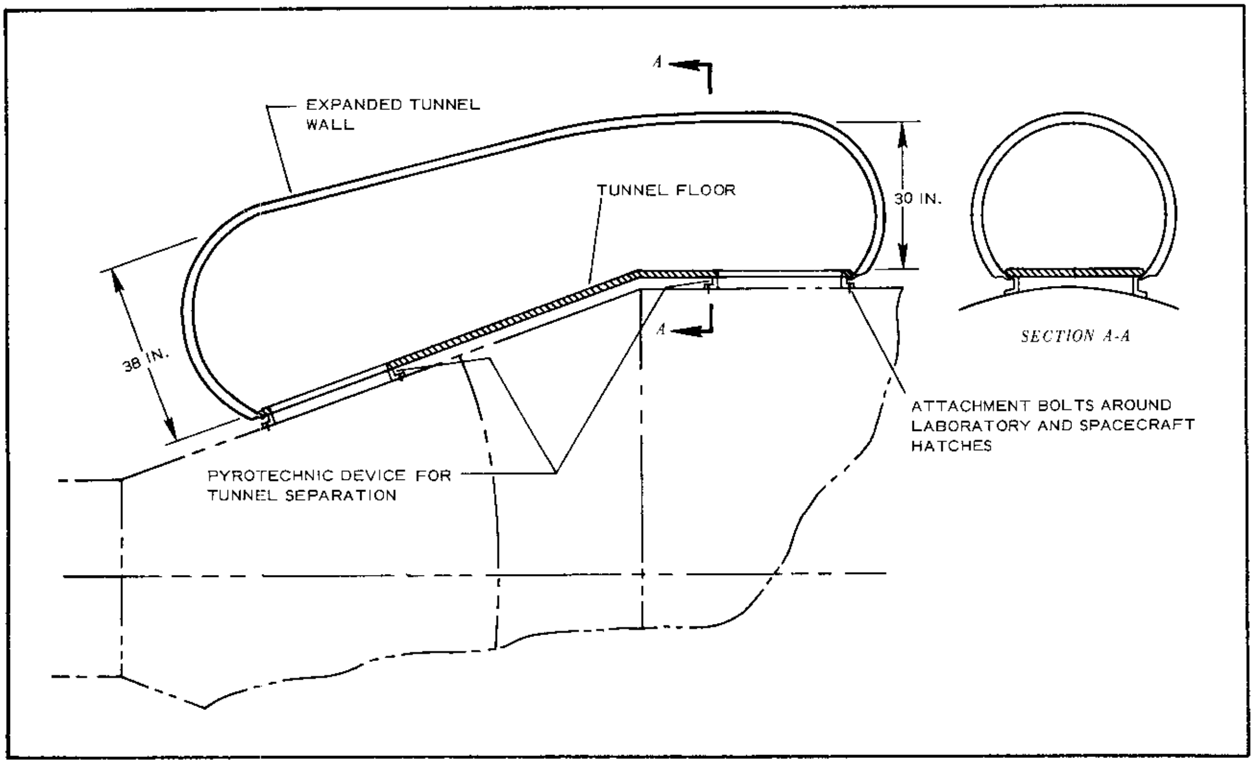


Figure 5 - Deployed Tunnel

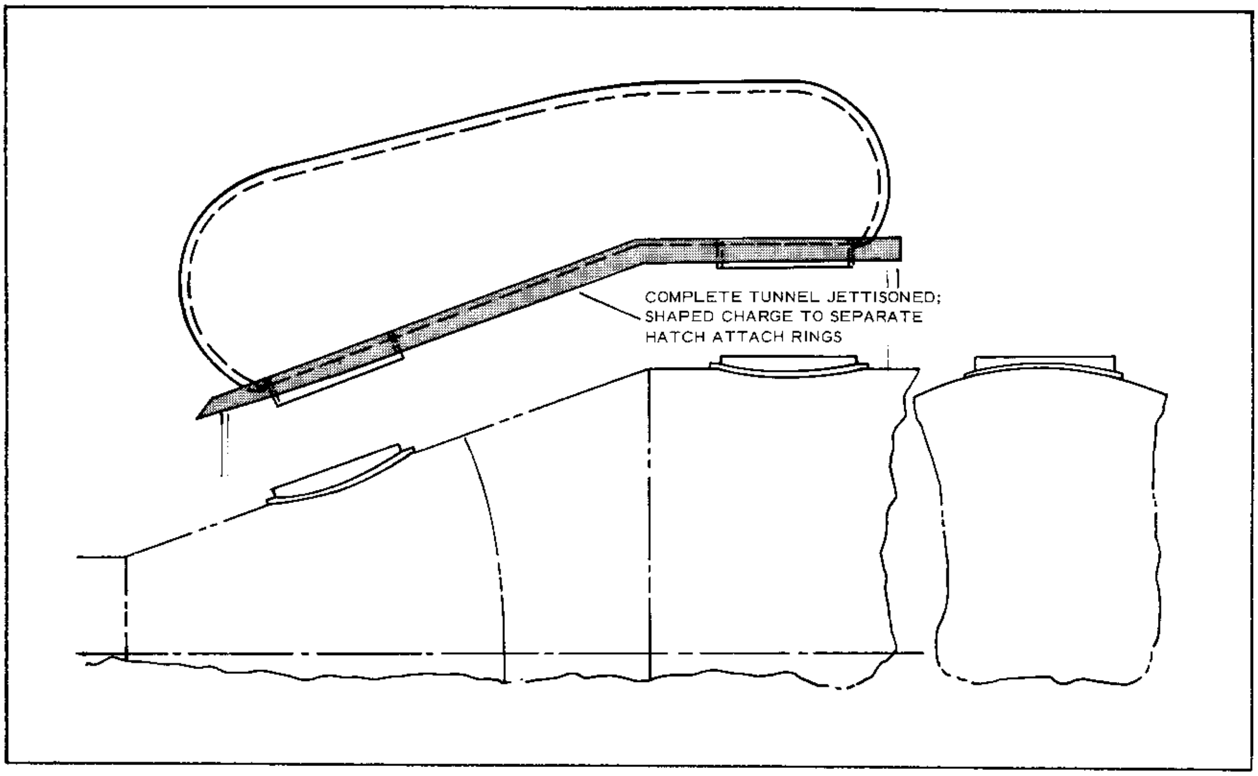


Figure 6 - Tunnel Jettisoned at Mission Termination

provisions to meet abort requirements at launch. The hatch attach rings incorporate a shaped charge to burn through the rings. In the event of abort, the canister and the packaged tunnel will be jettisoned as a single unit.

Deployment of the packaged tunnel in orbit is shown in Figure 4. The frangible bolts used to attach the canister cover to the tunnel floor will be activated, ejecting the canister cover and initiating tunnel deployment. The elastic recovery characteristics of the tunnel should then deploy the structure to its expanded volume. Figure 5 shows the geometry of the fully expanded tunnel. At mission termination, the expanded tunnel will be ejected, permitting separation of the re-entry vehicle (see Figure 6). The jettisoning system will be the same as that used for launch abort.

SECTION III - EXPANDABLE MATERIALS AND ENVIRONMENTAL COMPATIBILITY

1. MATERIALS COMPOSITE

A materials survey was conducted by the Air Force to determine if current technology could be applied to an expandable crew transfer tunnel for use in a space environment for an extended period of time. This research indicated that the concept of an expandable tunnel was feasible and that such a structure could be fabricated from several different combinations of materials and material techniques.

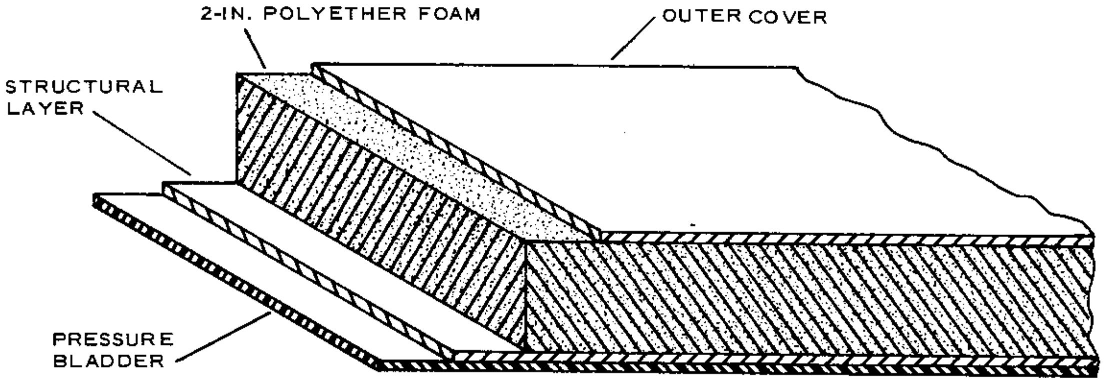
The materials approach selected to best meet the overall requirements of tunnel design was a material composite. Figure 7 depicts the composite, which is comprised of four distinct layers bonded together into a homogeneous structure. The inner layer is an unstressed pressure bladder, whose only function is to maintain pressure tightness and to transmit pressure loads to an adjacent structural layer. The structural layer carries structural loads resulting from internal pressure. The flexible foam layer performs a dual function. It acts first as a micrometeoroid barrier, protecting the pressure bladder from penetration. A secondary function is deployment and shaping of the structure through the use of stored energy inherent in the foam compressed for packaging. The outer cover also does a dual job. It is used as a smooth base for the application of a thermal coating and also encapsulates the total composite for evacuation and compression prior to packaging for launch.

2. PRESSURE BLADDER

The pressure bladder is a laminate of three individual sealant layers (see Figure 8). The inner layer is a laminate of Capran film sandwiched between two layers of lightweight nylon cloth. This layer is bonded with polyester adhesive to a second layer of closed-cell vinyl foam 1/16 in. thick. The outer sealant is a close-weave nylon cloth coated with a polyester resin. The total weight of the bladder composite is about 0.13 psf and is independent of design pressure.

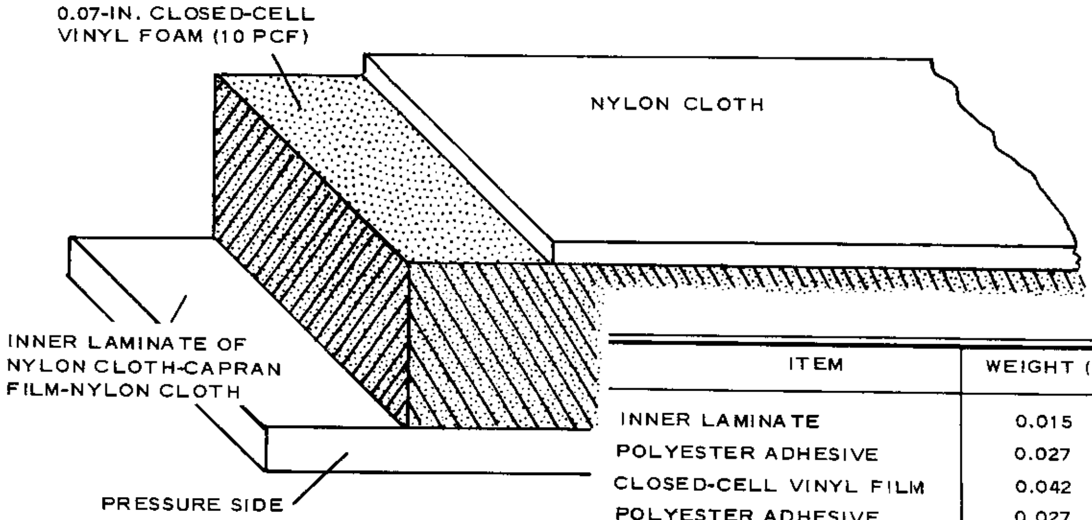
Tests were conducted on the pressure bladder to determine permeability rate, possible toxicity, and environmental effects due principally to vacuum. Permeability was determined with oxygen as a test gas at 7.5 psia using a Dow cell. The measured rate was less than 10^{-4} psf per day. Relating this rate to the tunnel design, the anticipated gas loss is 0.02 lb per day, substantially less than the maximum allowable of 1 lb per day. A survey of toxic materials known to be used in the construction of the pressure bladder indicated the possible presence of toluene, xylene, methyl ethyl ketone, methylene chloride solvents, and toluene diisocyanate. Although carbon monoxide was not known to be contained, tests for it were also included. The bladder material was exposed to 5 psia of oxygen for 24 hr prior to a chemical analysis and check for toxic gases. Test results indicated that all the above contaminants were below the threshold limits established by the National Bureau of Standards for occupational exposure.

The principal environmental effect for which the bladder was checked was a hard vacuum. This check was made first to ensure that delamination of the composite bladder would not occur, and second to determine the degree of off-gassing to be expected. The bladder construction technique proved successful both in preventing delamination and in minimizing off-gassing. Off-gassing stabilized in about 96 hr with a 6.3-percent weight loss.



ITEM	WEIGHT (PSF)
PRESSURE BLADDER	0.132
STRUCTURAL LAYER	0.219
FOAM LAYER	0.167
OUTER COVER	0.068
INTERLAYER POLYESTER ADHESIVE	0.063
TOTAL	0.649

Figure 7 - Tunnel Composite Wall



ITEM	WEIGHT (PSF)
INNER LAMINATE	0.015
POLYESTER ADHESIVE	0.027
CLOSED-CELL VINYL FILM	0.042
POLYESTER ADHESIVE	0.027
OUTER NYLON CLOTH	0.021
TOTAL	0.132

Figure 8 - Pressure Bladder

3. STRUCTURAL LAYER

The structural layer is a four-ply laminate of Dacron bonded to a polyester resin, then cured under heat and pressure. The design pressure of 7.5 psia, which along with a safety factor of five and allowance for creep rupture, requires a load capability of 1070 lb per inch. This load must be carried entirely by the structural layer. The basic structural concept of the multi-ply technique is that joints in the individual plys are staggered in such a way as to offer an essentially seamless construction. Strip tensile tests of this technique indicate an 85-percent load capability, as compared to that of the parent structural cloth. The degradation in strength is attributed to the "locked-in" crimp of the bonded polyester joint. A similar degradation also is incurred in elastomer-coated fabrics and is attributed to the same effect. Even in a mechanically sewn joint, seam efficiencies beyond 85 percent are unlikely. It thus appears that a 100-percent structural efficiency for a fabric structure is not attainable. However, because the structural weight of an overall composite is only 25 percent of the total, the weight penalty incurred by an 85-percent structural efficiency is not significant.

Particular emphasis was placed on the design and development of a structural joint between the rigid floor of the tunnel and the structural layer. The technique that evolved from this investigation (see Figure 9) uses an epoxy resin rigid bond. The locked-in crimp effect was again found in this joint design, resulting in an efficiency of 50 percent. Attempts to improve joint efficiency by using a more elastic epoxy bond were not successful and only resulted in shear failure of the joint. A polyester resin bond similar to that used

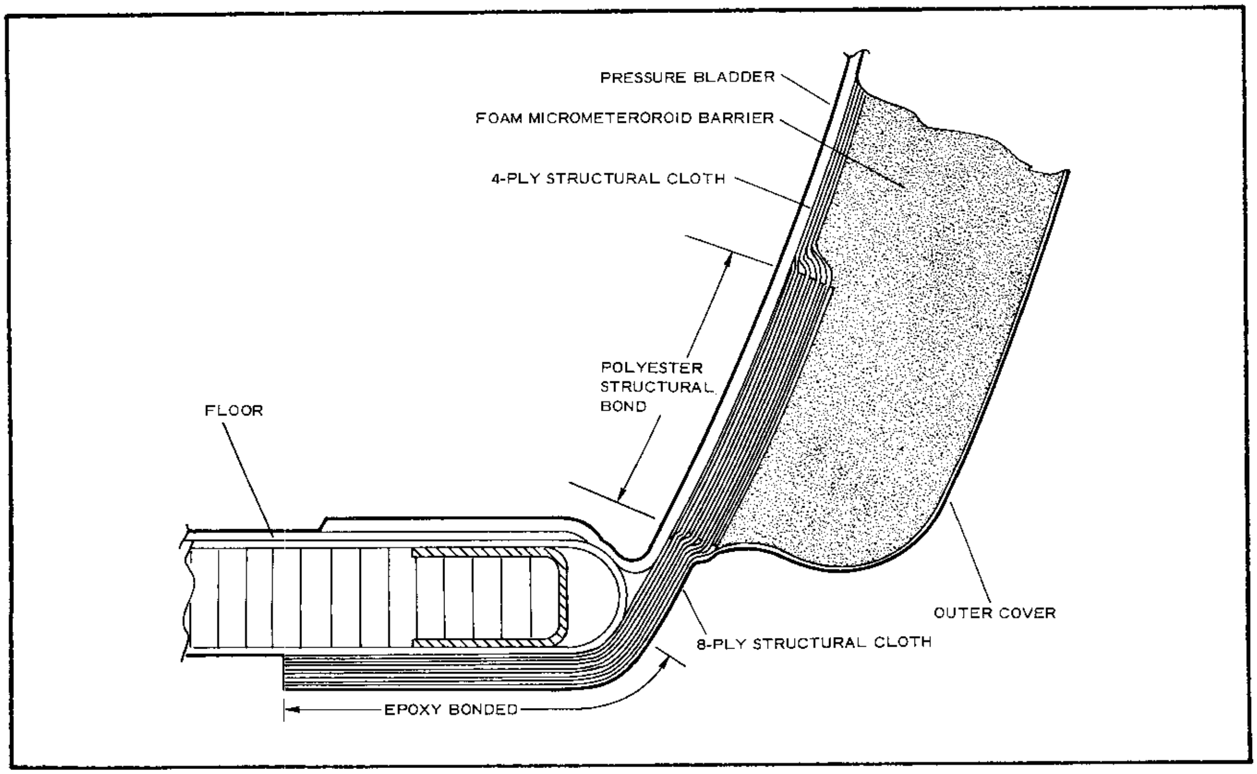


Figure 9 - Structural Joint Between Expandable Wall and Rigid Floor

in the multi-ply wall was also tested, but was wholly inadequate for the required bond. Consequently, the rigid epoxy bond technique was adopted as the required design technique and resulted in an eight-ply bond to the structural floor joined to the four-ply structural layer with a polyester resin bond. Strip tensile tests of this overall joint design indicated that the full load capability of 1070 lb per inch could be carried by both the joints and the basic four-ply structural layer.

Structural tests have been conducted to investigate environmental effects due to vacuum and high-energy radiation (Van Allen electrons). Strip tensile tests on Dacron have indicated negligible effects of hard vacuum on the structural characteristics. Similar tests on fabrics irradiated with 10^6 rads of 1.3-mev gamma radiation have also indicated negligible degradation. Accordingly, there is no reason why synthetic fiber structures should not be used in structural space applications, if their physical characteristics are known and related to the operational environment.

4. FOAM LAYER

The tunnel will be protected from micrometeoroid penetration by a two-inch layer of flexible polyether foam. Flexible foam of 1 pcf density has been selected as a suitable barrier material, based on hypervelocity particle impact tests conducted by Goodyear Aerospace and on tests conducted at the micrometeorite testing facility at Wright-Patterson AFB. Both series of tests (the latter conducted at 27,000 fps with an average particle mass of 0.005 g) indicate that a two-inch foam barrier is equivalent in barrier effectiveness to single-sheet aluminum 0.20 in. thick (2.7 psf). Figure 10 shows the Air Force near-earth micrometeoroid environment spectrum in terms of particle mass and accumulative particle flux. When the previously mentioned test results are correlated with single-sheet aluminum penetration theory, the critical penetrating flux level is about 5.23×10^{-7} particles/sq ft-day. Relating the critical flux with the exposed surface area of the deployed tunnel (130 sq ft) and the mission time (60 days), the probability of zero penetration is 0.995.

While the primary function of the foam will be as a micrometeoroid barrier, it can serve also as a tunnel deployment aid. During packaging, the foam layer will be compressed to about 10 percent of its original thickness and will be restrained by the packaging canister. Upon deployment in orbit, the canister will be jettisoned, and the elastic recovery characteristics of the foam will shape the tunnel to its fully expanded volume. Figure 11 shows the recovery characteristics of the foam under vacuum conditions and for varying temperatures. From Figure 11 it can be seen that the packaged structure must be insulated against extreme cold if full recovery is to be achieved.

Environmental effects should be evaluated to establish compatibility with the environment. Of principal concern are the effects of vacuum, temperature, and high-energy radiation. The effect of foam recovery in a vacuum has already been discussed. Off-gassing induced by vacuum was negligible; it amounted to a 0.4-percent weight loss and stabilized in 1.5 hr. Expected temperature extremes have not yet been established. High-energy radiation is not expected to present any problem because the foam tolerance is about an order of magnitude higher than the anticipated dose of 10^6 rads.

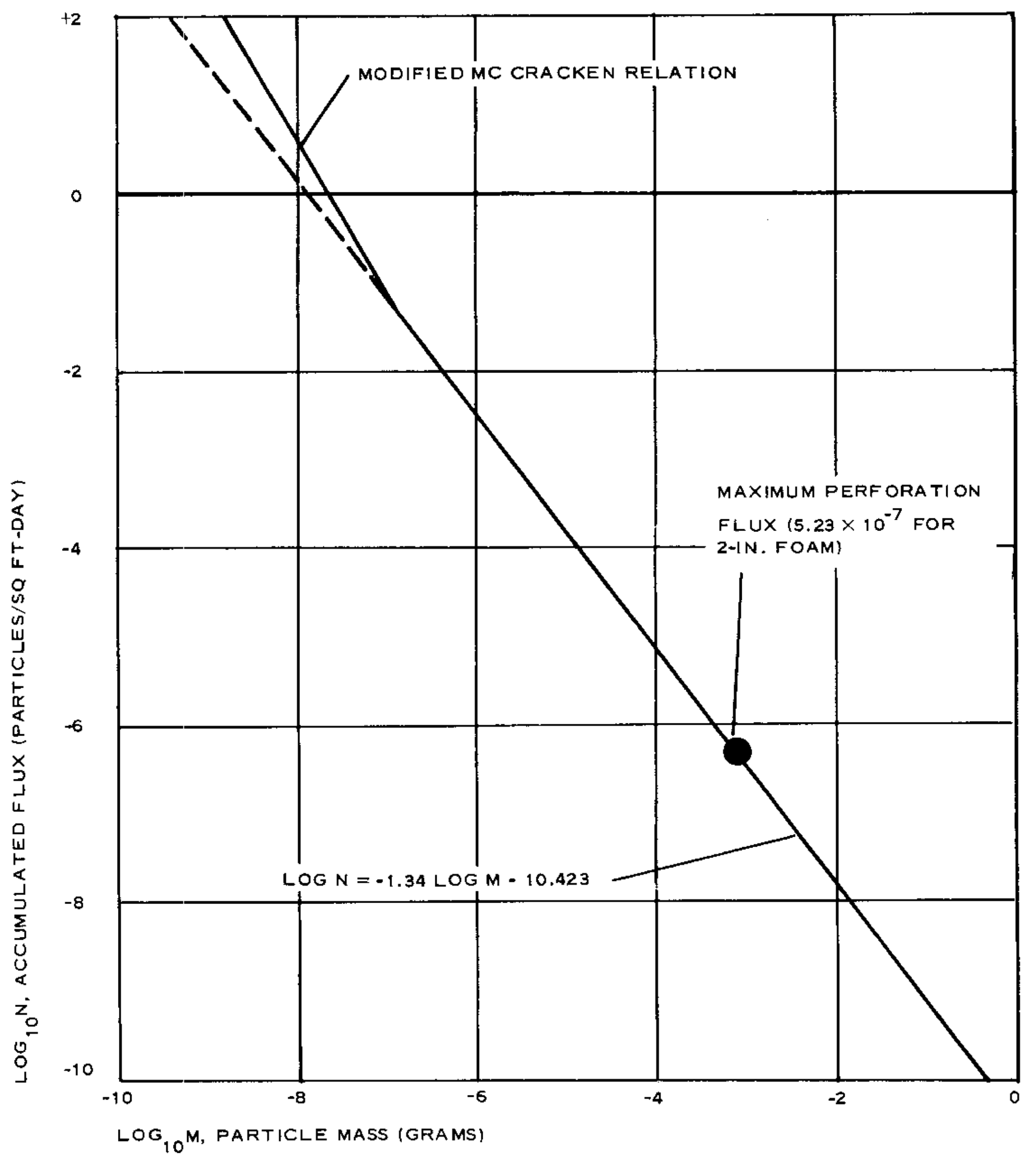


Figure 10 - Near-Earth Micrometeoroid Environment

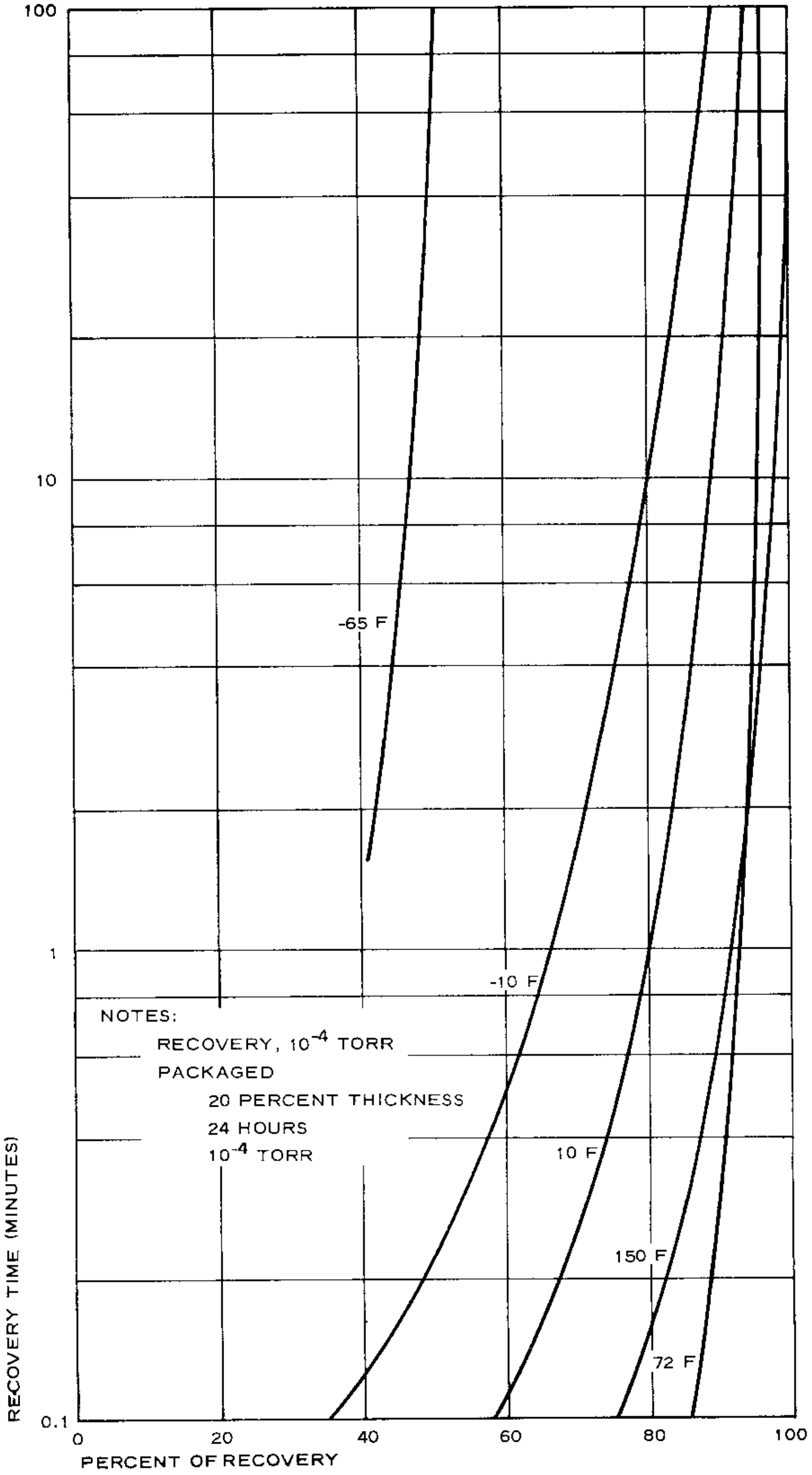


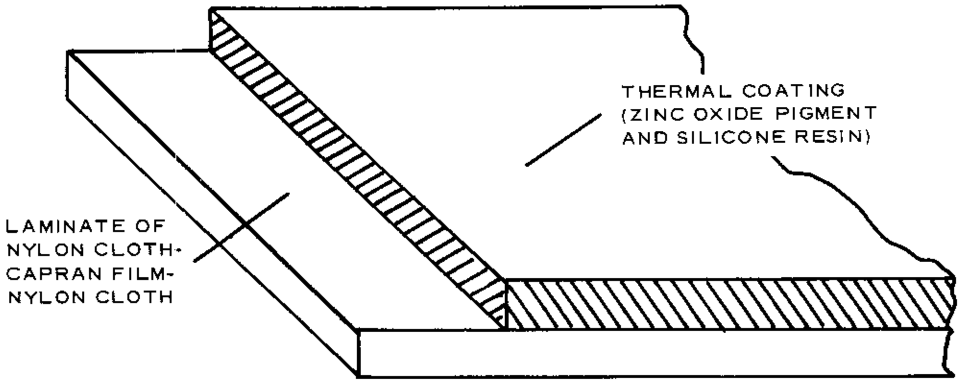
Figure 11 - Foam Thickness Recovery versus Time

5. OUTER COVER

The outermost layer of the composite wall structure encapsulates the wall and provides a smooth base for the application of a thermal coating. The construction of this layer is shown in Figure 12.

Inasmuch as the outer cover encapsulates the composite wall, it serves as an aid in packaging the tunnel prior to launch. By a vacuum technique, the wall thickness can be compressed from the fully expanded 2 in. to about 3/8 in., suitable for folding and subsequent packaging in the canister. Also, a certain amount of air will still be trapped in the composite wall, even after evacuation. This air can be used as a thickness recovery aid, augmenting the elastic recovery characteristics of the compressed foam. Thus, full recovery of the wall thickness, even under adverse temperatures, will be ensured.

Zinc oxide in a silicone resin will be used as a thermal coating on the outer surface. It will provide an absorptance (α_s) of 0.17, an emissivity (ϵ) of 0.75, and an α_s/ϵ of 0.23. The purpose of this coating will be to maintain material temperatures within acceptable limits during full solar flux. Maximum temperatures will be limited to about 60 F; minimum temperatures will be limited by the emissivity of the coating, the thermal conductance of the composite wall, and the heat capacity of the structure. A computer program is currently underway to evaluate these factors relative to orbital inclination, orbital altitude, and orientation of the tunnel relative to the earth. The objective of this program is to establish temperature gradients of the composite wall. These gradients will be used to establish minimum and maximum temperatures and



ITEM	WEIGHT (PSF)
FILM CLOTH LAMINATE	0.015
THERMAL COATING	0.053
TOTAL	0.068

Figure 12 - Outer Cover of Composite Wall

will permit the correlation of material thermal characteristics with the expected temperature extremes.

Environmental effects compatibility requires the consideration of combined vacuum and ultraviolet radiation, the thermal environment, and high-energy radiation from Van Allen electrons. The portion of the outer cover most sensitive to the orbital environment will be the thermal coating. The combined effect of vacuum and ultraviolet radiation will cause some degradation of the coating. The α_s/ε ratio is expected to increase by roughly 10 percent for a 60-day mission, resulting in a slight increase in materials temperature. Off-gassing due to vacuum is a minute effect, causing less than 0.5-percent weight loss and stabilizing in 1.5 hr. Thermal effects relative to extremes in temperature are still to be evaluated, but no problems are anticipated. And finally, the silicone elastomer of the coating is expected to absorb 10^6 rads of electron radiation. However, the tolerance of this elastomer to high-energy radiation is on the order of 10^7 to 10^8 rads.

SECTION IV - PLANNED TEST EVALUATION

1. GENERAL

Pending completion of fabrication, the tunnel will be subjected to a series of tests to evaluate the application of such structures to actual space missions. These tests will involve gas leakage, structural integrity, deployment, and crew transfer under conditions of no gravity.

2. GAS LEAKAGE

Gas leakage of the tunnel will be evaluated primarily from the standpoint of leakage, and/or permeability, through the composite wall. The hatch ports will be sealed off with aluminum plates and "O"-ring seals. Similarly, the rigid floor will be sealed carefully at joints, edges, and connections to pinpoint any leakage of the expandable material.

The leakage characteristics of the tunnel will first be established prior to folding and packaging. This will permit the definition of a reference leak rate to account for possible degrading effects of folding and packaging. After a reference is established, the tunnel will be folded and packaged, simulating the launch requirement. It will remain packaged for 24 hr, then deployed and inflated with air to the 7.5-psia design pressure. The tunnel will remain pressurized for seven days, during which time the pressure will be monitored and the leak rate determined from the variations in pressure.

3. STRUCTURAL INTEGRITY

The structural integrity of the tunnel will be checked with a "time under load" test at proof pressure (10 psi) and a cyclic load test from zero to the design pressure (7.5 psi). For the "time under load" test, the proof pressure will be maintained continuously for seven days. During this period, unusual deformations or possible areas of stress concentration will be noted. The cyclic load test is intended to simulate possible cycles of pressurization and depressurization in orbital applications. Sixty cyclic load tests will be conducted. These tests will also be observed for possible deformations, particularly at the floor joint.

4. DEPLOYMENT

Full-scale tunnel deployment tests will be conducted in the 40- by 80-ft vacuum facility at the Arnold Engineering and Development Center. These tests are intended to simulate packaging, canister ejection, and subsequent tunnel deployment in orbit. The tunnel will be packaged in its canister, and the canister will be attached to a special test rig and placed in the vacuum facility. The deployment sequence will be initiated under 10^{-4} torr by jettisoning the canister previously attached with frangible bolts. With the canister jettisoned, the stored energy inherent in the packaged tunnel should deploy the tunnel to its final expanded configuration automatically. The entire sequence of deployment will be filmed.

5. ZERO-G CREW TRANSFER

The tunnel will be finally evaluated and checked out from a human factors standpoint under conditions of no gravity. These tests will be conducted in the KC-135 zero-g aircraft at Wright-Patterson AFB, which is capable of simulating zero g in multiple trajectories, each up to 30 sec in duration. The objective of these test flights will be to check out the tunnel geometry and the locomotion devices needed for effective transfer through the tunnel. During these tests the tunnel will be unpressurized; it will depend only on the inherent stiffness of the material to maintain the expanded tunnel geometry.

Tests will simulate astronaut transfers in both pressurized and nonpressurized suits. Transfers will be conducted from both ends of the tunnel simulating either entry from or return to a parent vehicle. Further, the astronaut will be encumbered by umbilicals to determine their effect on effective transfer. The ability to transfer equipment also will be evaluated; simulated equipment packages of approximately one cubic foot in volume will be used. And finally, tests will be conducted to determine if an incapacitated astronaut can be pulled through the tunnel.