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STUDY OF STRUCTURAL-THERMAL INSULATION-METEOROID PROTECTION INTEGRATION NAS8-21430

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THE BOEING COMPANY · AEROSPACE GROUP
SOUTHEAST DIVISION

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STUDY OF STRUCTURAL-THERMAL INSULATION - METEOROID PROTECTION INTEGRATION

NAS8-21430

Prepared by,

D. W. Cornett and W. H. Armstrong,

Structures Technology

MAY 15, 1969

W H Armstrong

for R. L. Finley

Program Manager

H-12

NASA

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FOREWORD

This report was prepared by The Boeing Company under Contract NAS8-21430, "Study of Structural - Thermal Insulation - Meteoroid Protection Integration", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. This work was administered under the technical direction of the Engineering Division, Structural Development Branch of the George C. Marshall Space Flight Center, with Mr. C. D. Nevins acting as the Contracting Officer Representative.

ABSTRACT AND LIST OF KEY WORDS

This report contains the results of a study conducted to assess the feasibility of satisfactorily integrating the qualities of structural integrity, low thermal conductivity, and resistance to meteoroid penetration into a common tank wall. The results of this study indicate that these qualities can be integrated into a thick composite consisting of alternating layers of load-carrying sheets and spacer material; however, suitable materials having as low a thermal conductivity as is required are not presently available. Defining a conventional concept to consist of a two-sheet meteoroid shield and thermal insulation superimposed upon a basic tank wall and assuming that all desirable materials are available for an integrated concept, this study indicates that a weight savings as high as 50 percent over the conventional concept can be realized when using an integrated concept.

Integrated Concept

Meteoroid Shield

Thermal Insulation

Nuclear Stage

Areal Density

Multiwall Concept

SECTION 1 - INTRODUCTION

1.0 PROBLEM DEFINITION

The practical propulsion system for future space exploration is assumed to be nuclear propulsion. Due to the size of nuclear powered vehicles and length of the missions, the protection of the liquid hydrogen (LH_2) propellant from the thermal environments and meteoroid hazards will present very significant design problems. Usually the simplest approach to these design problems, and the approach that has received the most attention, is to consider each design problem independent of other design problems. In such a design, a vessel is designed to contain the LH_2 propellant and to withstand a pressure equal to the required ullage pressure plus the acceleration head; a meteoroid shield, usually of sandwich construction, is designed to withstand the predicted meteoroid environment, placed outboard of the propellant container, and assumed to withstand the Earth-launch loads; and an efficient insulation is sized to protect the propellant container against the predicted thermal environment and is placed on the meteoroid shield, on the propellant container, or both. Such a concept is shown in Figure 1-1.

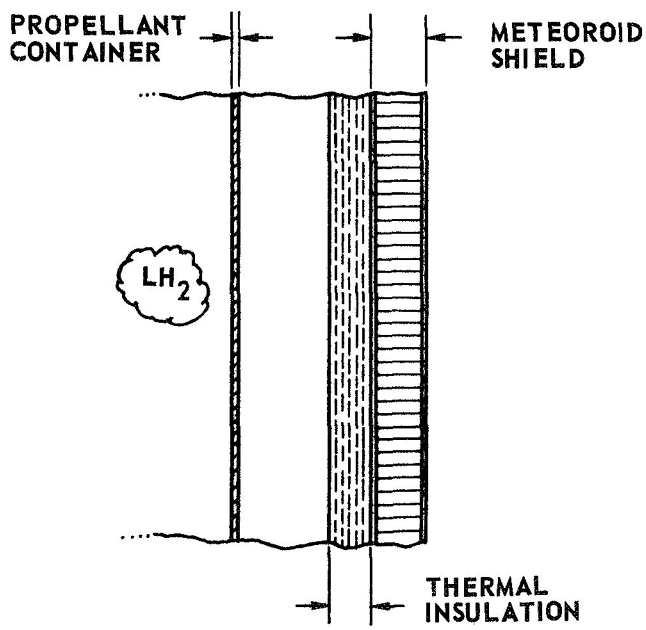

Figure 1-1. CONVENTIONAL SIDEWALL CONCEPT

With the above design approach, the pressure vessel, meteoroid sheild, and thermal insulation are each optimized separately with the result that, in many instances, the total system is excessively heavy and the full potential of the three subsystems is not always realized. A better approach to satisfying the requirement for structure, meteoroid shield, and thermal insulation from a system standpoint would be to satisfy more than one requirement with only one system; or, better still, to satisfy all three separate requirements with a single system. This is the problem to which this study is directed.

1.1 STUDY OBJECTIVE

The objective of this study is to formulate advanced design concepts for cryogenic propellant tanks suitable for long-term space missions. More specifically, it is to assess

1.1 (Continued)

the feasibility of satisfactorily integrating the qualities of structural integrity, low thermal conductivity, and resistance to meteoroid penetration into a common tank wall construction which would require neither supplemental thermal insulation nor supplemental meteoroid protection during a representative space mission. Repair techniques are not within the scope of this study and will not be given consideration.

It is not deemed desirable, nor is it anticipated that an integrated system will find application in all future propulsion stages; however, if an integrated system does have potential application for a particular vehicle, the decision to use an integrated concept is a fundamental consideration in the vehicle design and requires careful consideration during the concept selection phase of the design. Consequently, the integrated sidewall must be given prime consideration in the vehicle design and the vehicle must be designed around the integrated sidewall and not vice versa.

1.2 STUDY PLAN

To accomplish the objectives described above, the following study plan was outlined:

a. Select a series of representative space missions which envelop the range of potential application for the integration of the functional design requirements, and identify specific missions which appear suitable for the following system characteristics:

   1. A structural shell with superimposed thermal insulation, the combination of which also provides adequate meteoroid protection,

   2. A conventional structure with a combination meteoroid protection and thermal insulation material applied externally (This differs from Item 1 in that additional material other than that required solely for thermal insulation is applied to achieve adequate meteoroid protection),

   3. An integrated tank wall construction which affords a measure of meteoroid protection and thermal insulation by suitable arrangement of the material required for structural integrity;

b. Perform parametric analyses which will substantiate recommendations for achieving minimum weight systems through integrating functional capabilities of structural integrity, thermal insulation, and meteoroid protection;

c. Review existing experimental and analytical data pertinent to the efficient design of structural integrity, thermal insulation, and resistance to meteoroid penetration;

d. Perform laboratory tests as required and within the budgetary limits to supplement existing data;

e. Develop design configurations which best satisfy the requirements of minimum weight for a vehicle designed for a mission as defined in Item a.3 above.

SECTION 2 - SUMMARY

2.0 SUMMARY

This feasibility study has been accomplished through reviewing the structural, thermal insulation, and meteoroid shielding requirements and by establishing the features of each subsystem which constitute efficient and minimum weight designs. Each subsystem is then assumed to be combined in turn with each of the other two subsystems and the compatibilities of such combinations are evaluated. Finally, considering the individual subsystem design requirements and using the results of the subsystem combinations, the requirements of an integrated system are established and a general configuration for meeting these requirements is presented.

With regard to structural requirements, it is assumed in this study that the vehicle propellant tanks are pressure stabilized, requiring a pressure of approximately 35 psig, and that operational ullage pressure for a nuclear stage is 10 psig. Assuming pressure stabilization and neglecting areas of structural discontinuities, structural components may be subjected to their full strength capacity; and therefore present no difficult design problems. Regarding thermal insulation requirements, the results of this study indicate that the insulation thermal conductivity required on the missions for which an integrated concept is applicable must be no greater than 10^{-4} BTU/HR-FT-^{o}F, and that the lower this conductivity, the lighter the total insulation weight. To obtain these low thermal conductivities, an insulation that functions in the same manner as a conventional multilayer must be used; i.e., solid heat conduction must be reduced to a point where solid heat conduction and radiation heat conduction are on the same order of magnitude and both are small. Concerning meteoroid shielding requirements, the results of this study indicate that the lightest possible meteoroid shield is a thick, low-density media. A limited test program was conducted during the course of this study which supports the assumed functional relationship between the media density and the required thickness to defeat a given meteoroid.

The combination of the structural and meteoroid protection subsystems indicate their requirements are completely compatible. The combination of the thermal insulation and meteoroid protection subsystems indicates also that their requirements are completely compatible; furthermore, it is shown that a relationship between the required insulation thermal conductivity and the required meteoroid shield density can be established. Because of a limitation on available materials, the combination of the structural and thermal insulation subsystems indicates the requirements of these subsystems are not compatible. However, assuming that proper materials were available, it is shown that the weight of the combined structural, thermal insulation system can be minimized with respect to the final propellant vapor pressure.

The results of this study indicate that if proper materials become available, a general class of configurations for meeting the requirements of an integrated system is a multiwall concept in which numerous, thin, load-carrying sheets are separated by a low-density, low-conductivity spacer material. By using a spacer with an extremely low solid construction, the sidewall will act similarly to the conventional multilayer insulations. The resulting thick, low-density media will serve as the meteoroid shield.

2.0 (Continued)

This study indicates that such a configuration can be as much as 50 percent lighter than the conventional system using a two-sheet meteoroid shield and thermal insulation superimposed upon a basic propellant container.

SECTION 3 - MISSION SELECTION AND DESIGN ENVIRONMENTS

3.0 MISSION CATEGORIES

A spectrum of missions for this study has been considered with mission times ranging from 3 to 1000 days. Corresponding to each interplanetary or lunar mission, there exists a vehicle configuration which would most likely be used for that mission, and for a particular mission and a corresponding vehicle, the product of the mission time and the vehicle area may be calculated. This area-time ($A\theta$) product has been used, along with other secondary considerations, to define the severity of the thermal and meteoroid environments for selection of three missions corresponding to the requirements set forth in Paragraph 1.2. These categories, henceforth called Mission Categories 1, 2, and 3, are respectively:

a. A lunar mission using a Centaur stage, area-time is 7.59×10^5 m^2-seconds;

b. A Jupiter mission using a Centaur stage, area-time is 4.41×10^8 m^2-seconds;

c. An unmanned Jupiter mission using a nuclear vehicle, area-time is 7.80×10^{10} m^2-seconds.

A consideration which influenced the selection of a Jupiter mission for Categories 2 and 3 was the Asteroidal Belt between Earth and Jupiter which was expected to dictate the meteoroid shield requirements for these missions. The properites of an asteroidal meteoroid are such that its impact onto a shield can be simulated in a laboratory. A manned Mars mission using a nuclear stage falls into the Category 3 mission; however, this mission was not considered in this study because it is impossible to simulate the cometary meteoroid flux with present laboratory facilities. The procedures and analyses presented in this study are, in general, applicable to either the asteroidal or the cometary meteoroid flux.

3.1 DESIGN ENVIRONMENTS - METEOROID ENVIRONMENT

All meteoroid environmental data used in this study are taken from Reference 1. The cometary meteoroids encountered on a Category 1 mission have a density of 0.50 gm/cc and a velocity of 20.4 km/sec; the flux model is shown in Figure 3-1. The asteroidal meteoroids encountered on Category 2 and 3 missions have a density of 3.5 gm/cc. The meteoroid velocity and flux vary across the Asteroidal Belt; therefore, for this study the velocity and flux at the mean radius of the Asteroidal Belt have been used. The mean asteroidal velocity is 7.87 km/sec; this flux model is also shown in Figure 3-1.

For the cometary and asteroidal meteoroids, the mass, m, of the largest encountered particle may be obtained from the flux model relating this mass to the numbers of encounters per area-time, N. These relationships are shown in the right-hand figure of Figure 3-1. The average number of encounters of mass, m, or smaller for a mission whose area-time is $A\theta$ is given as

$$\lambda = NA\theta \quad . \tag{1}$$

3.1 (Continued)

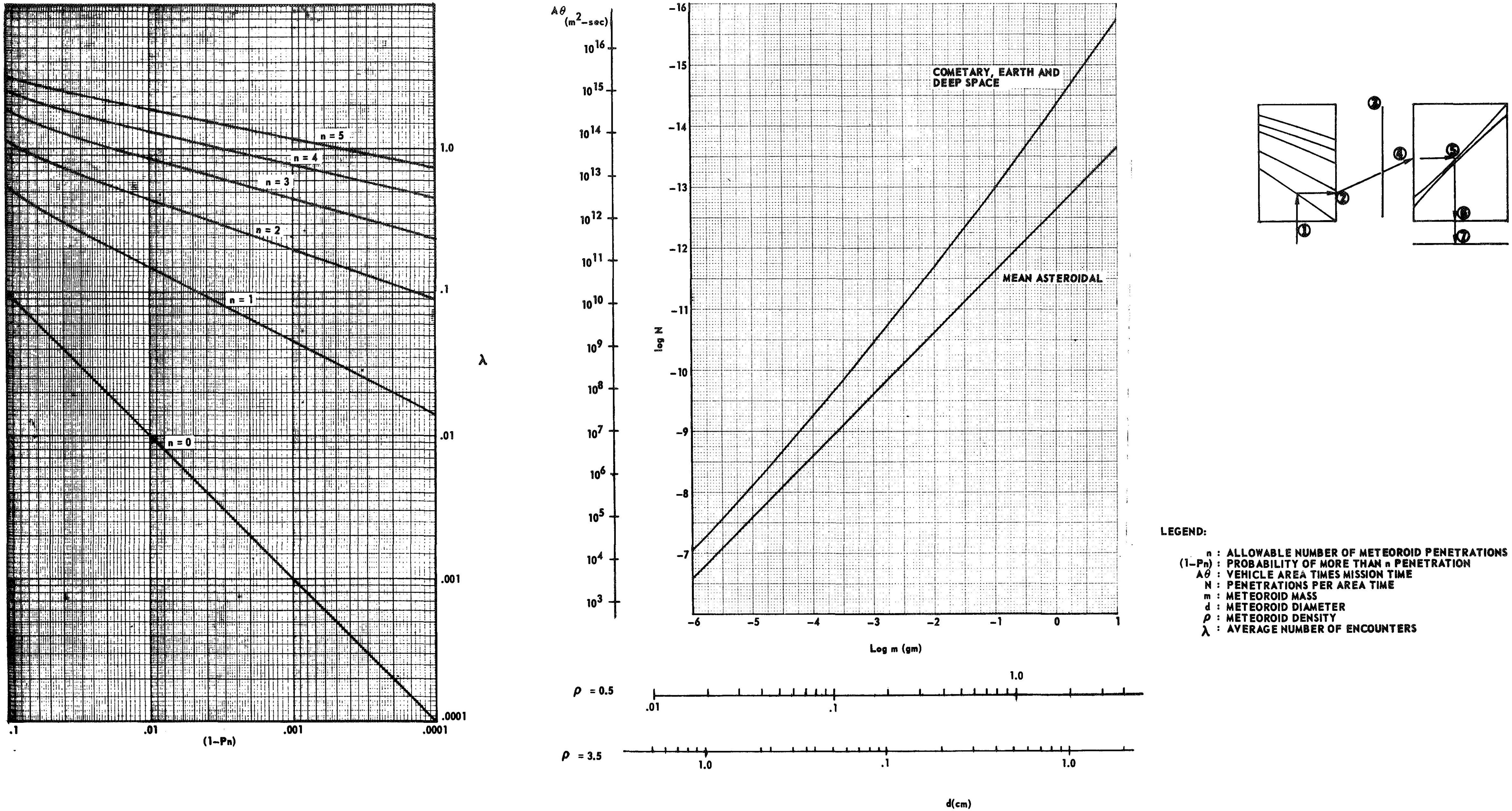

Figure 3-1. NOMOGRAPH FOR DETERMINING DESIGN SIZE METEOROID

3.1 (Continued)

Using a Poisson distribution, the average number of expected encounters is used to determine the probability of encountering any number of particles of mass, m, or smaller. This process of determining the design size particle is presented in Figure 3-1. A meteoroid shield reliability of 0.995 with no (zero) penetrations of the meteoroid shield was used in this study.

3.2 DESIGN ENVIRONMENTS - THERMAL ENVIRONMENT

For this study the ratio of the solar absorbtivity, α, to the emissivity, ϵ, has been taken as 0.20. For this ratio and for the defined mission categories, the average surface temperature for the mission vehicles are shown in Table 3-I.

Table 3-I. AVERAGE SURFACE TEMPERATURES

Orbital Conditions:	
Earth Moon	430°R
Jupiter	190°R
Space Flight; Earth to:	
Earth Moon	340°R
Jupiter	210°R

For determining insulation requirements, a nonvented propellant tank was considered; thus, variables used in evaluating insulation requirements include initial propellant condition, mission area-time, propellant volume, and final propellant vapor pressure.

3.3 DESIGN ENVIRONMENTS - STRUCTURAL ENVIRONMENTS

The integrated sidewall in this study was assumed to be pressure stabilized during Earth-launch. For a nuclear stage module, the ullage required for pressure stabilization was taken to be 35 psig, and the operational ullage pressure for the nuclear module as 10 psig. This operational pressure was assumed to be representative of nuclear vehicles, since a conservative estimate of the required ullage pressure is 5 psi over the propellant (LH_2) vapor pressure. The structure used during Earth-launch, but not required during nuclear stage operation, will be used as meteoroid protection and, if possible, thermal insulation.

Because of the possibility of generating high-pressure shock waves and causing tank rupture, no meteoroid debris is allowed to impact onto the tank wall. Therefore, the pressure vessel defined to sustain the 10 psig mentioned above will not constitute part of the meteoroid shield.

SECTION 4 - PARAMETRIC ANALYSES

4.0 GENERAL

This section presents analyses and evaluations of the qualities which constitute an efficient structure, meteoroid shield, and thermal insulation and the qualities of each which allow it to be integrated with the remaining two. First, the desired qualities of each system are enumerated, evaluated and analyzed; second, the combination of three sets of two subsystems each is analyzed; and finally, the evaluation of these three combinations is used to arrive at the desired features of an integrated system and the feasibility of integrating each subsystem into an integrated concept. The discussion that follows pertains primarily to a vehicle required for a Category 3 mission.

4.1 INDIVIDUAL SYSTEM FEATURES

4.1.1 Structural System

As stated in Section 3, the propellant tank sidewall is assumed to be a pressure stabilized structure; therefore, neglecting areas of discontinuity such as cylinder wall-to-bulkhead attachments, the cylinder can be designed to the full strength of the load-carrying material without regard for the modulus of elasticity of the material. Hence, the lightest structure will result from using a material with the highest strength-to-weight ratio. In the final analysis, consideration should be given to the state of biaxial stress existing in a cylindrical wall subjected to axial load and internal pressure, and an orthotropic structure designed to withstand this stress state. This is considered a refinement not relevant to this study.

4.1.2 Thermal Insulation System

It is generally accepted that the insulation required to accomplish a Category 3 type mission must have a thermal conductivity no greater than 10^{-4} BTU/HR-FT-^{o}F, or using present technology, the insulation must be of multilayer construction. Ideally a multilayer concept is used in an attempt to reduce solid heat conduction to a point where the principle mode of heat transfer is through radiation, and then to create surfaces with low absorbtivity and high emissivity (highly reflective surfaces) to reduce radiative heat transfer. Presently, such a system is constructed of very loosely packed, alternating layers of radiation shields (e.g., aluminized Mylar) and low-conductivity spacer material. The loosely packed construction increases the thermal resistance of the spacer material by decreasing the spacer contact area.

Regardless of the type of insulation used or the thermal conductivity, the thickness of required insulation is

$$t = \frac{(R \, \Delta T A \theta) K}{Q} \qquad (2)$$

where,

K = thermal conductivity,

4.1.2 (Continued)

R = ratio of total heat loss to insulation heat loss (accounts for insulation penetrations),

ΔT = temperature change between inner and outer surface,

A = total vehicle area,

θ = mission time, and

Q = allowable heat loss.

Multiplying each side of Equation (1) by insulation density, (ρ), the insulation areal density (weight per unit area) is given as

$$W_i = \frac{(K\rho)(R\Delta T A\theta)}{\left(\frac{Q}{M}\right) M} \qquad (3)$$

where

W_i = t x ρ, the areal density of the insulation, and

M = propellant mass.

Figure 4-1 shows the relationship between the final tank vapor pressure and the tank heat-load (Q/M) for various initial LH_2 propellant conditions. For a specified mission, Figure 4-1 may be used in conjunction with Equations (2) and (3) to determine insulation thickness and areal density for any combination of insulation thermal conductivity, final vapor pressure, and initial propellant condition.

4.1.3 Meteoroid Protection System

An extensive survey was made to arrive at a list of candidate configurations which would serve as a meteoroid shield. Shield configurations which were investigated include (in decreasing order of information available), thick plates, multiple sheets, multiple sheets with fillers, unbumpered low-density media, and bumpered low-density media. Next to thick plates, which are of no interest in this study, the most extensively evaluated shield configuration is a multiple sheet concept, and particularly, a two-sheet system. Basic investigation and test data appear in References 3, 4 and 5, and the application of such a concept to a specific vehicle appears in Reference 2. Data on multiple sheet configurations with fillers appears in References 3 and 6. Data on unbumpered and bumpered low-density media appears in References 7 and 8 respectively. Additional calculations on bumpered low-density media appear in Appendix A.

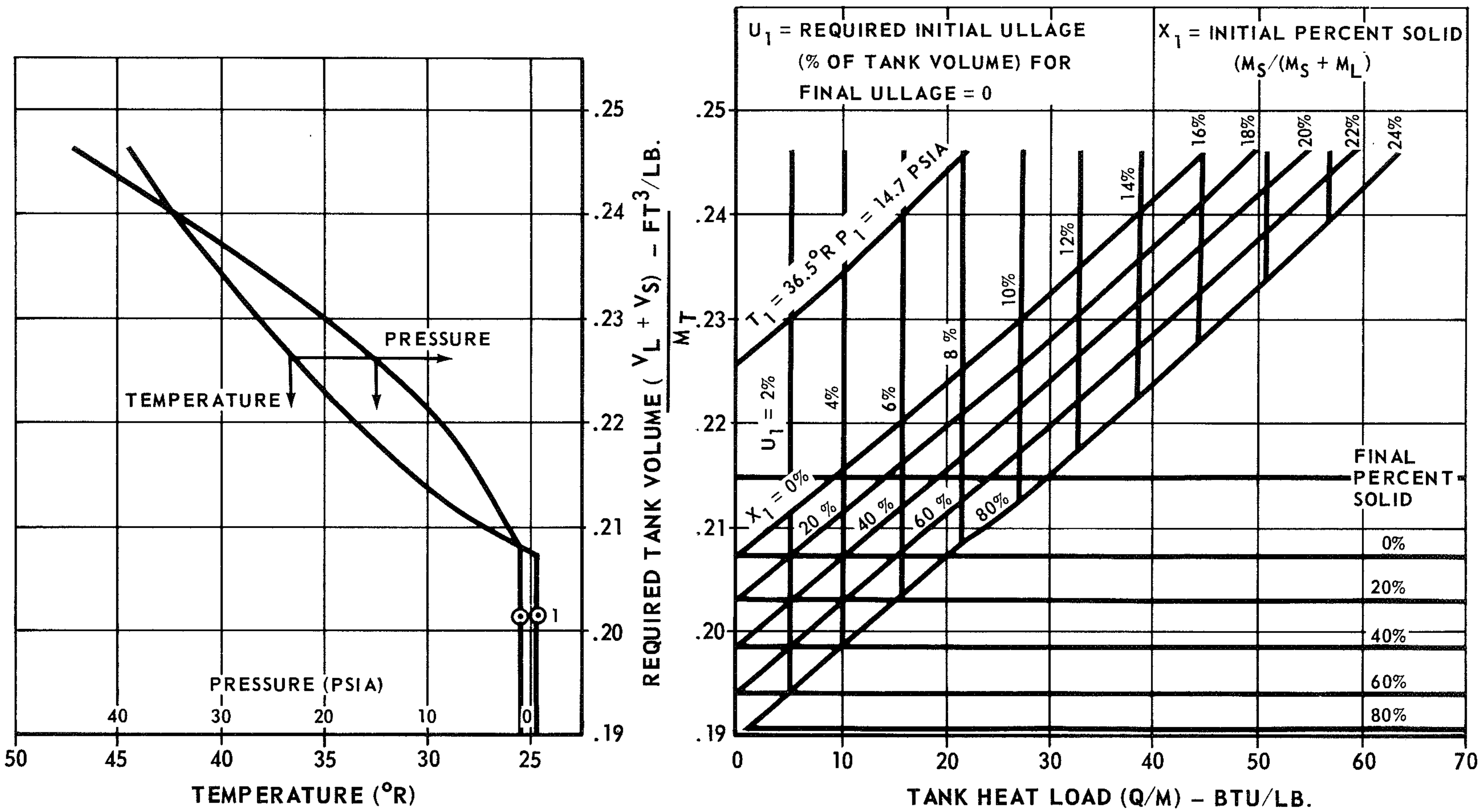

Figure 4-1. STORAGE CHART FOR NONVENTED HYDROGEN TANK

4.1.3 (Continued)

A comparison of the areal densities for an unbumpered low-density media, a bumpered low-density media, and a two-sheet aluminum shield is made in Figure 4-2 for one impact case. Curve I was taken from data appearing in Reference 7; curve II was derived from calculations appearing in Appendix A; curve III was derived from the following empirical formula from Reference 3,

$$\left(\frac{t_2}{d}\right)^{-7/12} = \frac{\left(\frac{V}{c}\right)^{4/3} \left(\frac{S}{d}\right)^{5/12}}{\left[2.42\left(\frac{t_1}{d}\right)^{-1/3} + 4.26\left(\frac{t_1}{d}\right)^{1/3} - 4.18\right]} \qquad (4)$$

where

t_2 = thickness of second sheet,

t_1 = thickness of first sheet,

d = particle diameter,

V = particle velocity,

C = sonic velocity for aluminum, and

S = sheet spacing.

Curves I and II represent data for a 1/16-inch diameter Pyrex sphere impacting at approximately 21,000 ft/sec whereas curve III represents data for a 1/16-inch diameter aluminum sphere impacting at approximately 21,000 ft/sec. For comparison purposes, the particle material discrepancy is not considered serious because each have approximately the same density.

Figure 4-2 indicates that, if thick enough, an unbumpered low-density media provides a more efficient meteoroid shield than does a two-sheet system. In fact, these data indicate that a low-density media will provide the lightest possible meteoroid shield of those considered.

For application of a low-density media to the three mission categories, scaling laws are applied to the data appearing in Reference 7. It was assumed that the areal density is proportional to the 1/2 power of the meteoroid density, the 2/3 power of the meteoroid velocity, and the first power of the meteoroid diameter. These scaling laws are consistent with other scaling laws for semi-infinite media. It was further assumed that media of equal density are equally effective in defeating a meteoroid. This relation is shown in Figure 4-3.

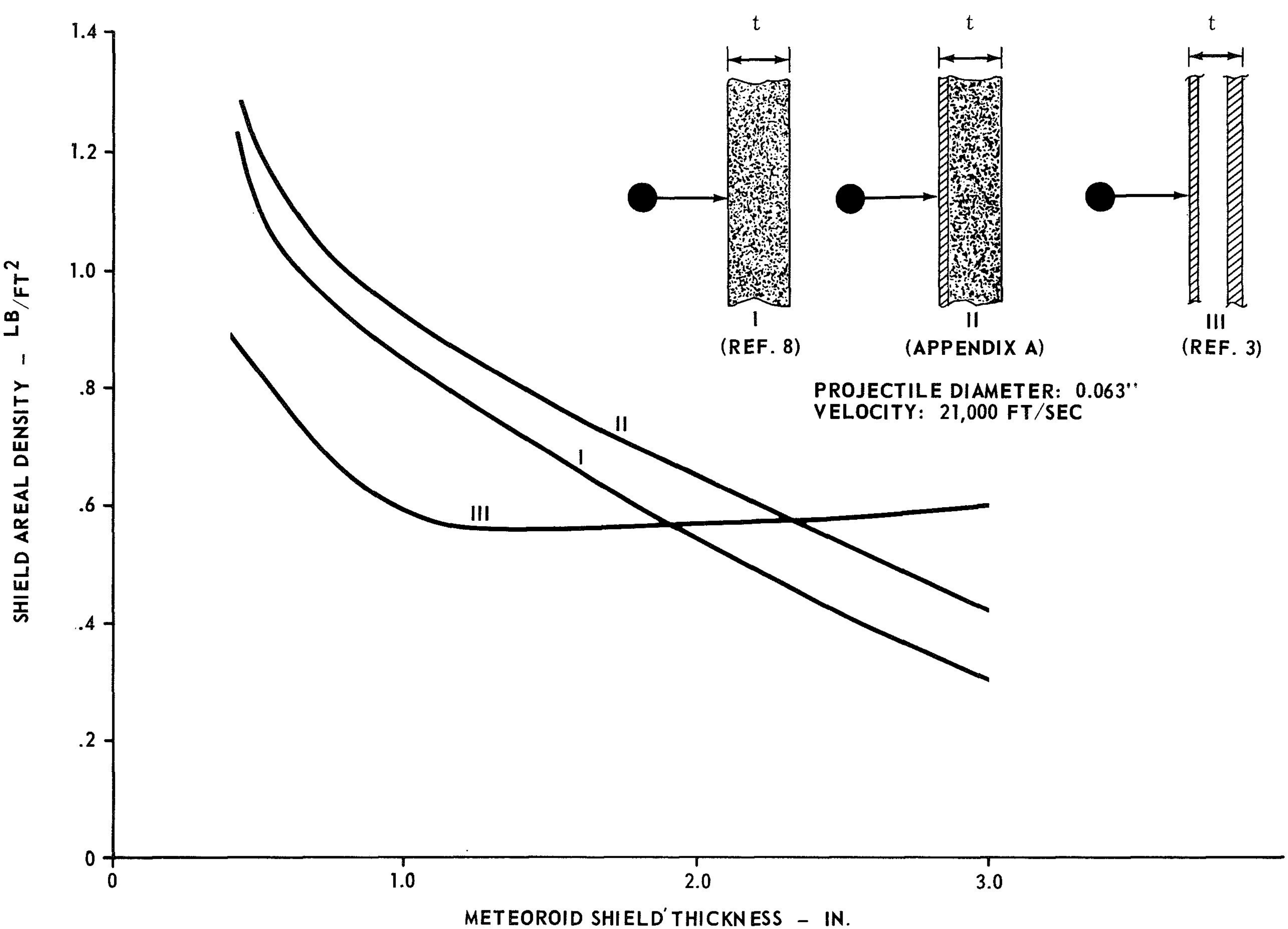

Figure 4-2. COMPARISON OF THREE METEOROID SHIELD CONFIGURATIONS

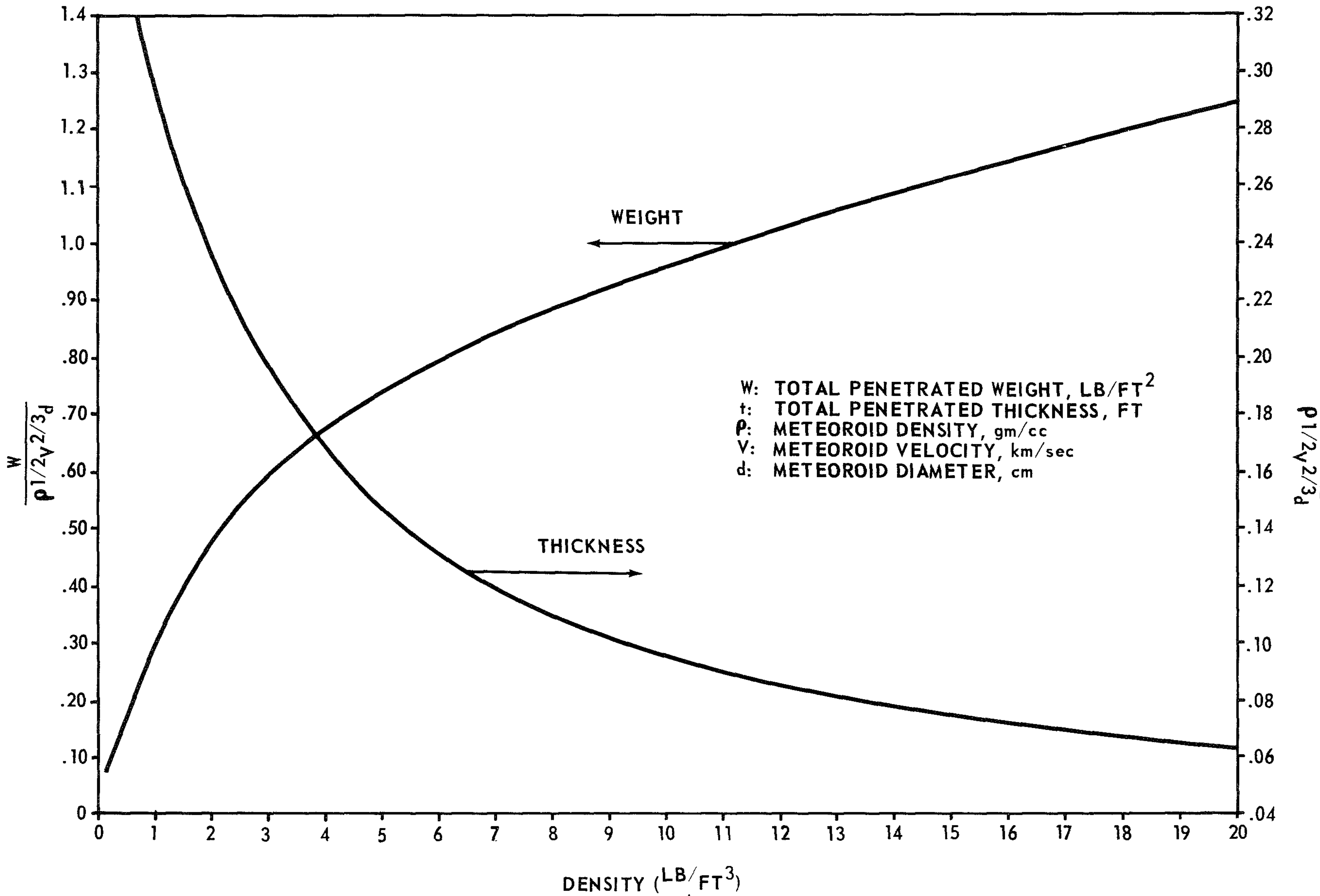

Figure 4-3. REQUIRED THICKNESS AND AREAL DENSITY FOR LOW-DENSITY METEOROID SHIELDS

4.2 COMBINED STRUCTURAL/METEOROID PROTECTION SYSTEM

The purpose here is to determine under what conditions structural and meteoroid protection requirements can be satisfactorily combined to meet both requirements. As stated above, only tension critical structures are considered; therefore, the load carrying material may be subjected to its full strength capacity and structural requirements are easily met.

Figure 4-2 indicates that a thick, low-density media provides the least possible meteoroid shield weight; therefore, the structural and meteoroid shield requirements are compatible because it is possible to incorporate structural requirements into a thick, low-density material. As examples, two methods of combining a structural and meteoroid protection system are shown in Figure 4-4.

In the absence of thermal gradients, it is easily verified that if the spacers shown in Figure 4-4(b) are thin or if their modulus of elasticity is high, then each load-carrying sheet is stressed almost equally. Furthermore, under these conditions the pressure distribution through successive spacers decreases linearly from inboard to outboard.

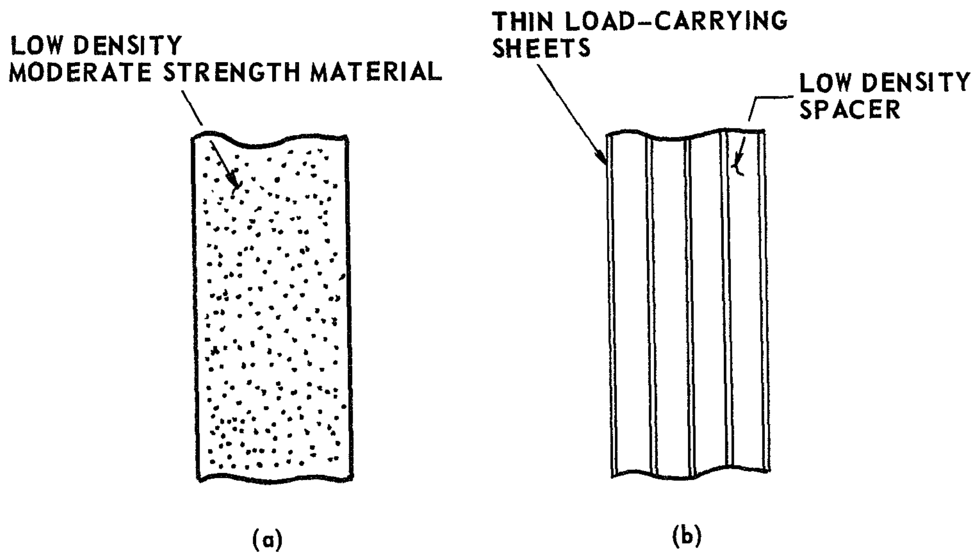

Figure 4-4. COMBINED STRUCTURAL/METEOROID PROTECTION SYSTEMS

4.3 COMBINED THERMAL INSULATION/METEOROID PROTECTION SYSTEM

Thermal insulation required on any of the mission categories should have as low a thermal conductivity as possible and should be as thick as possible to prevent heat flux into the cryogenic propellant, Equation (2). Obviously for a specified heat flux, trades may be made between the insulation thermal conductivity and the insulation thickness. A survey of insulating materials for cryogenic application (References 9, 10, 11, 12) indicates that, in general, low thermal conductivity and low density are synonymous. For example, low-density foams are known to increase in thermal conductivity as density increases. Multilayer concepts, being the most efficient insulation presently available, have also exhibited low densities (typically 1 to 4 lb/ft^3).

4.3 (Continued)

As indicated above, one of the most efficient meteoroid shields is a thick low-density media. It is obvious that this property of an efficient meteoroid shield is completely compatible with thermal insulation requirements. In fact, tests conducted in Reference 10 indicated that 2 lb/ft^3 multilayer insulation has a significant role in defeating a hypervelocity particle. One test point obtained during the present study, Appendix B, shows that 3.5 inches of a 1.7 lb/ft^3 multilayer can defeat a 1/16-inch diameter aluminum projectile with a velocity of 20,000 ft/sec.

The requirements for thermal insulation and meteoroid protection are noted to have two common quantities, namely the total insulation/shield thickness and the mean density. It is of interest to determine the relationship between the required insulation conductivity, K, and the insulation/meteoroid shield mean density, ρ. Rewriting Equation (2), the required thickness of thermal insulation is given as,

$$t = \frac{K\,Cm}{Q/M} \qquad (5)$$

where

$$Cm = \frac{R \Delta T A \theta}{M} \qquad (6)$$

and is related to a specific mission and vehicle. All terms are defined in Paragraph 4.1.2.

The meteoroid shield thickness/density relationship for a Category 3 mission is given approximately as (from Figure 4-3)

$$\rho\left(\frac{t}{d}\right)^2 = 5.8 \qquad (7)$$

where d, the meteoroid diameter, is a function of the shield reliability and ρ is measured in lb/ft^3, t in feet, and d in centimeters. Combining Equations (5) and (6) gives the thermal conductivity, density relationship for the combined thermal insulation/meteoroid protection system of a Category 3 mission. Thus,

$$\frac{CmK}{Q/M} = \sqrt{\frac{5.8}{\rho}}\ d. \qquad (8)$$

The specific heat flux, Q/M, is a function of the final vapor pressure and can be determined from Figure 4-1.

4.4 COMBINED STRUCTURAL/THERMAL INSULATION SYSTEM

From Equation (3), the required areal density of the thermal insulation is given as

$$W_i = \frac{(K\rho)(R \Delta T A \theta)}{\left(\frac{Q}{M}\right) M}.$$

The term $(R \Delta T\ A \theta)$ is a direct measure of the thermal severity of a mission, while the $(K\rho)$ term provides a measure of the insulation performance.

4.4 (Continued)

For a nonvented hydrogen tank using a destratification device, the tank vapor pressure, p, at the end of the storage period is determined by the initial hydrogen condition and the total mission heat leak per pound of hydrogen, Q/M. For a fixed amount of hydrogen, the final tank pressure may be reduced by using higher performance insulation, thereby reducing Q/M, or by loading hydrogen at a lower initial energy state (enthalpy). The relation between these parameters is shown in Figure 4-1 for initial propellant conditions ranging from an 80 percent solid hydrogen mixture to LH_2 saturated at one atmosphere pressure. A more detailed discussion of this figure may be found in Reference 12.

For determining the structural weight, the tank wall is assumed to be isothermal at a temperature of -420°F. The total thickness of the tank wall is therefore

$$t_w = \frac{(p + p_o)r}{\sigma_w} \tag{9}$$

where

σ_w = Yield strengths of tank wall,

p = Final LH_2 vapor pressure,

p_o = pressure differential required for propulsion system, and

r = tank radius.

Using a radius of 198 inches and assuming the tank wall is constructed of 2219-T87 aluminum, the structural weight is given as

$$W_s = \rho_{AL}\, t_w = 0.0435\,(p + p_o)\ \text{lb/ft}^2 \tag{10}$$

where p and p_o are in psi.

The combined structural/insulation weight is then

$$W_t = W_s + W_i = 0.0435\,(p + p_o) + \frac{(K\rho)(R\,\Delta T\,A\,\theta)}{\left(\frac{Q}{M}\right) M}\ . \tag{11}$$

For discussion purposes, p_o is taken as zero and Equation (11) has been plotted in Figure 4-5 for an initial 60 percent slush hydrogen condition for the Category 3 mission. Using Figure 4-1 and Equation (11), curves for other initial propellant conditions may be prepared. Total combined areal density for the structure and insulation is related to maximum tank vapor pressure (pressure at the end of the storage period) using insulation performance ($K\rho$) as the independent variable. It can be seen that a minimum weight point exists for any specified $K\rho$ and that this minimum, and its corresponding tank pressure, decrease with improved insulation performance (lower $K\rho$). However, the minimums are not well defined, particularly for the lower per-

4.4 (Continued)

CONDITIONS:
1. CYLINDRICAL LH_2 TANK 396" DIAMETER
2. 350,000 LB. LH_2 INITIAL LOAD
3. UNMANNED JUPITER MISSION (1000 DAYS)
4. NON-VENTED TANK WITH DESTRATIFICATION DEVICE

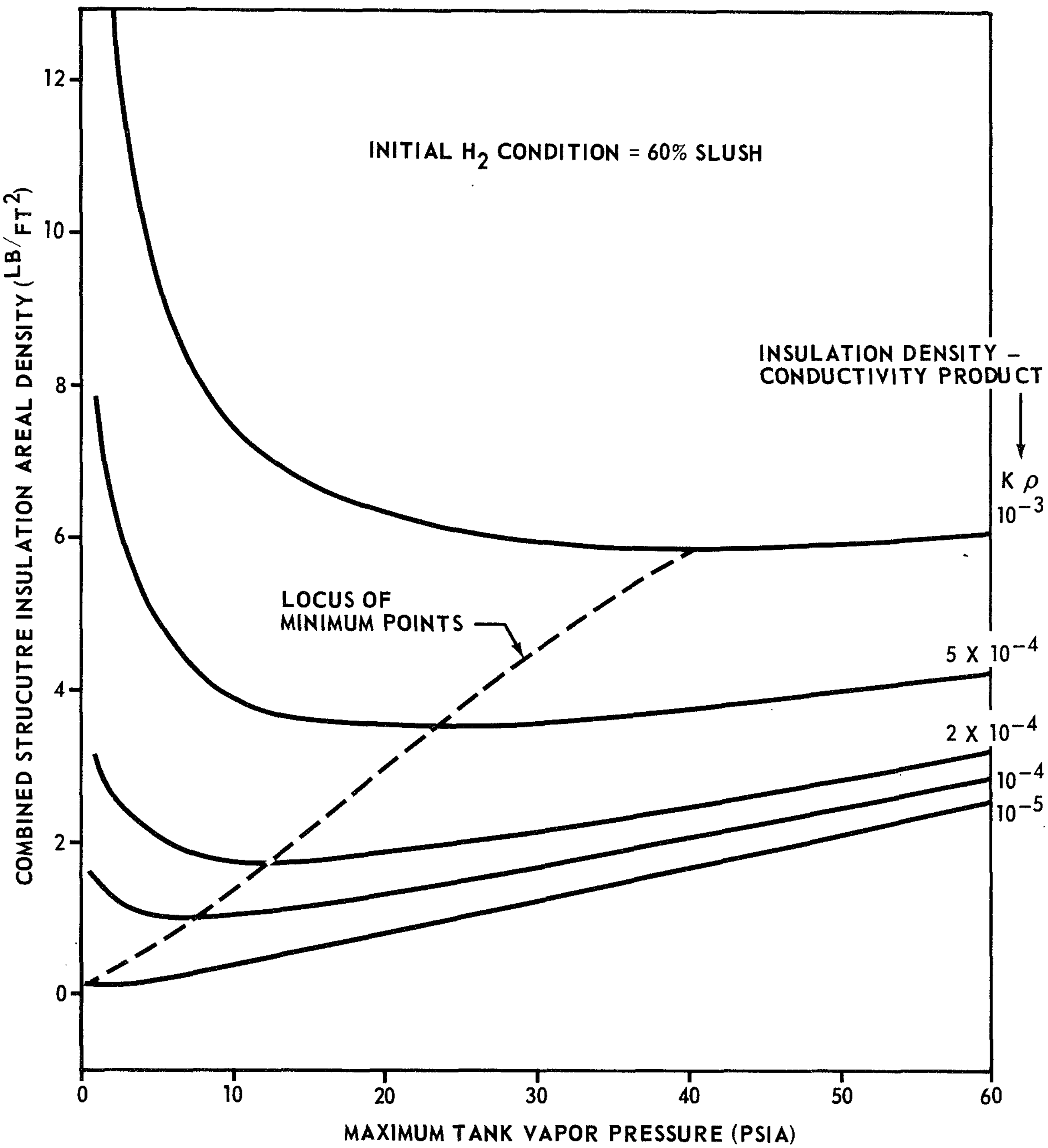

Figure 4-5. COMBINED STRUCTURAL/INSULATION WEIGHT - 60 % SLUSH LH_2

formance insulations, and little penalty is incurred within approximately $\pm$ 30 percent of optimum tank pressure. The locus of the minimum points is shown on each figure, and these locci have been replotted on Figure 4-6 along with lines of constant Kρ product to show the effect of initial hydrogen conditions on the structure and insulation

4.4 (Continued)

system combined weight. Figures 4-5 and 4-6 permit evaluation of the effects of insulation performance, initial energy state, and design pressure for the Category 3 mission. It is apparent from Figure 4-6 that significant weight savings can be realized for a given insulation (constant $K\rho$) by loading hydrogen at a lower initial energy state and designing the tanks for a lower pressure. An apparent contradiction exists in Figure 4-6, indicating that at a constant tank pressure, the combined weight increases as the initial energy state is lowered. As indicated by the lines of constant $K\rho$, this weight increase results from greater required insulation weight; i.e., lowering the initial energy state for a fixed tank design requires a higher heat leak to obtain the same design pressure, which in turn is accomplished by using lower performance insulation.

The above discussion is somewhat academic since it was assumed that structural requirements may be physically combined with thermal insulation requirements. In fact the requirements of these two systems are incompatible with materials technology at its present state. The reasons leading to these conclusions are discussed in the following paragraph.

As previously stated, the only practical insulation for a Category 3 mission is a multilayer concept. Because, historically speaking, the materials of structural components have an extremely high thermal conductivity when compared to multilayer, these components themselves cannot be efficiently used as insulation. One possible solution to the implied problem is to use load-carrying members as radiation shields. However, by definition, the spacer material must transfer pressure to successive radiation shields. Because this will produce a large, positive contact area between shield and spacer, one of the essentials of multilayer insulation is lost. It is thus concluded that unless an extremely low conducting material is obtained for a spacer, structural and thermal insulation requirements cannot be combined.

4.5 CONCLUSIONS OF PARAMETRIC ANALYSES

4.5.1 Category 1

A Category 1 mission is typified by a small area-time factor, and neither the thermal nor the meteoroid environment is expected to be very severe. It is anticipated that both requirements can be met with the configuration shown in Figure 4-7. In this configuration, the combined insulation, meteoroid shield is a low-density, low-conductivity material. A multilayer could serve this purpose.

4.5.2 Category 2

A Category 2 mission is typified by a moderate area-time factor for which the meteoroid environment is expected to be dominant over the thermal environment. For such a case, a meteoroid bumper could be placed external to the meteoroid shield shown in Figure 4-7. If the propellant tank is not designed for a specific heat flux, however, a lighter system can be realized by adding additional low-density material instead of a bumper. Such a concept is shown in Figure 4-8. Figure 4-3 may be used to determine the total required meteoroid shield thickness.

4.5 (Continued)

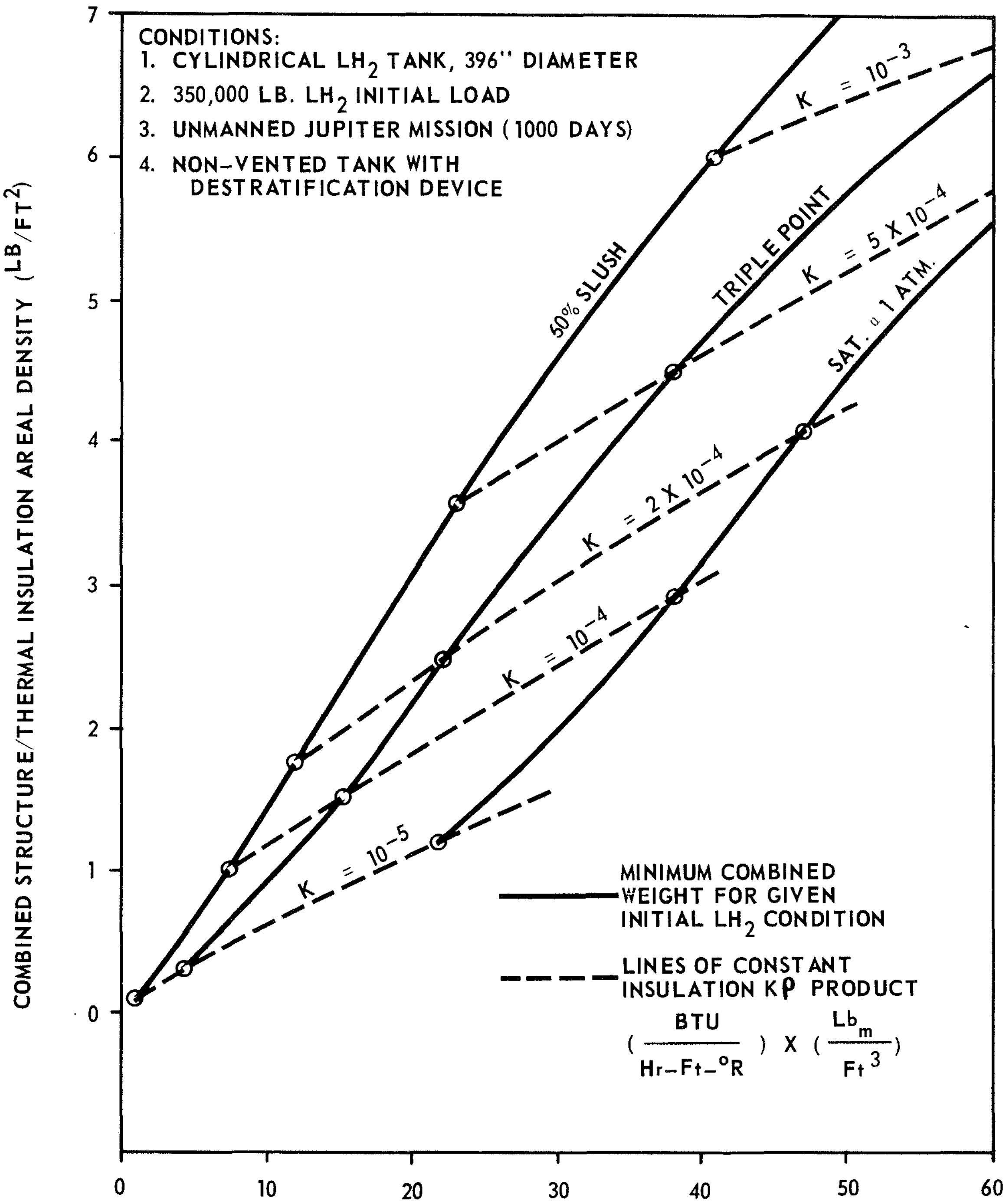

Figure 4-6. COMBINED STRUCTURAL/INSULATION WEIGHT MINIMIZATION

4.5 (Continued)

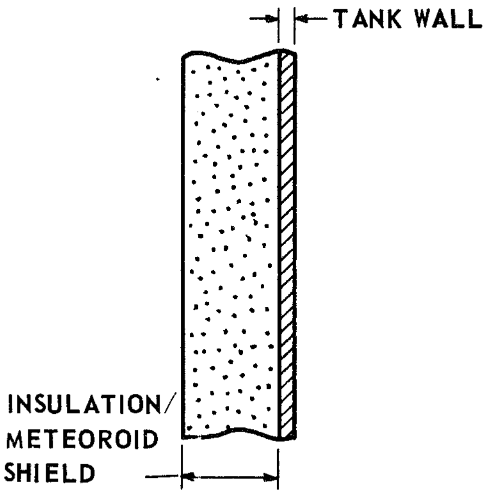

Figure 4-7. GENERAL CATEGORY 1 CONCEPT

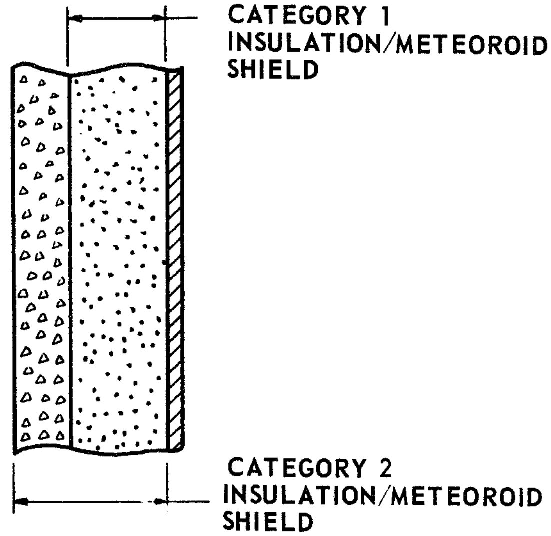

Figure 4-8. CATEGORY 2 CONCEPT

4.5.3 Category 3

A Category 3 mission is typified by a mission with a large area-time factor for which a meteoroid shield and thermal insulation superimposed upon a basic shell structure would represent such a weight penalty as to degrade or preclude the mission objectives. From the discussions above, it is concluded, a) that meteoroid shield requirements can best be met by using a thick, low-density material; b) that thermal insulation requirements can best be met by using a multilayer concept or by using a material with an extremely low solid conductivity; c) because a pressure stabilized structure is assumed, structural requirements are easily satisfied.

SECTION 5- INTEGRATED CONCEPTS

5.0 GENERAL

Presented in this section is a class of concepts which integrate the requirements, as set forth in Section 4, of the structure, meteoroid shield, and thermal insulation subsystems into a common sidewall for the Category 3 mission. Concepts are presented with the assumption that materials required for the concepts are available. Areal densities for the integrated concepts are compared to those required for a conventional concept with all concepts being designed for the requirements of a Category 3 mission as defined in Paragraph 3.0.

5.1 BASIC INTEGRATED CONCEPT

For the required features of the structural, meteoroid protection, and thermal insulation subsystems as presented in Section 4, the most probable concept for satisfying these requirements appears to be a basic multiwall concept. This concept is depicted in Figure 5-1 and consists of a number of thin, load-carrying sheets separated by spacer materials which transfer pressure load to successive sheets. The spacers are assumed to be a very low heat-conducting material so that the system acts similarly to a conventional multilayer concept. The resulting thick, low-density media acts as a meteoroid shield.

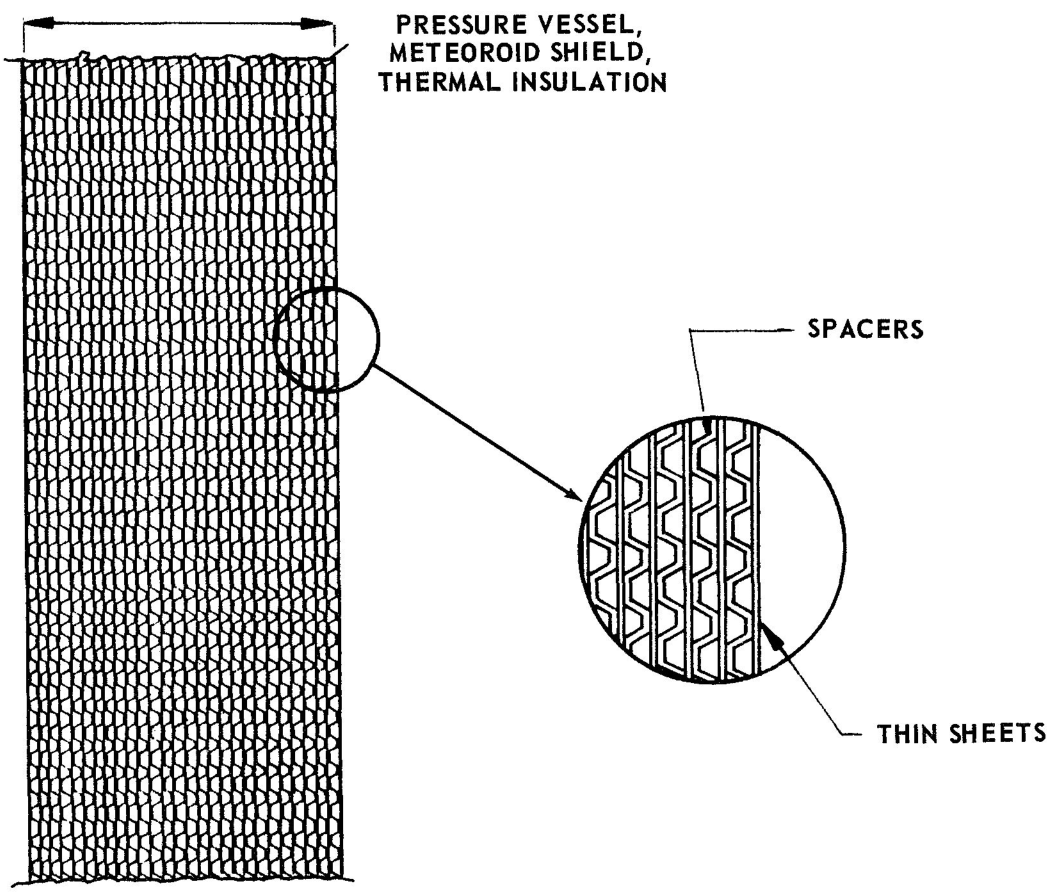

Figure 5-1. FULLY INTEGRATED SYSTEM

5.1 (Continued)

For such a concept it can be shown that if the mean radius of the wall is large in comparison to the thickness of the wall and if the ratio of the spacer thickness to the spacer modulus of elasticity (in radial direction) is small, then the stress in each load-carrying sheet is approximately equal, and that the pressure distribution through successive spacers decreases linearly from inboard to outboard. Since the spacers near the exterior of the wall are subjected to a lower pressure than those near the interior, the allowable strength of these spacers can be less.

In a multilayer concept where the spacers have a high thermal resistance and radiation heat transfer is on the same order as solid head construction, the first few layers of insulation reduce the heat flux by a larger percentage than the remaining layers combined. If the spacer material in the multiwall concept has a high thermal resistivity, then it will perform in much the same manner as a true multilayer and, therefore, the first few layers will be most effective in reducing heat flux. For this reason, special attention should be given to the outboard load-carrying sheets to ensure that they, in particular, have high emissivities and low absorbtivities. As indicated above, meteoroid protection can be obtained from the thick, low-density sidewall containing the structural and insulation components. Properties desirable as meteoroid shielding in such a concept are discussed below.

The damage resulting from the impact of a hypervelocity meteoroid on a shield can be separated into two distinct categories. These are, the damage caused by the impact induced shocks, and that caused by the debris cloud of the shattered meteoroid. The damage caused by debris clouds in low-density materials is readily observed as being an elongated void; damage from impact induced shocks results from these shocks being reflected from material interfaces and free boundaries. Spall is a typical example. These shocks can also be beneficial. When a meteoroid impacts onto a shield, shock waves are initiated, the strength of which depends on the meteoroid and shield materials. No matter what the strength of the shock, the kinetic energy of the meteoroid is reduced by the amount of energy contained in the expanding shock. Therefore, the stronger the initial shock, the lower the debris kinetic energy and the less the damage from the debris. Thus the outer surface of the meteoroid shield should be a material which induces a strong shock in the shield. The remainder of the shield should be a low-density material.

5.2 DESIGN CRITERIA

The integrated concepts presented are applicable to a Category 3 mission. As previously indicated, such concepts must be considered at the inception of a vehicle and, by definition, are not applicable to a Category 1 and 2 mission.

During Earth-launch of a vehicle using an integrated concept, it is assumed that the structure is pressure stabilized. Experience has indicated that the tank ullage pressure required for pressure stabilization of a 350,000 pound nuclear stage is approximately 35 psig. For operation of the vehicle propulsion system in space, a conservative estimate of the required ullage pressure is 5 psig above the propellant vapor pressure; therefore, operational ullage pressure is taken as 10 psig.

5.2 (Continued)

By definition, the Category 3 mission is a 1000 day, unmanned Jupiter mission using a 350,000 pound nuclear stage. It is estimated that 300 days of such a mission will be spent in the Asteroidal Belt, and due to the size and density of the asteroidal meteoroids, this meteoroid environment will determine the meteoroidal shield design. The expected meteoroid density is 3.5 gm/cc and the velocity is approximately 7.8 km/sec. For a 0.995 probability of no meteoroid shield penetrations, the design particle has a diameter of 0.84 centimeters. For the Category 3 mission, the time average temperature of the external surface is 210^{o}R. It is assumed that the initial propellant condition is 60 percent slush and that the final vapor pressure is 5 psia.

5.3 DESIGN PROCEDURE

Using data similar to that of Section 4, a design procedure can be prepared for determining parameters yielding a minimum weight integrated system. This procedure is as follows:

a. Select initial propellant condition and final propellant vapor pressure;

b. From Figure 4-1, determine Q/M for above conditions;

c. From Figure 4-5, determine insulation $K\rho$;

d. Using this $K\rho$ and Equation (8), determine the insulation/meteoroid shield density, P;

e. Substitute back and determine insulation K value;

f. Use Equation (2), to determine insulation/meteoroid shield thickness, t;

g. Iterate as required.

5.4 SELECTED INTEGRATED CONCEPTS

There are probably an unlimited number of detailed multiwall concepts which could be designed to accomplish the Category 3 mission, and since it was not the purpose of this investigation to perform complete trade studies for a multiwall concept, only a selected integrated concept will be presented. As stated above, it is assumed that ullage pressure at Earth-launch is 35 psig, while at stage ignition it is 10 psi. Therefore, the material required for Earth-launch but not required for stage operation will be used as meteoroid shielding. Since no meteoroid debris can be allowed to impact onto the stage tank wall, this material will in fact constitute the meteoroid shield.

The procedure outlined in Paragraph 5.4 was followed to determine the parameters of a minimum weight system for the Category 3 mission. These results indicate that minimum weight will occur for an insulation/metoroid shield density of approximately 0.25 lb/ft^3, and requiring a thickness of 46 inches. Both these dimensions are considered to be impractical.

5.4 (Continued)

Figure 5-2 shows a comparison of the areal densities of an integrated system and a conventional system required for a Category 3 mission; the basis of comparison is taken as the total sidewall thickness. The configurations being compared are shown in Figures 1-1 and 5-1. As may be deduced from Figure 5-2, it cannot be unequivocally stated that an integrated system is always more efficient than the conventional system. However, using the procedures presently available for designing a conventional system and the data available for estimating the weight of an integrated system, it appears that a weight savings as high as 50 percent can be obtained if the thickness of the integrated system can be tolerated. It is difficult to state whether this estimate is conservative or not since it is anticipated that future detailed design studies will allow weight reduction. However, additional hypervelocity impact tests may reveal a requirement for more meteoroid shielding than is now estimated.

5.5 MATERIAL REQUIREMENTS

Presented below is a range of physical and mechanical properties that is required in the construction of an integral multiwall concept. Following this list are explanations of each item.

E, Skin :	No bounds
E, Spacer :	$\geq p \times 10^4$, (p = tank operating pressure)
ρ, Skin :	0.04 to 0.30 lb/in^3
ρ, Spacer :	$\leq$ 15.0 lb/ft^3
t, Skin :	0.001 to 0.10 inch
t, Spacer :	0.03 to 0.25 inch
σ, Skin :	30 to 150 ksi
σ, Spacer :	$\geq p$
K, Spacer :	$< 10^{-4}$ $\frac{\text{BTU}}{\text{FT-HR-}^{\circ}\text{F}}$

5.5.1 Modulus of Elasticity for Skins

The multiwall concept is expected to be designed as a tension critical structure; therefore, the modulus increases in importance only in areas where the multiwall configuration attaches to other vehicle components. Because the skins of the multiwall concept are designed by tensile strength properties rather than stiffness properties, the modulus of the skins is not a prime consideration.

5.5.2 Modulus of Elasticity of Spacer

In a linear analysis of a multiwall concept, small strains are assumed to exist in all constituents under application of load. It is not absolutely necessary to restrict the constituents to small strains; however, the analysis becomes considerably more complex when large strains are allowed, because a nonlinear analysis is then required. To ensure small strains in the spacer material, the minimum allowable modulus of elasticity for the interior spacers is approximately the maximum tank operating pressure times 10^4. The modulus can be decreased linearly from inboard to outboard.

5.5.2 (Continued)

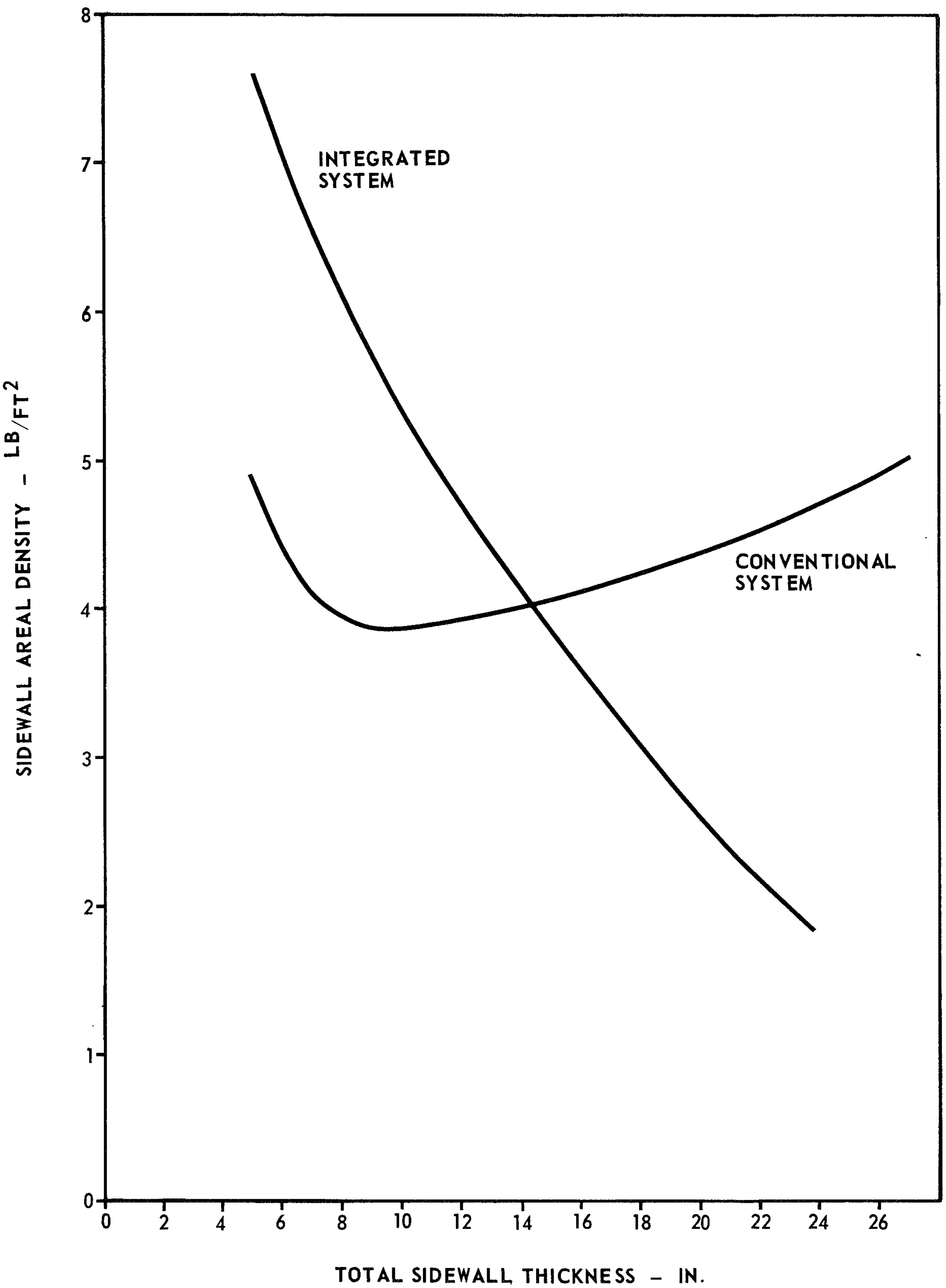

Figure 5-2. COMPARISON OF SIDEWALL AREAL DENSITY FOR CATEGORY 3 MISSION

5.5.3 Skin Density

The variety of materials available for use as a pressure container is almost unlimited; however, a probable range of material densities for this application is taken to be 0.04 to 0.30 lb/in^3. The former represents fiberglass and the latter, steel.

5.5.4 Spacer Densities

The spacer density is used, in part, to adjust the mean density of the multiwall configuration for meteoroid shielding purposes. For the lightest weight meteoroid shield, the multiwall configuration should be the lowest possible density. Therefore, no lower limit is set on the density of the spacer. The upper limit on the density is set at 15 lb/ft^3, but further testing may reveal that higher densities can be used (Appendix B).

5.5.5 Skin Thickness

The mean density of the multiwall configuration must be low. Therefore, numerous thin, load-carrying sheets should be used. From handling and other practical considerations, the lower limit on the thickness is set at 0.001 inches. No thickness greater than 0.10 inches is anticipated in the multiwall design.

5.5.6 Spacer Thickness

To meet the requirement of low multiwall density, many spacers will be required to separate the load-carrying sheets. The thicker these spacers, the lower the mean density can be driven; however, the thicker the spacer, the more heterogeneous the configuration becomes. The probable range of spacer thickness is expected to be 0.030 to 0.25 inches.

5.5.7 Skin Strength

Like the range of skin densities, the range of skin strengths is almost unlimited. The probable range of skin strengths is expected to be 30 to 150 ksi.

5.5.8 Spacer Strength

In a small strain analysis of a multiwall configuration, the radial pressure distribution in the spacer material varies approximately linearly from the inner to outer spacer. For a configuration with many spacers, the inner spacer must sustain a pressure only slightly less than the tank operating pressure. Therefore, for the inner spacers, the minimum compressive strength must be equal to or greater than the maximum operating tank pressure. The allowable strength can decrease linearly towards the outboard spacers.

5.5.9 Spacer Thermal Conductivity

Because long-term space missions require extremely high thermal insulation efficiencies, the multiwall configuration is required to have a thermal conductivity not greater than 10^{-4} BTU-FT/HR-FT^2-^oF. Because the load carrying constituents of the multiwall are not expected to have low conductivities, the thermal conductivity of the spacer material must be equal to or less than 10^{-4} BTU-FT/HR-FT^2-^oF.

SECTION 6 - INTEGRATED SYSTEMS TEST PLAN

6.0 INTEGRATED SYSTEMS TEST PLAN

A test plan to verify the analytical results obtained in this study is presented below. The testing involves the study of response of a selected integrated concept to the structural load and meteoroid impact environments. A total of five specimens will be used to perform the tests. Each specimen has been designed for use both as a structural test specimen and a hypervelocity impact specimen. No thermal insulation tests are included.

6.1 TEST SPECIMEN ANALYSIS

The design criteria and material requirements established in Paragraphs 5.2 and 5.5 were used to define the selected integrated structural-meteoroid protection tank wall system for test. Figure 5-2 shows that for tank walls designed to the environment specified in Paragraph 5.2, the weight of the selected multiwall concept is equal to the weight of a conventional system when the total thickness of the multiwall is approximately 14.5 inches. As the thickness is increased (and areal density decreased) the multiwall concept offers a significant weight savings over the conventional tank wall system. For this study, the cross-over point of the curves in Figure 5-2 was used to select the integrated concept to be tested. The significant design parameters for this wall are:

a. Design pressures:

   1. 35 psig during launch phase,
   2. 10 psig during space operation;

b. Total tank wall thickness - 14.5 inches;
c. Radius to mid-plane of wall - 205.5 inches;
d. Design meteoroid diameter - 0.331 inches;
e. Density of meteoroid - 0.126 lb/in^3;
f. Meteoroid velocity - 25,600 ft/sec.

The material selected for the tank wall is 2219-T87 aluminum alloy.

The tank wall was designed so that the innermost sheet would sustain the 10 psig internal pressure in space. The outer sheets in the wall were then designed to sustain the remainder of the 35 psig launch pressure. To make the test specimens feasible from the standpoint of fabrication, the number of outer sheets was limited to 10. The resulting tank wall parameters are:

a. Thickness of the inner sheet - 0.040 inches;
b. Thickness of each outer sheet - 0.010 inches (10 required);
c. Thickness of each filler - 1.45 inches (10 required);
d. Modulus of elasticity of sheets - 10.5 x 10^6 psi;
e. Modulus of elasticity of filler $\geq$ 25,000 psi.

6.1 (Continued)

Because the possibility of full-scale testing such a large specimen is not feasible, models were designed for experimental verification of response of the prototype to structural loading and meteoroid impact. Model design equations were developed from dimensional analysis theory. The models were based upon a linear scaling relation between the total wall thickness of the model and prototype. The scale factor selected was 10. To fully satisfy the design conditions of the prototype, the following significant characteristics are required in the model:

a. Design pressures:

1. 35 psig for launch phase,
2. 10 psig for space operation;

b. Total wall thickness - 1.45 inches;
c. Radius to mid-plane of wall - 20.55 inches;
d. Thickness of inner sheet - 0.004 inches;
e. Thickness of each outer sheet - 0.001 inches (10 required);
f. Thickness of each filler - 0.145 inches (10 required);
g. Sheet material - 2219-T87 aluminum alloy;
h. Modulus of elasticity of filler $\geq$25,000 psi;
i. Impact particle diameter - 0.033 inches;
j. Impact velocity - 25,600 ft/sec;
k. Density of impact particle - 0.126 lb/in^3;
l. Density of filler material - 2.0 lb/ft^3.

It is possible to satisfy all model requirements with available materials. For example, the impact particle could be made from foamed nickel. There is some difficulty, however, in meeting the requirements of the filler material used in the model. In addition to density and modulus requirements, it is probable that there is a relation between particle size and maximum void size in the filler if the filler is to be effective in defeating the meteoroid. A plastic foam would satisfy the density and void size requirements for the model of the impact particle, but low-density foams do not currently possess the required stiffness to transmit the pressure loading to the aluminum sheets in the multiwall. Hence it was necessary to design a composite material consisting of alternate layers of aluminum foil and urethane foam as shown in Figure 6-1.[1] The calculated density and elastic modulus for this composite are respectively 2.0 lb/ft^3 and 46,000 psi.

6.2 TEST SPECIMENS

The configuration of the test specimens is shown in Figure 6-2. The specimens are 16 x 16-inch multiwall cylindrical panels formed on a 19.80-inch radius. The edge of

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1 As noted in Figure 6-1, the aluminum foils in the composite are perpendicular to the load-carrying sheets; this is required to obtain the proper radial stiffness in the composite.

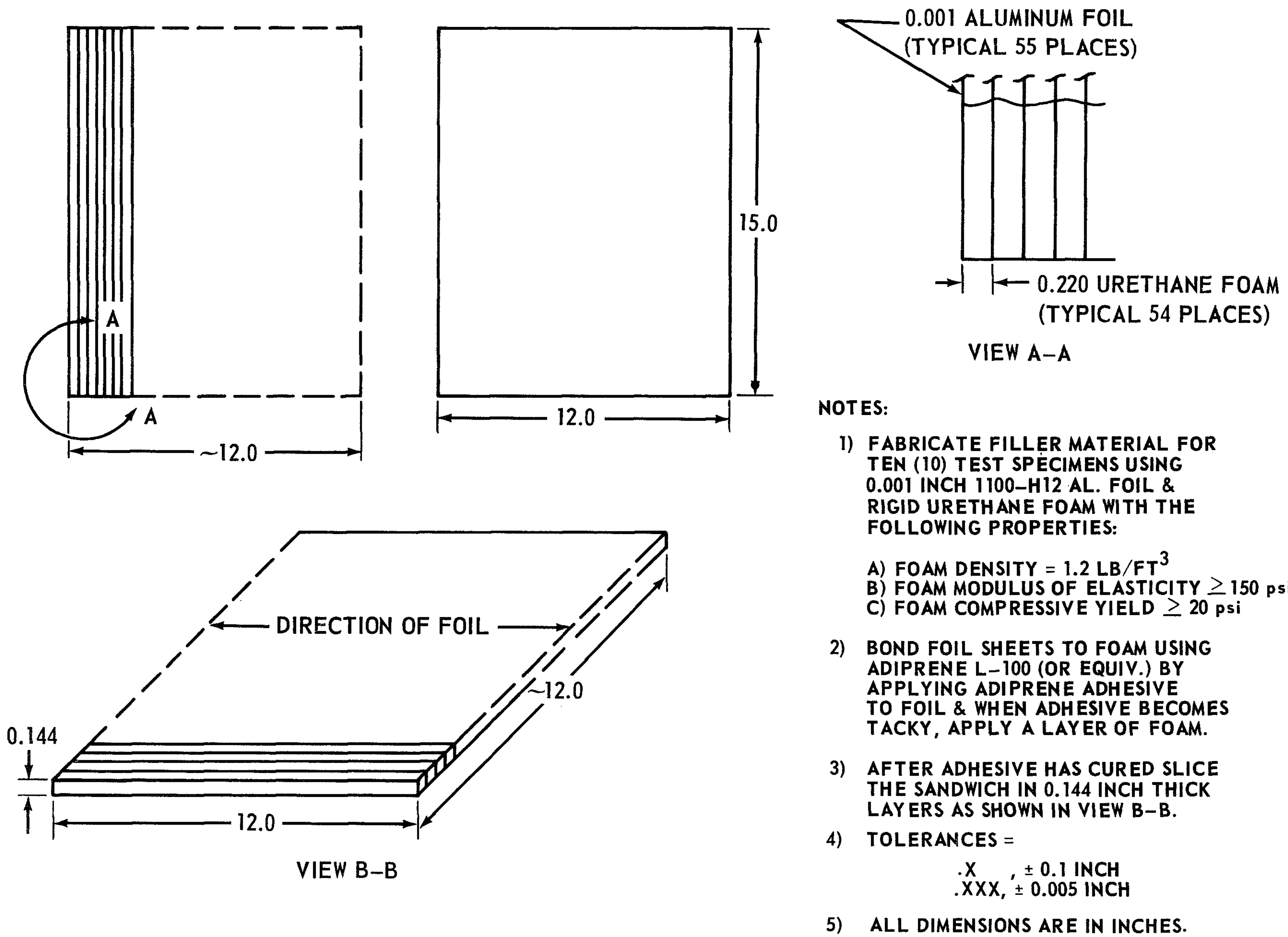
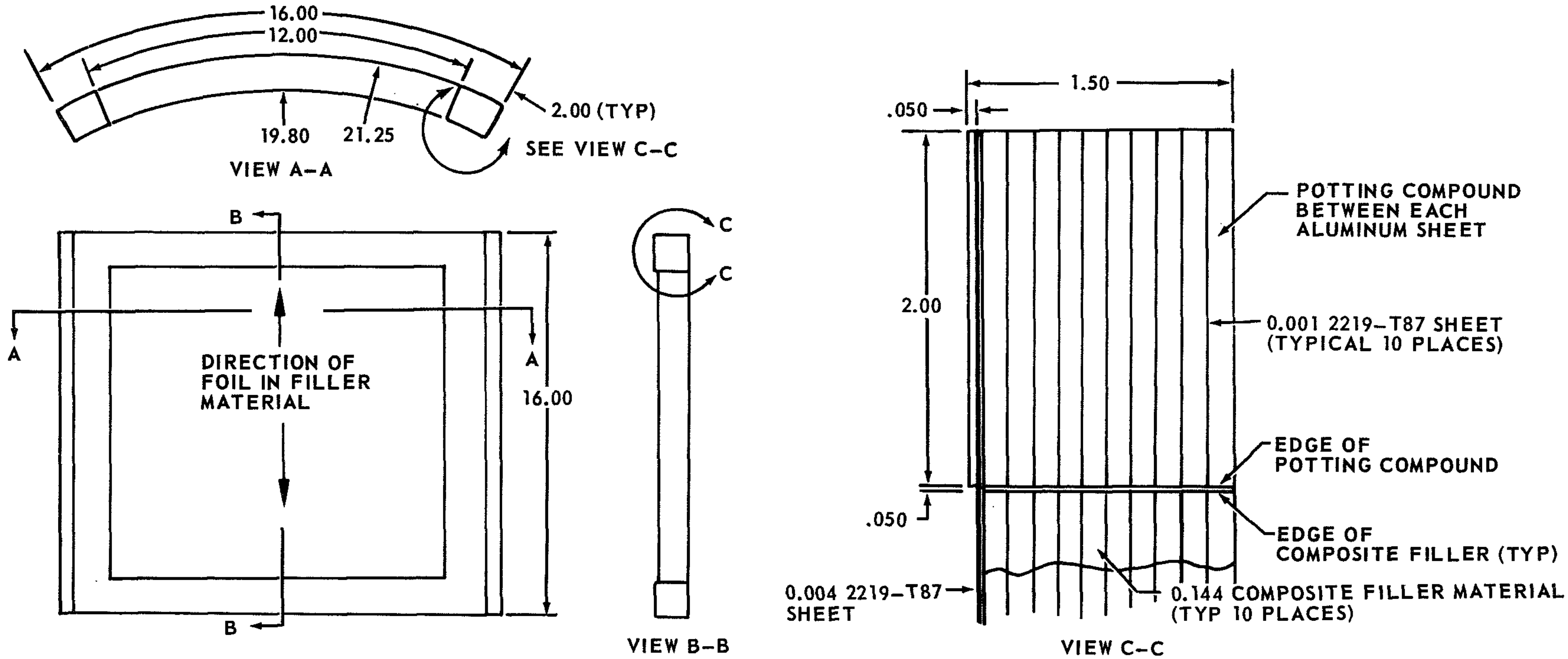


Figure 6-1. INTEGRATED STRUCTURAL/METEOROID PROTECTION TANK WALL MODEL, COMPOSITE FILLER MATERIAL DETAILS



1) FABRICATE TEN (10) TEST SPECIMENS USING COMPOSITE FILLER MATERIAL, 0.001 INCH 2219-T87 (10 SHEETS PER SPECIMEN), & 0.004 INCH 2219-T87 (1 SHEET PER SPECIMEN).

2) EACH SPECIMEN SHALL BE FABRICATED BY STACKING ALTERNATE LAYERS OF 2219-T87 FOIL & COMPOSITE FILLER MATERIAL. STRAIN GAGE INSTRUMENTATION SHALL BE INSTALLED IN THE SPECIMENS DURING ASSEMBLY AS SHOWN IN FIGURE 6-6.

3) THE EDGES OF THE SPECIMENS SHALL BE POTTED WITH ADIPRENE L-100 (OR EQUIV) AS SHOWN IN VIEW C-C. THE POTTING PROVIDES FOR ATTACHMENT OF SPECIMEN TO LOAD FIXTURE & SEALING SURFACE ON INSIDE RADIUS.

4) TOLERANCES:

.XX ,± .05
.XXX ,± .010

5) ALL DIMENSIONS ARE IN INCHES.

Figure 6-2. INTEGRATED STRUCTURAL/METEOROID PROTECTION TANK WALL MODEL, TEST SPECIMEN DETAILS

6.2 (Continued)

each specimen is potted with Adiprene L-100 to provide an attachment to the loading fixture as shown in Figure 6-3. The effective test section of each panel is a 12 x 12-inch area. The external surface of 0.001-inch aluminum sheet will be subjected to initial impact by the simulated meteoroid.

6.3 TEST SETUP

Each panel will be installed in the test fixture as shown in Figure 6-3. Specimen loading will be applied to the inner surface of the specimen through a pressurization system connected to the test fixture. It is recommended that the test fixture be installed in a light-gas gun range tank as shown in Figure 6-4. The range tank would be evacuated during impact testing. Pressurization of the specimen will be accomplished at room temperature and liquid nitrogen temperature.

6.4 TEST CONDITIONS

6.4.1 Test Number 1

One test specimen will be mounted in the test fixture as shown in Figure 6-3 and subjected to a maximum hydrostatic pressure of 30 psig. The pressure will be applied in 5 psig increments. Test specimen strain and deflection data will be monitored at each increment of loading and deflections will be checked against predicted deflections shown in Figure 6-5. The analysis used in these predictions is discussed in Appendix C.

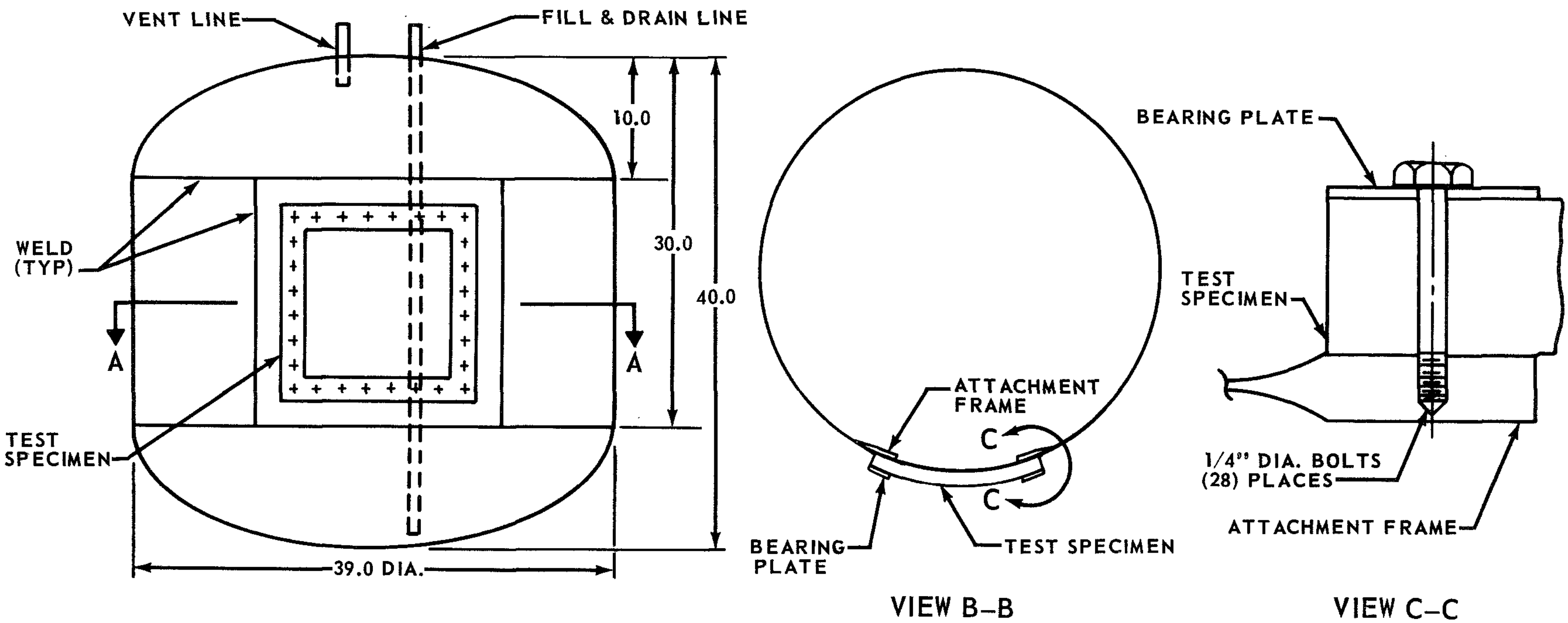
6.4.2 Test Number 2

Upon completion of Test Number 1, the pressure in the test fixture will be reduced to 10 psig maximum. The range tank will be evacuated to the pressure required for launching the model impact particle defined in Paragraph 6.1, and the particle launched against the test specimen.

6.4.3 Test Numbers 3 Through 6

Upon completion of Test Number 2, the test specimen will be mounted in the test fixture as shown in Figure 6-3. The range tank will be purged with gaseous helium and evacuated to the hypervelocity launch pressure requirement. The test fixture will be filled with liquid nitrogen. Pressure will be applied to the test specimen in 5 psi increments to a maximum pressure of 35 psi pressure differential between test fixture and range tank pressure. Test specimen strain and deflection data will be monitored at each increment of loading and deflections will be checked against predicted deflections shown in Figure 6-5.

Upon completion of the maximum pressure test, the test fixture pressure will be reduced to a pressure differential of 10 psi between test fixture and range tank pressures. Liquid nitrogen will be replenished as required to maintain a liquid level above the top edge of the test specimen. The specimen will then be impacted with the model impact particle.



NOTES: 1) FABRICATE LOADING FIXTURE (CYLINDER, HEADS, & ATTACHMENT FRAME) FROM 2219–T87 AL. VENT & FILL & DRAIN LINE MAY BE MADE FROM 6061 AL.

2) DRILL & TAP ATTACHMENT FRAME & DRILL BEARING PLATE & TEST SPECIMEN TO MATCH (28) PLACES FOR 1/4" BOLTS.

3) APPLY THIN LAYER OF ADIPRENE L–100 TO TEST SPECIMEN FAYING SURFACE & INSTALL SPECIMEN WHILE ADHESIVE IS TACKY.

4) TOLERANCES: .X , ± .1
.XX, ± .05
.XXX, ± .005

5) ALL DIMENSIONS ARE IN INCHES

Figure 6-3. INTEGRATED STRUCTURAL/METEOROID PROTECTION TANK WALL MODEL, RECOMMENDED TEST SPECIMEN LOADING FIXTURE

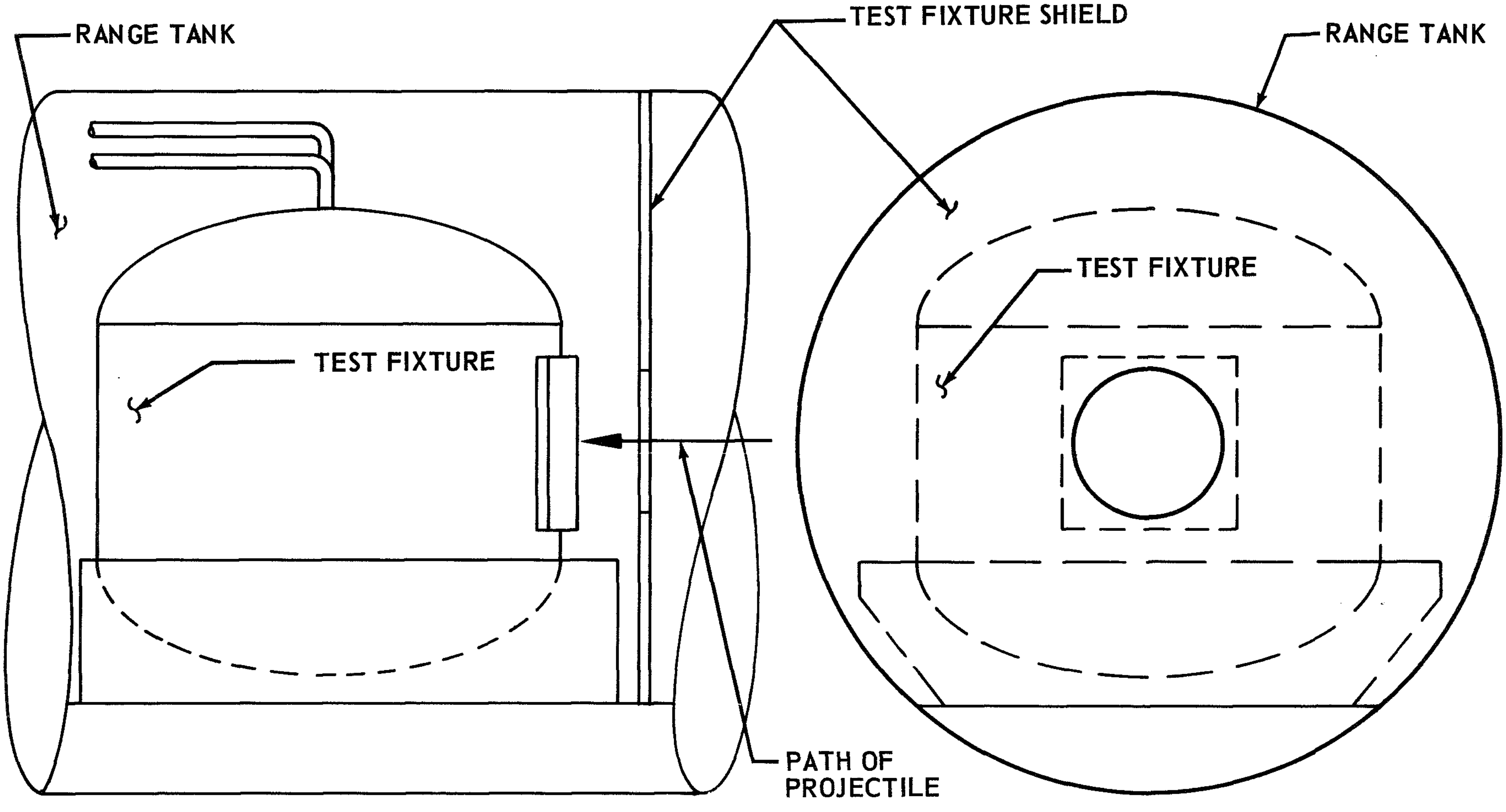


Figure 6-4. INTEGRATED STRUCTURAL/METEOROID PROTECTION TANK WALL MODEL, SCHEMATIC OF TEST FIXTURE IN LIGHT-GAS GUN RANGE TANK

6.4.3 (Continued)

Upon completion of impact test the test fixture will be evacuated and purged with gaseous helium. The test specimen will be removed for subsequent analysis.

6.5 DATA REQUIREMENTS

For each test the following data shall be recorded:

a. Specimen thickness and areal density;
b. Test fixture and range tank pressures;
c. Test specimen displacements and strains;
d. Test specimen temperatures at inner and outer sheets;
e. Impact particle diameter and weight;
f. Impact velocity.

Each specimen will be photographed prior to testing. After testing, each specimen will be bisected through the impact point and photographed. The total depth of penetration and diameter of impact induced void shall be recorded. Recommended instrumentation locations are shown in Figure 6-6.

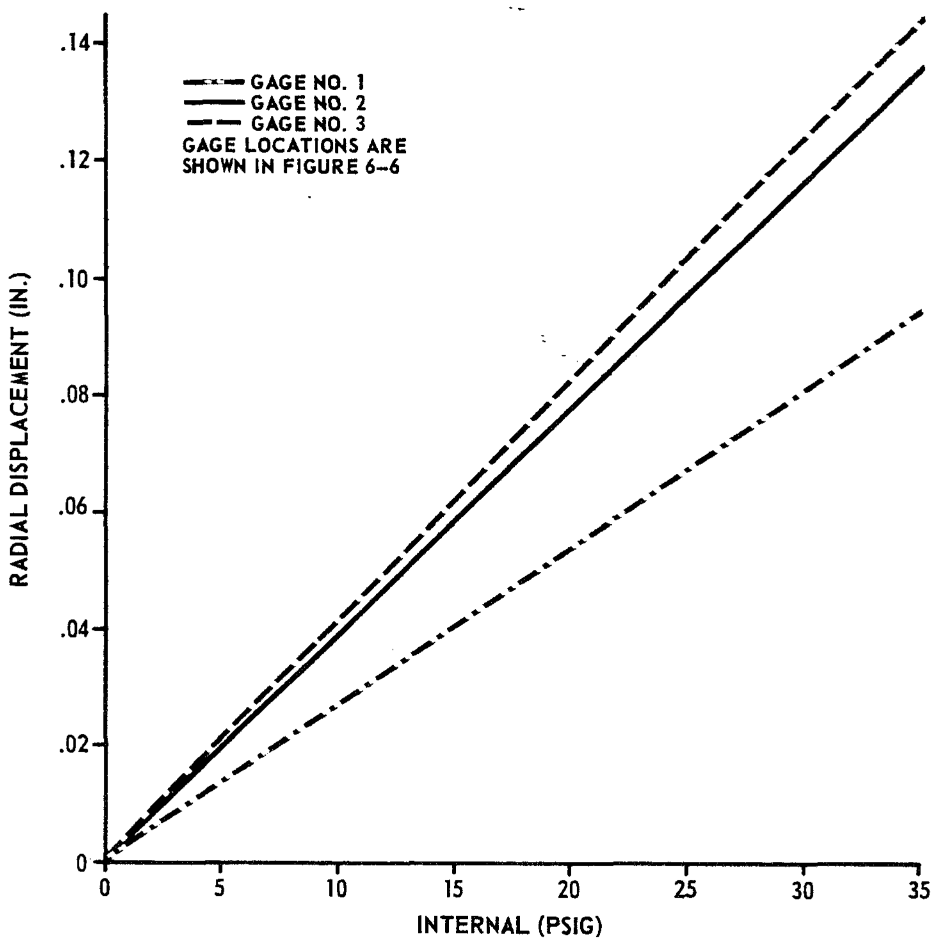
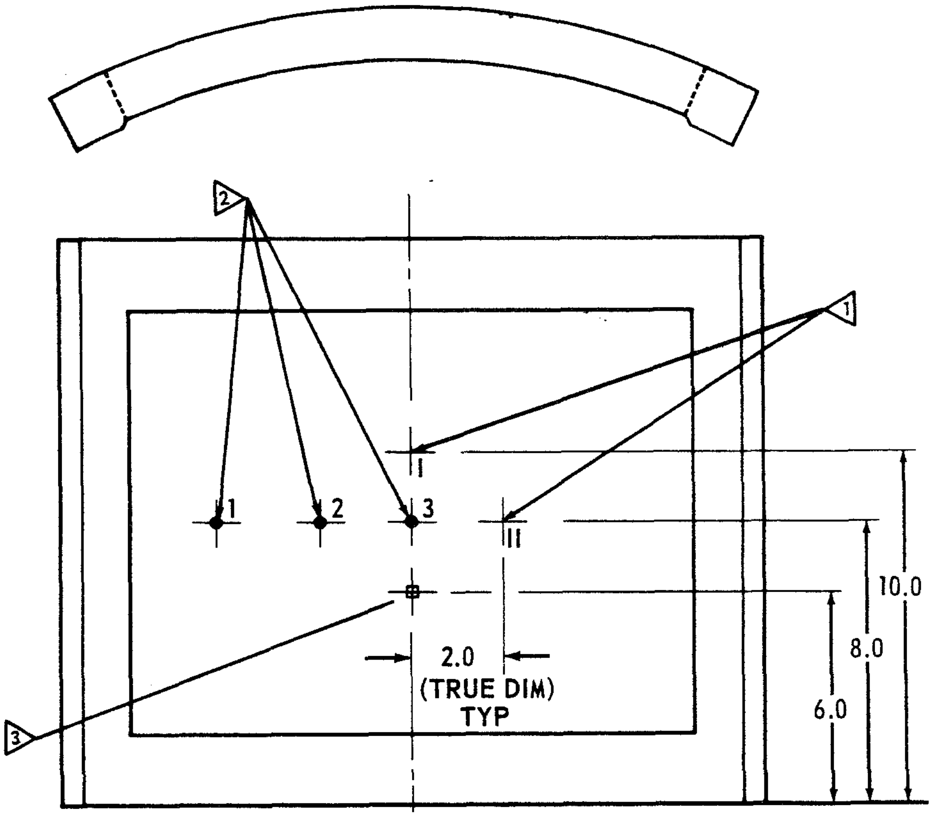


Figure 6-5. RADIAL DISPLACEMENTS AT DEFLECTION GAGE LOCATIONS ON OUTER SHEET - TEST SPECIMEN EDGES FIXED AGAINST DISPLACEMENT AND ROTATION

6.5 (Continued)



1. STRAIN GAGE LOCATIONS. APPLY STRAIN GAGES TO OUTER FACE OF EVERY OTHER SHEET BEGINNING WITH OUTERMOST SHEET (TOTAL NUMBER OF GAGES = 6). ALTERNATE GAGE LOCATIONS BETWEEN POSITIONS I & II.
2. DEFLECTION GAGE LOCATIONS. DEFLECTION GAGES TO BE USED DURING STRUCTURAL TESTING ONLY AND SHALL BE REMOVED PRIOR TO IMPACT TEST. DEFLECTION GAGES TO MEASURE RADIAL DISPLACEMENT OF OUTER SHEET.
3. THERMOCOUPLE LOCATION. APPLY THERMOCOUPLE TO INNER, MIDDLE & OUTER SHEETS. TEMPERATURE DATA TO BE USED TO EVALUATE MATERIAL PROPERTIES AT TEST TEMPERATURE. THERMOCOUPLES NOT REQUIRED ON SPECIMEN FOR TESTS NUMBER 1 & 2.

TOLERANCES: ± 0.1 INCH ALL DIMENSIONS ARE IN INCHES.

Figure 6-6. INTEGRATED STRUCTURAL/METEOROID PROTECTION TANK WALL MODEL, RECOMMENDED INSTRUMENTATION

SECTION 7 - CONCLUSIONS

7.0 CONCLUSIONS

The following conclusions were reached as a result of this study.

A general class of concepts which may be used to meet the requirements of a fully integrated sidewall is a multiwall concept. In such a concept, numerous thin, load-carrying sheets are separated by low-density spacer materials which transfer pressure load to successive sheets. The spacers must be an extremely low conducting material so that the system acts similar to a conventional multilayer insulation. The resulting thick, low-density media acts as a meteoroid shield.

A sidewall concept which integrates the qualities of structural integrity, low thermal conductivity, and resistance to meteoroid penetration is feasible. However, suitable materials having as low a thermal conductivity as is required in the integrated concept are not presently available.

When compared to a conventional concept consisting of a two-sheet meteoroid shield and insulation superimposed upon a propellant container, an integrated concept can be as much as 50 percent lighter in weight if the thickness of the sidewall required for the integrated concept can be tolerated.

Parametric data can be prepared for any mission and vehicle requiring an integrated concept so that weight minimization and trade studies can be performed. This study indicates that the most important factors to consider in minimizing the sidewall weight are the initial propellant condition, the insulation thermal conductivity, the insulation/ meteoroid shield mean density, the allowable final propellant vapor pressure, and the required probability of meteoroid shield penetration.

Additional studies and research should be initiated to obtain materials which possess the low thermal conductivity required in the integrated concept, to obtain further information of the effectiveness of low-density media as meteoroid shields, and to devise means of managing impact induced shocks and debris damage in low-density media.

SECTION 8 - RECOMMENDED FOLLOW-ON STUDIES

8.0 RECOMMENDED FOLLOW-ON STUDIES

8.1 MATERIALS EVALUATION

As pointed out previously, the feasibility of an integrated concept is contingent upon obtaining a material with a solid thermal conductivity low enough to make its insulating qualities comparable to that of a conventional multilayer. Towards this end, it is recommended that basic material research be conducted with the objective of defining and developing a material with a solid thermal conductivity less than 10^{-4} BTU/HR-FT-^{o}F. Upon obtaining such a material, additional studies should be conducted to determine the processes necessary to make this material usable in an integrated concept. For example, foam and honeycomb construction appear very promising in the multiwall concept.

8.2 EVALUATION OF MULTIWALL AS METEOROID SHIELD

In this study, it has been shown that a low-density media is very effective in defeating a hypervelocity particle, and it has been assumed that materials of equal density are equally effective in defeating a meteoroid. Using existing test data, certain scaling laws have also been assumed for extrapolation of the existing data.

Using the multiwall configuration, it is recommended that an analytical and experimental program be conducted to determine to what extent the mean density of a multiwall and the physical and mechanical properties of the multiwall constituents affect the meteoroid shielding qualities of a multiwall configuration. Concurrently, the relation between the particle impact environment and the multiwall variables should be established for a variety of impact conditions.

Upon completion of the above, means of improving the efficiency of the multiwall concept should be analytically and experimentally investigated. This study should include methods of reducing the debris damage in a low-density material and means of managing the impact induced shocks.

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12. Boeing Document D5-13485, "Rocket Stage Cryogenic Storage", by M. J. Baker, et. al., February 1969.

13. NASA CR-664, "Multivariable Analysis of the Mechanics of Penetration of High-Speed Particles", by D. D. Bouma and W. C. Burkitt, December 1966.

APPENDIX A - COMPARISON OF BUMPERED AND UNBUMPERED LOW-DENSITY MEDIA

For a bumpered concept as depicted in Figure 4-2, the total meteoroid shield weight per unit area may be written as,

$$W_m = W_B + \eta W_{fo} \tag{A-1}$$

where

W_M = meteoroid shield weight, lb/ft^2;

W_B = bumper weight, lb/ft^2;

W_{fo} = filler weight without bumper to defeat particle in question, lb/ft^2; and

η = a factor, always less than 1.0, which for a particular meteoroid is a function of W_B only.

If the meteoroid shield weight is given by Equation A-1, then it can be seen that as the bumper weight W_B approaches zero, the factor η approaches 1.0, since by definition, W_{fo} is the weight required to defeat a specified meteoroid if no bumper is used. Using Equation A-1, it may also be reasoned that the factor η approaches zero as W_B approaches a semi-infinite shield.

Thus, since η is postulated to be a function of only W_B for a particular meteoroid, the following data points are known:

$$W_B = 0, \quad \eta = 1$$

$$\eta = 0, \quad W_B = W_{Bi}$$

where W_{Bi} is the weight of a thick plate required to defeat the meteoroid in question. Since the function between these two points is unknown at this time, a linear function as shown in Figure A-1 has been chosen for this study. Assuming a linear relationship between η and W_B, the two quantities are related as,

$$\eta = 1 - \frac{W_B}{W_{Bi}} \tag{A-2}$$

It is now desired to determine W_{Bi} for an aluminum projectile with a velocity of 6.00 km/sec impacting a thick aluminum shield. Using Reference 13, the ratio of the penetration to projectile diameter (h/d) is taken as 1.70.

APPENDIX A - (Continued)

Since W_{Bi} is the weight of a finite shield required to defeat the asteroidal meteoroid, the h/d ratio for semi-infinite shield will be multipled by a factor of 2.0 to account for spalling. W_{Bi} therefore becomes,

$$W_{Bi} = 2\ (1.70)\ d\ \rho_{AL} = 0.340\ d\ \frac{lb}{in^2} \qquad \text{(A-3)}$$

and taking $\frac{t_B}{d} = 0.15$

$$W_B = 0.015\ d\ \frac{lb}{in^2} \quad . \qquad \text{(A-4)}$$

Using Equations A-1 and A-4, the meteoroid shield weight becomes,

$$W_M = (0.850\ d + 0.956\ W_{fo})\ \frac{lb}{ft^2} \qquad \text{(A-5)}$$

with d measured in centimeters.

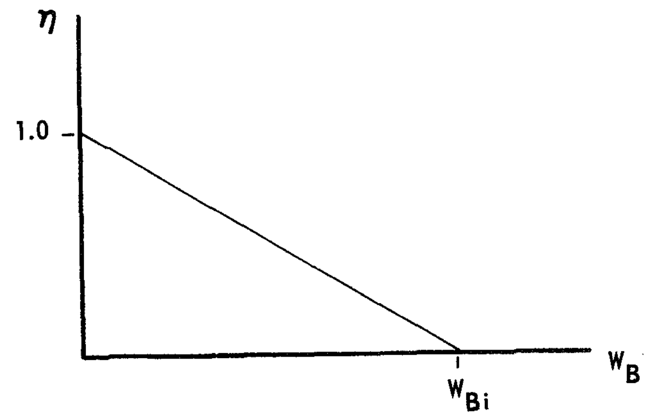


Figure A-1. BUMPER AREAL DENSITY VERSUS FACTOR η

APPENDIX B - LOW-DENSITY MEDIA IMPACT PROGRAM

1.0 GENERAL

To supplement the existing impact data in low-density media and to ascertain the effectiveness of a multiwall concept as a meteoroid shield, a limited impact test program was undertaken during the course of this study. A description and the results of this program follows.

2.0 TEST SPECIMENS

The impact test program used a total of six specimens. Five of these specimens were constructed of alternating layers of aluminum foil and various spacer materials. The sixth specimen was constructed of alternating layers of 1/4-mil, aluminized Mylar and red, rigid foam. Details of each specimen are given in Table B-I. During preparations of the test specimens using foam spacers, it was noted that the spacers tended to absorb the adhesive; therefore, it was not deemed advisable to bond the foam spacers to the sheets. Thus, only two specimens contained an adhesive. These were Specimen No. 1 with Mylar honeycomb bonded to aluminum foil and Specimen No. 3 which used a double adhesive foam as a spacer. The remaining specimens were encased in plastic housings along the four exposed surfaces.

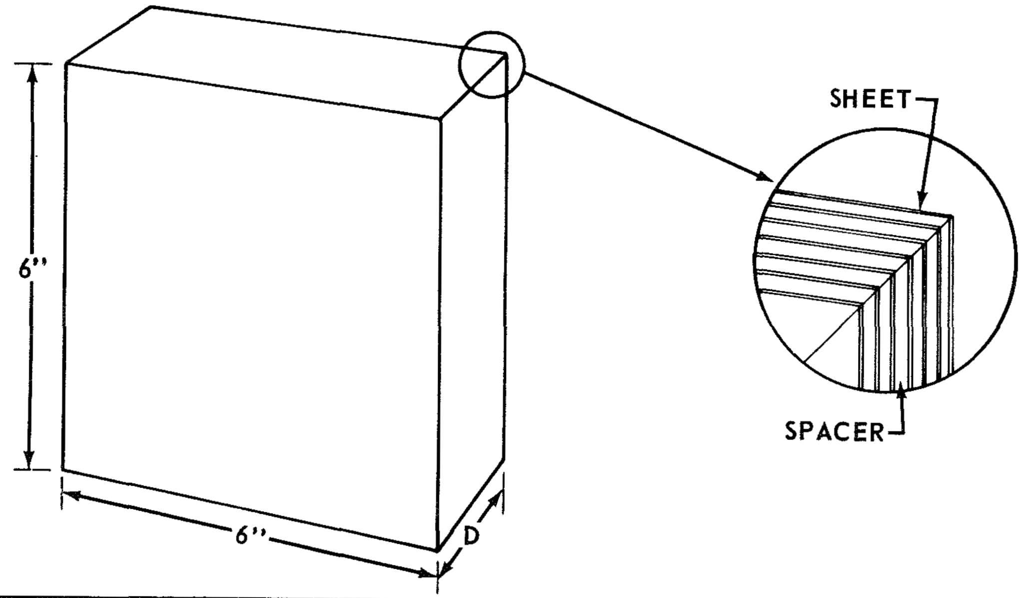
3.0 IMPACT CONDITIONS

All specimens were subjected to impacts with 0.075-inch (10 mg) aluminum spheres at velocities of approximately 20,000 FPS.

4.0 TEST RESULTS

The results of this test program are summarized in Figure B-1. This figure shows the penetrated thickness and weight obtained in these tests in comparison with predictions made from test results in Reference 7 and scaling laws used in this study. It is noted that predicted values agree reasonably well below a density of 18 lb/ft^3. It is significant to note also that if a datum point representing an impact into a thick aluminum plate is included in the data (ρ = 173 lb/ft^3) the penetrated weight exhibits a minimum value.

Photographs of the test specimens are shown in Figures B-2 through B-7.



SPECIMEN	D	SHEET DATA		SPACER DATA			MEAN DENSITY
		MAT'L	THICKNESS	MAT'L	DENSITY	THICKNESS	
1	2.5"	Al	0.003"	MYLAR HONEYCOMB	2.1 #/FT^3	0.10"	ρ = 11.6 #/FT^3
2	4.0"	Al	0.001"	RED RIGID FOAM	1.8 #/FT^3	0.032"	ρ = 4.5 #/FT^3
3	2.0"	Al	0.001"	DOUBLE ADHESIVE FOAM	32 #/FT^3	0.032"	ρ = 36 #/FT^3
4	6.0"	Al/MYLAR	0.00025"	RED RIGID FOAM	1.8 #/FT^3	0.032"	ρ = 1.67 #/FT^3
5	3.2"	Al	0.003"	CORK	8.0 #/FT^3	0.125"	ρ = 10.6 #/FT^3
6	3.3"	Al	0.006"	CORK	8.0 #/FT^3	0.125"	ρ = 14.3 #/FT^3

Table B-I. LOW-DENSITY TEST SPECIMENS

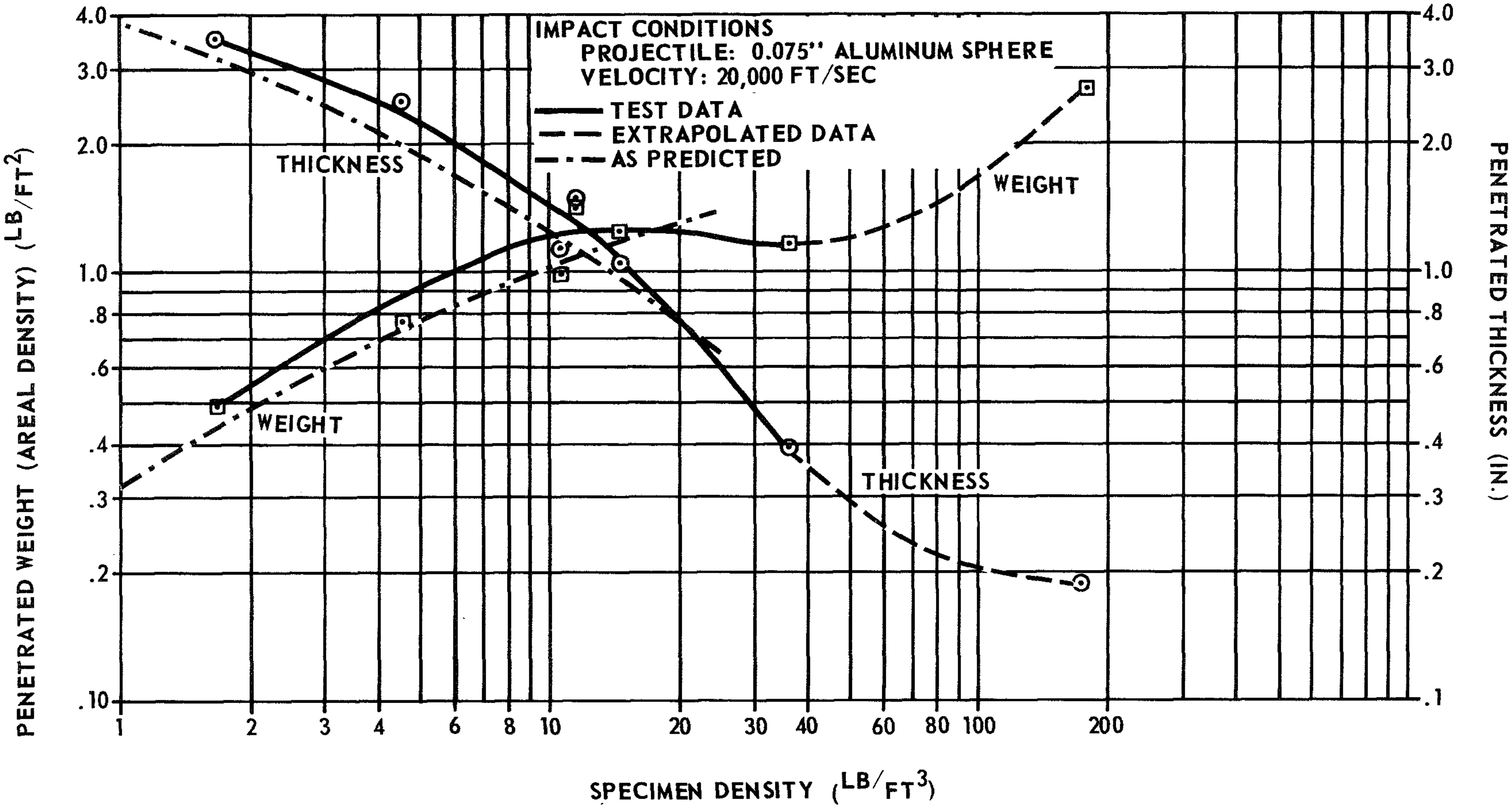


Figure B-1. LOW-DENSITY MEDIA TEST RESULTS

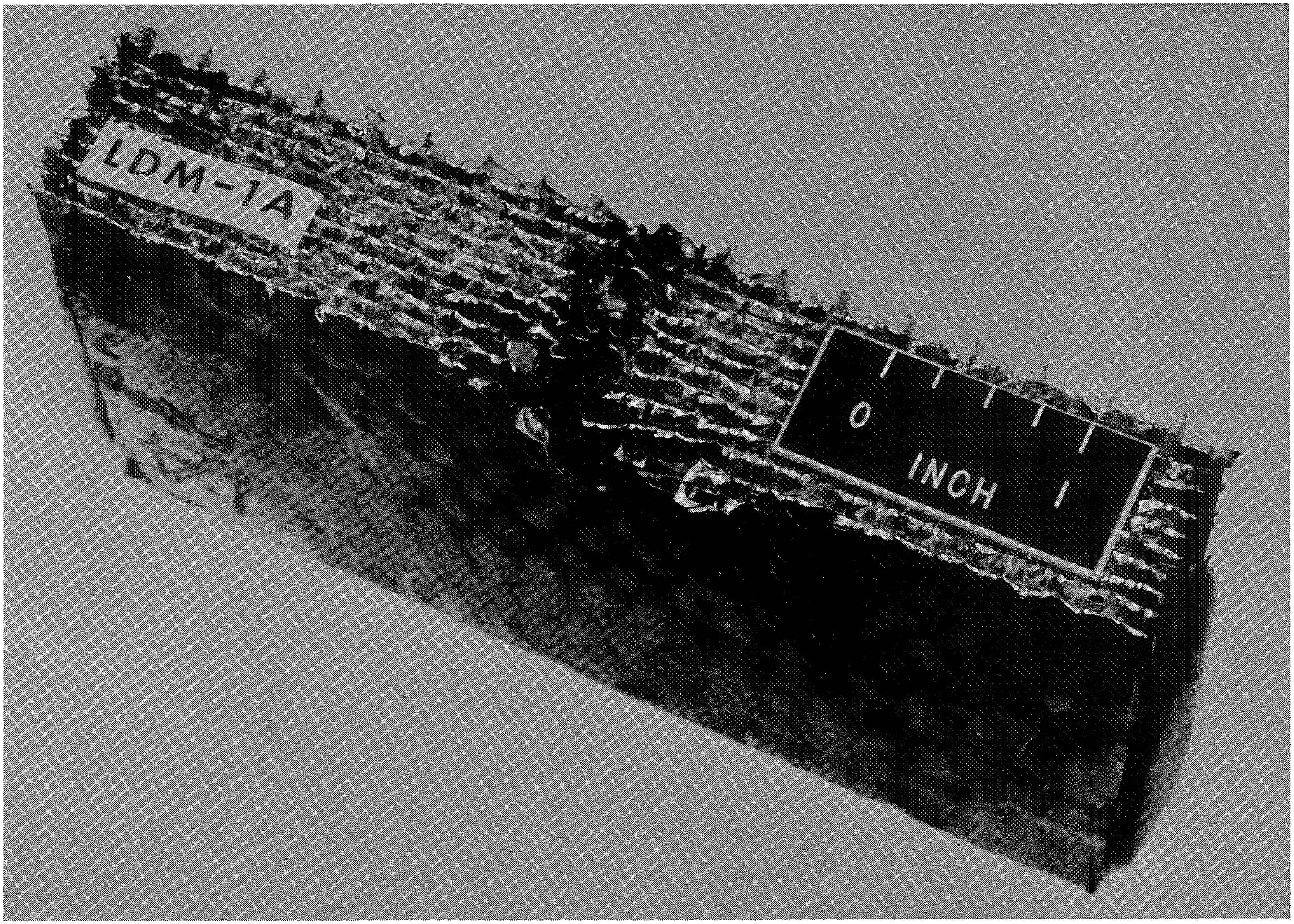


Figure B-2: IMPACTED SPECIMEN NUMBER 1

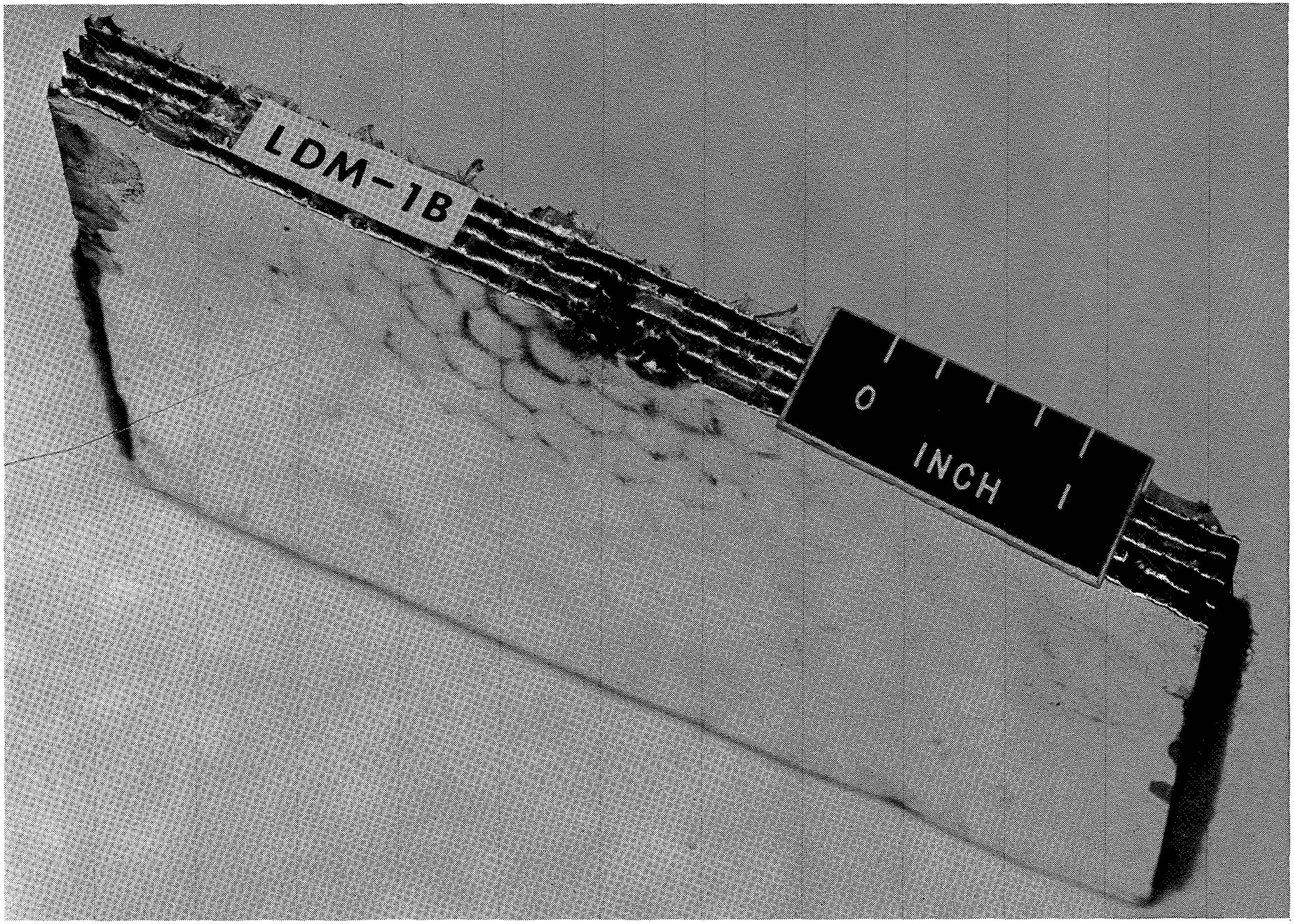


Figure B-2(Continued): IMPACTED SPECIMEN NUMBER 1

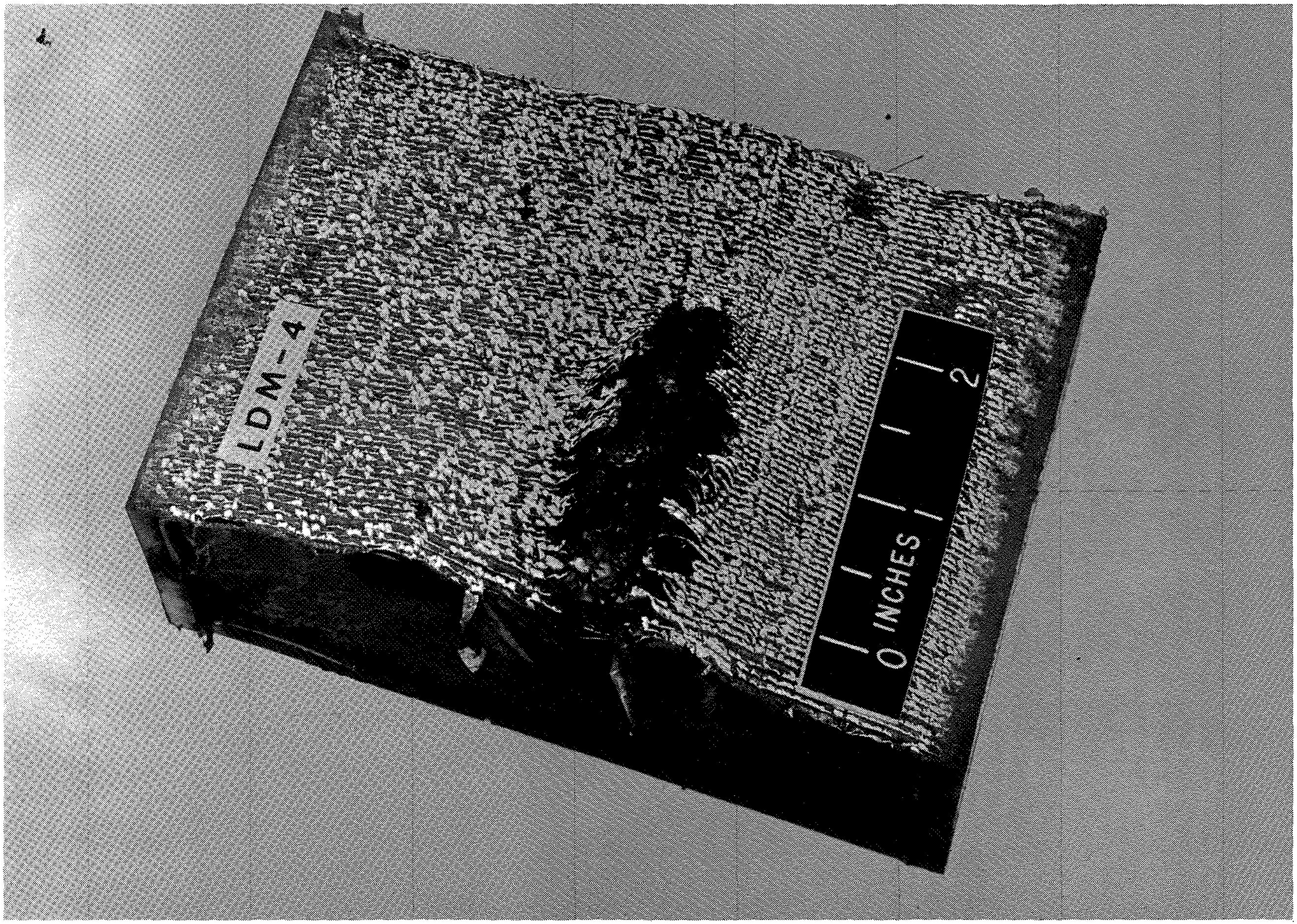


Figure B-3: IMPACTED SPECIMEN NUMBER 2

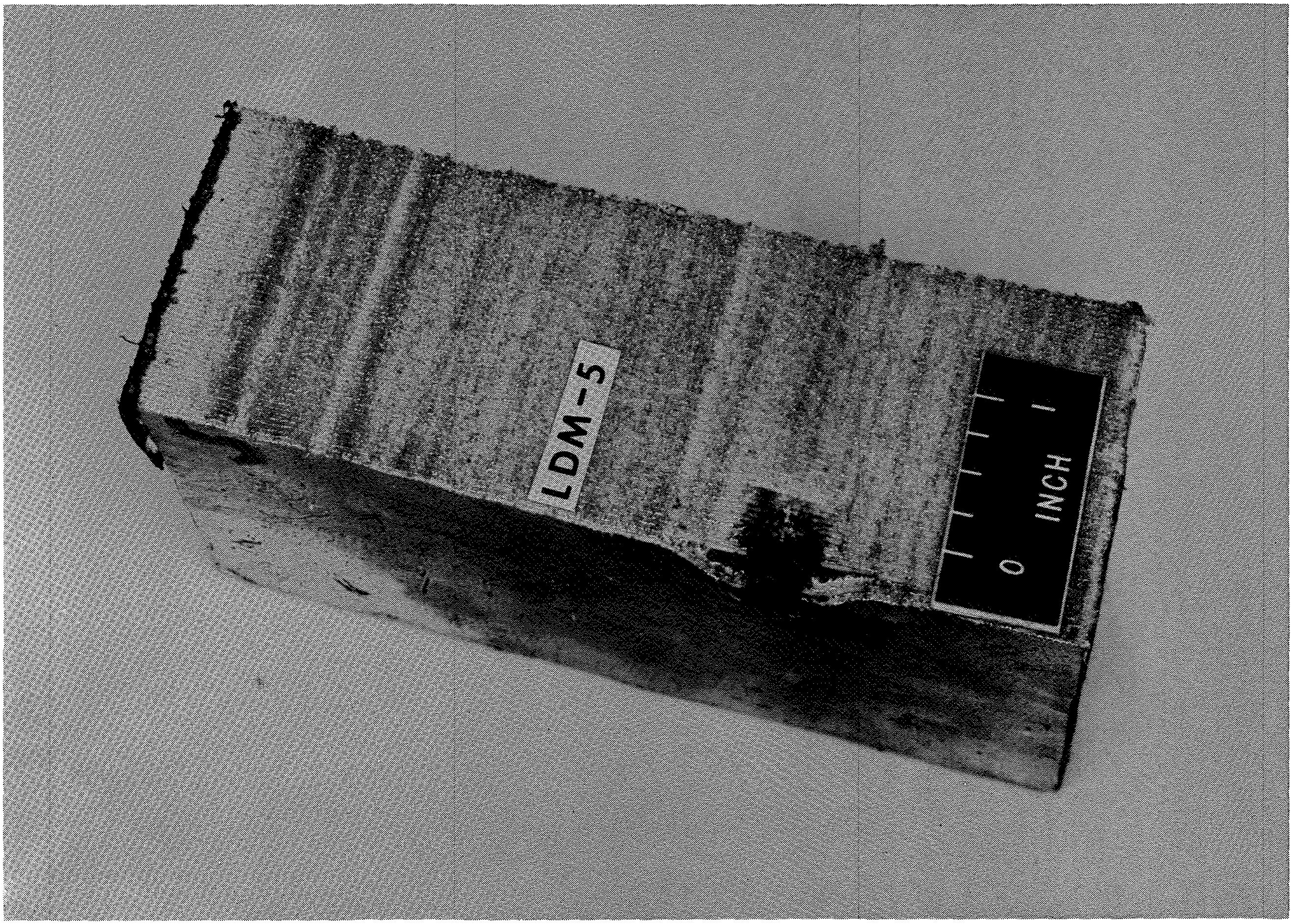


Figure B-4: IMPACTED SPECIMEN NUMBER 3

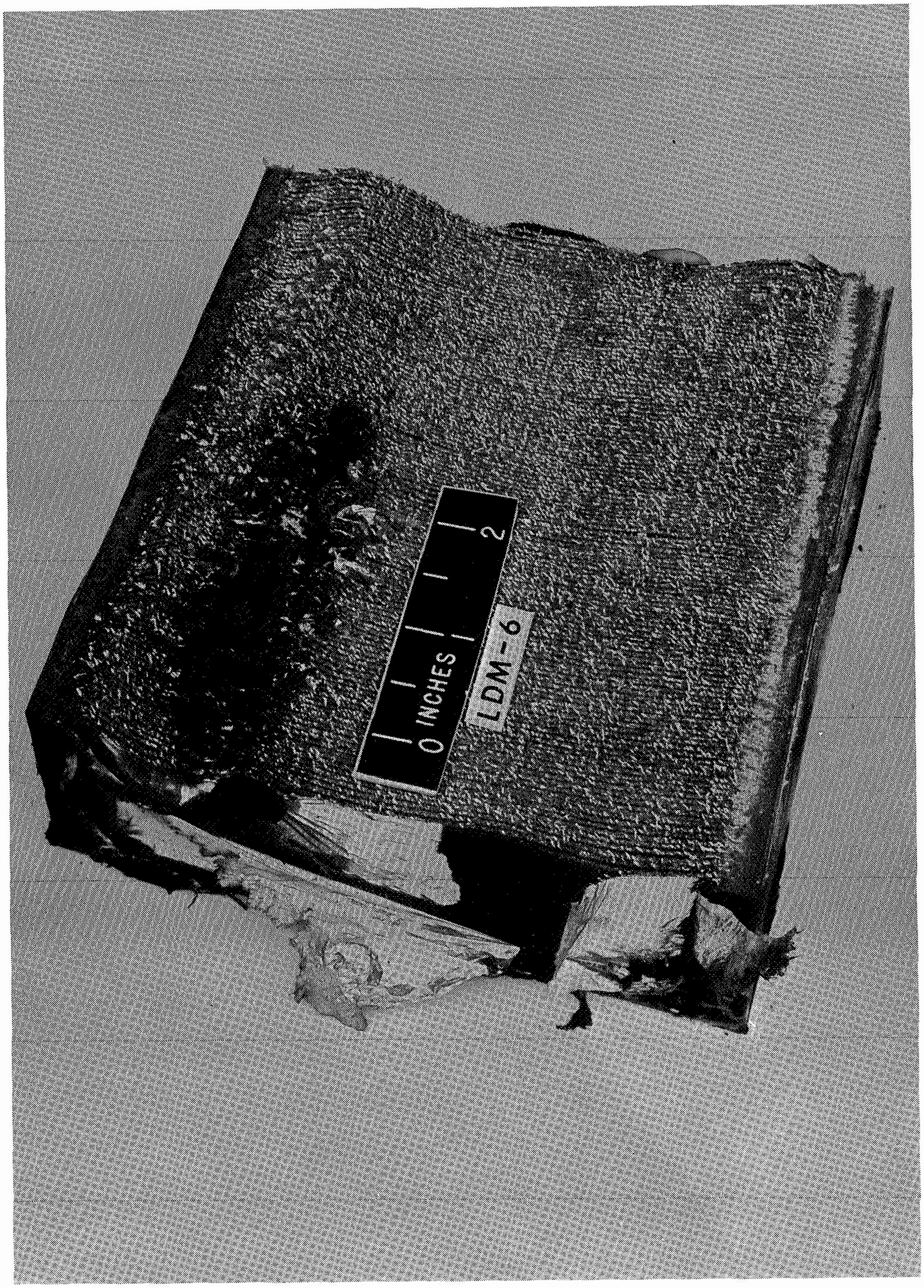


Figure B-5: IMPACTED SPECIMEN NUMBER 4

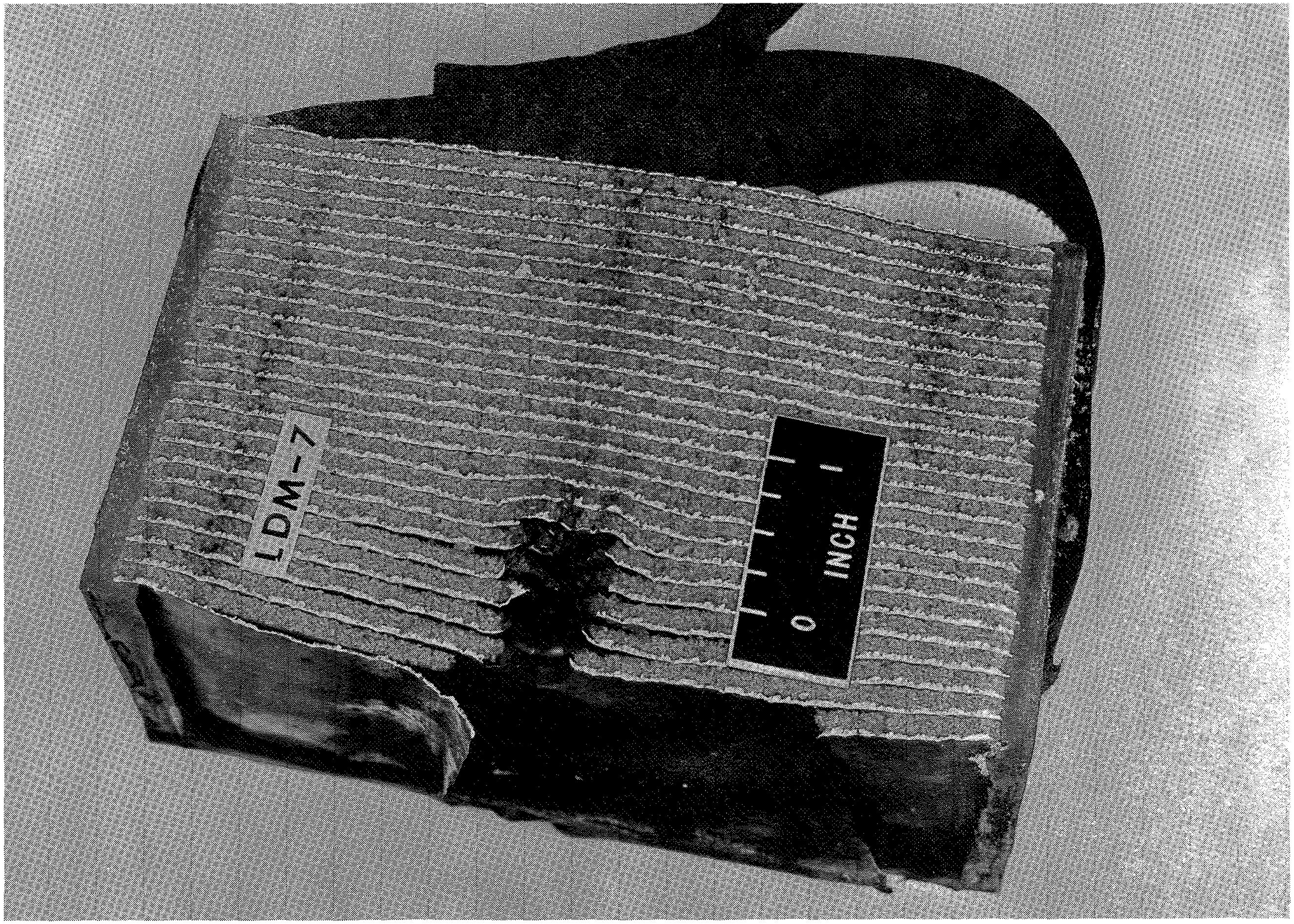


Figure B-6: IMPACTED SPECIMEN NUMBER 5

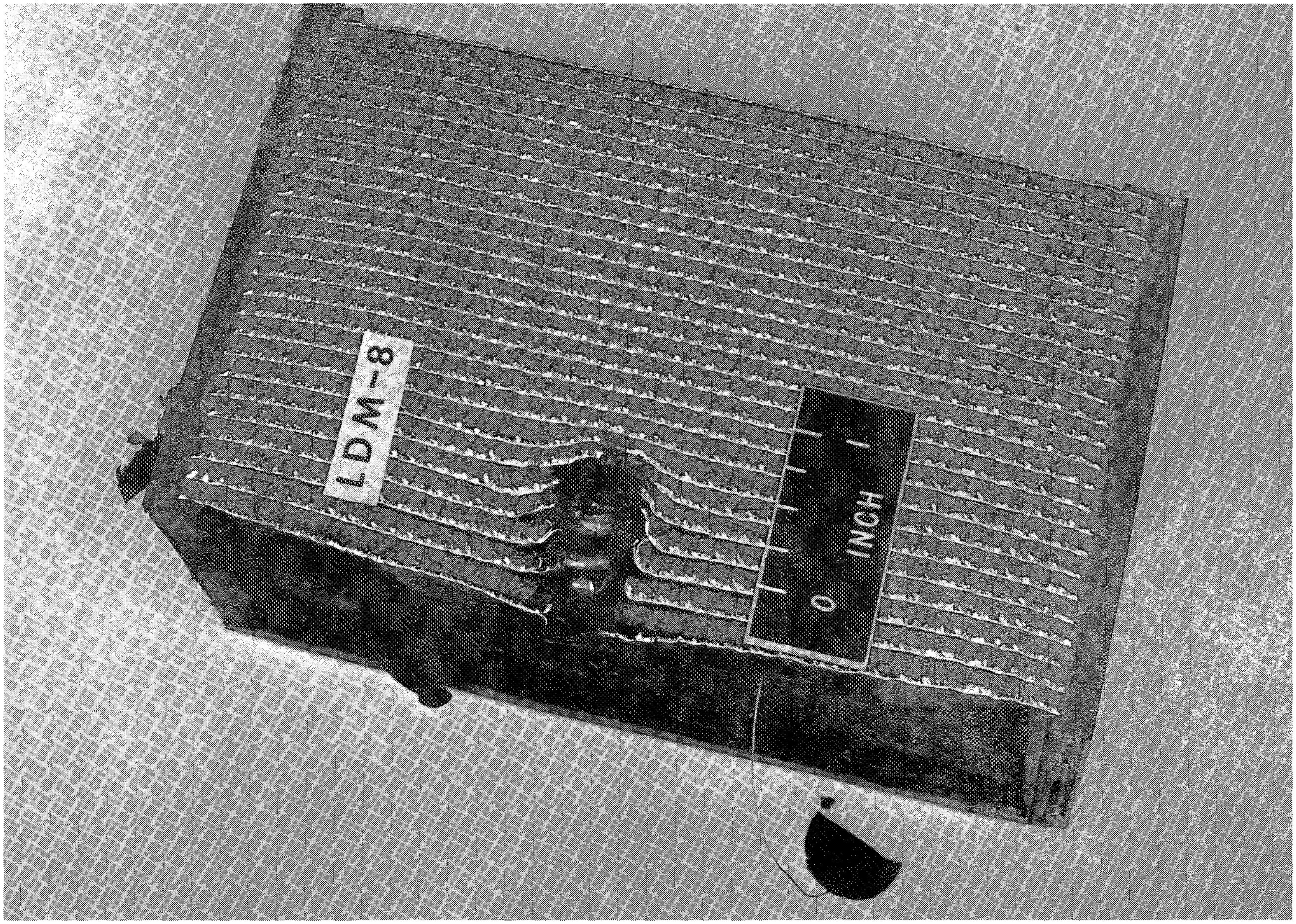


Figure B-7: IMPACTED SPECIMEN NUMBER 6

APPENDIX C - STRUCTURAL ANALYSIS OF MULTIWALL CONCEPT

1.0 GENERAL

Presented in this Appendix are two analyses for a multiwall structural concept consisting of alternating layers of load-carrying sheets and spacer material. The first analysis presented makes use of the equilibrium and continuity conditions existing in a multiwall concept and establishes a system of equations for solving for the stress distribution in the sheets and spacers of the concept. The second analysis presented uses the Boeing ASTRA computer program. In this analysis, the sheets and spacers are represented by discrete elements, and stress distributions are obtained using the direct stiffness method.

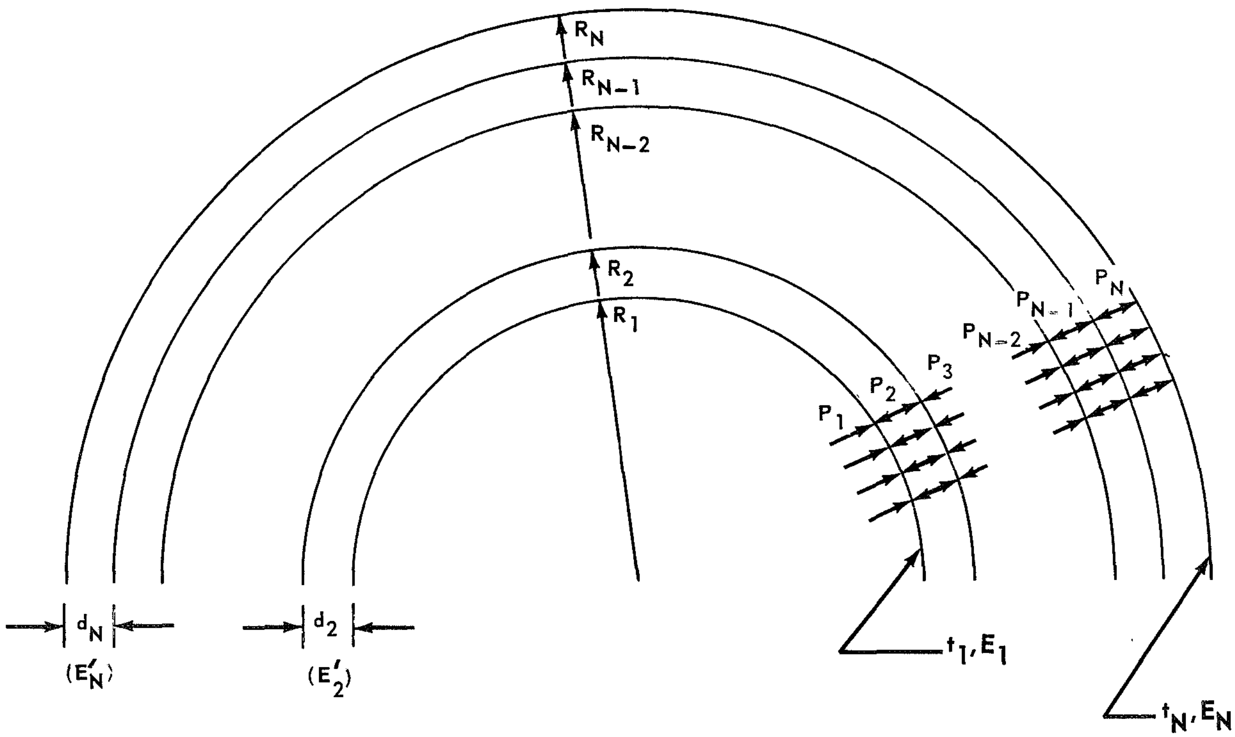


Figure C-1. MULTIWALL STRUCTURAL ANALYSIS GEOMETRY

1.1 SIMPLIFIED ANALYSIS

Consider a thick, multiwall cylinder as shown in Figure C-1, with the following definitions:

a. N = total number of load-carrying sheets;

b. P_n = pressure felt by the n^{th} sheet (also the pressure acting on the spacer between the n^{th} and $(n = 1)^{th}$ sheet);

c. d_n = spacer thickness between the n^{th} and $(n + 1)^{th}$ sheet;

d. t_n = thickness of the n^{th} sheet;

1.1 APPENDIX C (Continued)

e. E'_n = radial modulus of elasticity of the spacer between the n^{th} and $(n + 1)^{th}$ sheet;

f. E_n = circumferential modulus of elasticity of the n^{th} sheet;

g. r_n = radius of the n^{th} sheet.

Noting that the pressure sustained by each sheet will be reacted as a hoop force and that continuity must exist between the deflection of the spacers and sheets, the following system of equations may be established:

$$\begin{bmatrix} C_2 & -K_2 & 0 & 0 & \cdots & 0 \\ -K_2 & C_3 & -K_3 & 0 & \cdots & 0 \\ 0 & -K_3 & C_4 & -K_4 & 0 \cdots & 0 \\ \vdots & & & & & \vdots \\ 0 & \cdots & & & -K_{n-1} & C_n \end{bmatrix} \begin{bmatrix} P_2 \\ P_3 \\ P_4 \\ \vdots \\ P_n \end{bmatrix} = \begin{bmatrix} K_1 P_1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad \text{(C-1)}$$

where

$$K_n = \frac{r_n^{\,2}}{E_n\, t_n} \qquad \text{(C-2)}$$

$$C_n = \frac{d_n}{E'_n} + K_{n-1} + K_n \qquad \text{(C-3)}$$

and P_1 is the internal pressure.

Because the above analysis is linear, it may be used for a case which is not isothermal so long as the appropriate moduli are used, and thermal stresses are added to those calculated above.

Although the equations above might appear involved, approximations can be made in many cases which make the solution quite simple. If the thickness of the cylinder is small compared to the cylinder radius, then the term K_n and C_n can be approximated as

$$K_n = \frac{\bar{r}^{\,2}}{E_n\, t_n} \qquad \text{(C-4)}$$

$$C_n = \frac{d_n}{E'_n} + \frac{2\bar{r}^{\,2}}{E_n\, t_n} \qquad \text{(C-5)}$$

where $\bar{r}$ is the mean wall radius.

1.1 APPENDIX C (Continued)

Furthermore, for the multiwall concepts under consideration, the spacer thickness d_n is expected to be small and the modulus E'_n is expected to be moderate; therefore, the term $\frac{d_n}{E'_n}$ can be neglected in Equation C-5, thus,

$$C_n = \frac{2 \bar{r}^2}{E_n t_n} \qquad \text{(C-7)}$$

Consider as an example, a four-sheet system in which all sheets are the same thickness and have the same modulus. The solution with the above approximations yields

$$P_2 = 3/4 \, P_1$$
$$P_3 = 1/2 \, P_1$$
$$P_4 = 1/4 \, P_1$$

and it is noted that each sheet supports a pressure of $1/4 \, P_1$. This means that the first spacer passes on $3/4 \, P_1$, the second on $1/2 \, P_1$, and the last on $1/4 \, P_1$. This example serves to illustrate that each sheet will carry a proportional amount of the internal tank pressure and that the pressure in the spacer varies linearily from inboard to outboard. Furthermore, with these approximations, each sheet is subjected to the same stress level because $(P_n - P_{n-1})$ is constant and the stress is given as

$$\sigma_n = \frac{(P_n - P_{n-1}) \bar{r}}{t_n} \quad . \qquad \text{(C-7)}$$

1.2 COMPUTER ANALYSIS

To determine whether or not a multiwall concept could be modeled with conventional finite element techniques, and to validate the assumptions made in the above paragraph, the Boeing ASTRA (Advanced STRuctural Analyzer) program was used to analyze an eleven-sheet system. Using cylindrical coordinates, each of the eleven sheets were represented by nine quadrilateral plates as shown in Figure C-2. The spacer material between plates was lumped at the nodes of the quadrilateral plates and represented by spar elements which carry only axial loads. The modulus of elasticity of the spacer and spar element was the same.

The model shown in Figure C-2 was used to analyze cylindrical panels of the test configurations described in Section 6. This configuration has a minimum radius of 19.80 inches; the configurations have one inboard sheet 0.004 inches thick and ten additional 0.001-inch sheets each separated by spacers which are 0.145 inches thick. The sheet modulus is 10.5×10^6 psi and that of the spacer is 4.6×10^4 psi. For each sheet, the model uses nine, 4-inch square plates. Spar elements have a cross-sectional area of 16 in^2 each.

2.0 RESULTS

The results of the computer analysis have been compared to those obtained using the procedure described in Paragraph 1.1, Appendix C. The sheets stresses are shown in Table C-I.

2.0 APPENDIX C (Continued)

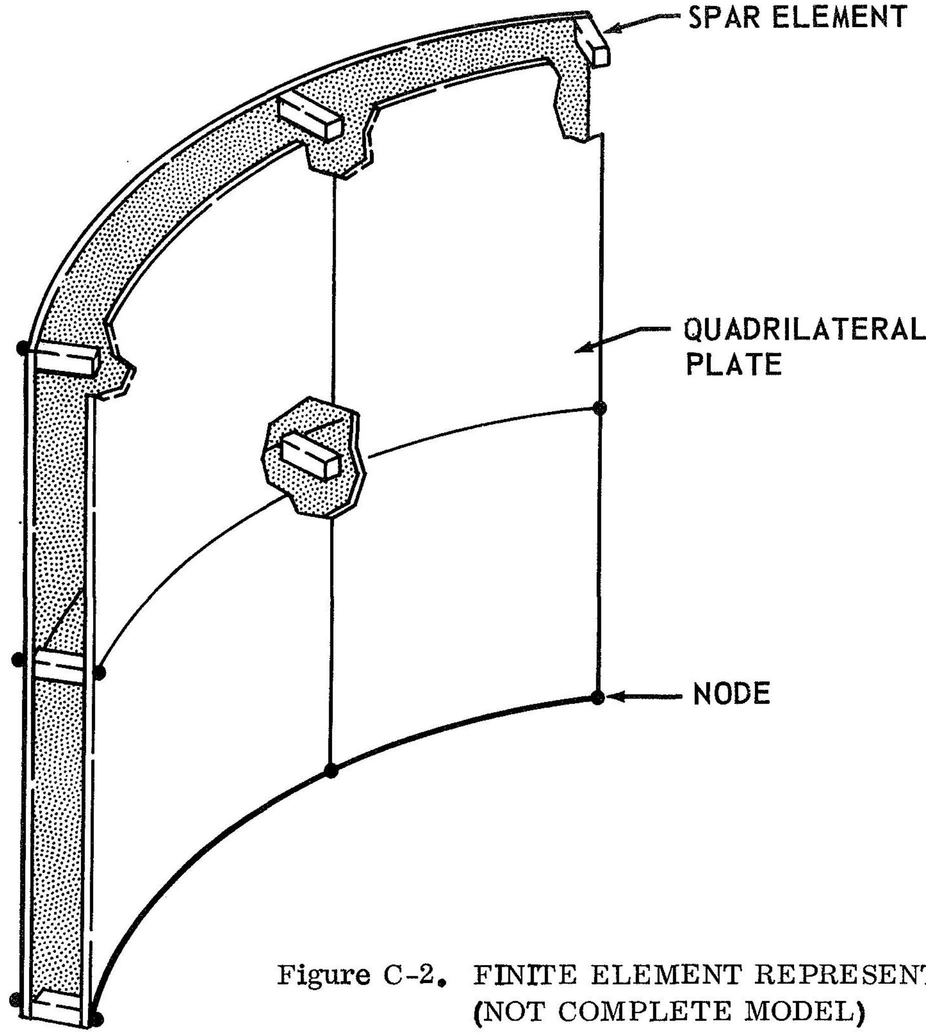


Figure C-2. FINITE ELEMENT REPRESENTATION (NOT COMPLETE MODEL)

Table C-I. PLATE STRESSES (psi)

Sheet	Radius (Ref.)	ASTRA	Paragraph 1.1
1	19.80	50,700	51,200
2	19.948	50,300	↓
3	20.093	49,900	
4	20.238	49,500	
5	20.383	49,200	
6	20.528	48,800	
7	20.673	48,400	
8	20.818	48,100	
9	20.963	47,700	
10	21.108	47,400	
11	21.253	47,100	51,200

2.0 APPENDIX C (Continued)

A comparison of the spacer pressures are shown in Figure C-3. It is seen that the computer analysis and the method described in Paragraph 1.1, Appendix C, agree very well. Thus, for a cylinder, this method may be used for analysis of multiwall concepts which have the same modulus in all sheets. The computer analysis may be used to analyze panel configurations with varied boundary conditions and will therefore be very useful in predicting the results of a test program using test panels.

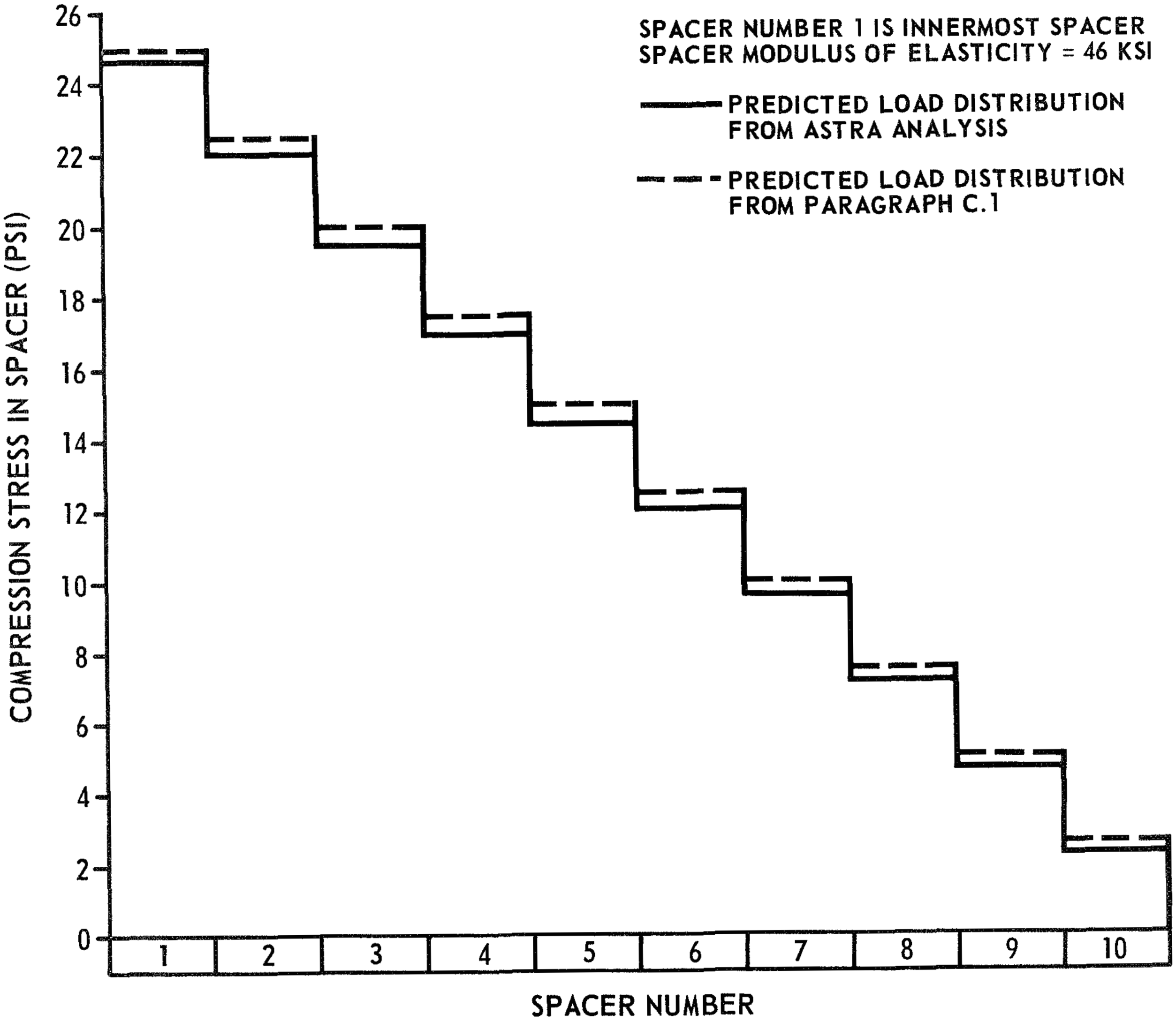


Figure C-3. COMPRESSIVE LOAD DISTRIBUTION IN LOW-DENSITY FILLERS USED IN 40-INCH DIAMETER MULTIWALL CYLINDER