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FILAMENT WOUND METAL LINED PROPELLANT TANKS FOR FUTURE EARTH-TO-ORBIT TRANSPORTS

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Filament Wound Metal Lined Propellant Tanks For Future Earth-to-Orbit Transports

By

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ABSTRACT

Currently, the main propellant tanks for rocket-powered Earth-to-orbit vehicles are expendable. For future Earth-to-orbit transports, both reusability and lighter weights are sought for these tanks. The tank wall materials and tank geometry are dictated by the size and shape of the vehicle body and by the propellant being stored. Filament winding with a metallic liner is proposed as a method of fabricating these tanks so that they will be lighter and reusable. Matching the operating pressure strain to the expected contraction of the liner at cryogenic temperatures is proposed as one design approach. Pre-stressing the liner in compression is a second approach proposed in order to accommodate the mismatches in strain between liner and overwrap.

INTRODUCTION

Future Earth-to-orbit transports (year 2000 and beyond) may well have no throw away or water recoverable elements. For these transports, the main propellant tanks will probably be located internally and will require most of the volume of the vehicle as suggested by figure 1 and described in reference 1. Unlike any previous large main rocket propellant tanks, these tanks must be reusable.

Past designs for future vehicles encompass a broad range of tank concepts including integral and non-integral configurations. A filament wound tank with a honeycomb intermediate layer and an aluminum liner is currently proposed. Two methods are considered for the accommodation of the differential expansion and contraction between the liner and overwrap. In one proposed design, the large contraction of the metallic liner in the presence of a cryogenic propellant is accommodated by designing the liner so that its expansion at operating pressure equals the expected contraction due to the presence of a cryogenic propellant.

In an alternate proposal, the liner is pre-stressed in compression during the fabrication process to accommodate the contraction at cryogenic temperatures. Stresses in the overwrap and the liner are shown for no stress and a pre-stress of 20,000 psi the liner for tank pressures ranging from 0 to 30 psi. An earlier proposal for a single metallic honeycomb sandwich shell that serves as tank, body structure, and insulation is cited. The various problems generally encountered in developing tanks with multi-layered, multi-functional walls are reviewed.

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VEHICLE SIZE AND SHAPE CONSIDERATIONS

The lightest and simplest vehicle to build is one with a circular shaped body. However, additional factors such as payload accommodation or aerodynamic design may require other shapes. Four possible body-shell-tank configurations are shown in figure 2 with projections for the portions of the cross sections that are not available for propellants. The following is an example of how the cross sections were estimated for a simple circular shape. Assume the outer moldline of the vehicle is 32.8 ft. To obtain an estimate for the inner moldline of the tank, 1.5 inches is allowed for high temperature insulation, 7 inches for the body shell structure (including ring frames), 6.5 inches for clearance between tank and body, and 3.0 inches for tank shell (including cryogenic insulation). The radial distance required is 18 inches, which makes the inner tank wall diameter 29.8 ft compared with a 32.8-ft outer body diameter.

In the above estimates, the allowance for ringframes may be non-conservative for a vehicle of the size used as an example. Further, the 6.5 inches allowed for clearance to accommodate deflections in the structure is probably inadequate. Certainly, maintenance would not be possible on the exterior of the tank or the interior of the body shell without removal of panels in the body shell. Non-integral circular tanks within a non-circular body shell are projected to have the largest portion unavailable for propellants at an estimated 35 percent for a typical future transport, whereas the internally braced oblate shell is assumed to have the best at only 5 percent unavailable for propellants. However, the advantage of the latter may be outweighed by the weight penalty for the internal bracing and heavier ringframes required to maintain body shell shape under internal pressure.

Vehicle size is an important consideration. Tanks on single-stage vehicles or on large payload capacity two-stage systems tend to be large; therefore, the tank walls tend to be thicker to accommodate the pressures. At the same time, this trend places no penalty on tank structural fraction, since this fraction theoretically remains constant as tank size is increased (ref. 2). In these studies, tank structural fraction is the ratio of tank mass to propellant mass.

TANK AND BODY SHELL DESIGNS

A conventional near-term technology structural arrangement for a tank in a future vehicle is depicted in figure 3. The tank and body shell are separate structures with a clearance allowed between the two for thermal expansion and contraction and structural deflection under load.

Some type of high temperature insulation is required on the outside of the structure to protect it during ascent and entry, and some type of cryogenic insulation is required to prevent boiloff of the propellant stored in the tank. A reusable insulation is the only element of this conventional system that has not been developed.

The most volumetrically efficient tank concept is the integral system with a single honeycomb shell proposed in reference 3. This relatively thin metallic shell (about 1-1/4 in. thick overall) functions as an insulator, propellant container, and supporter of internal pressure and body loads (fig. 4). In addition to low unit weight and parts count, the vehicle outer moldline can be reduced significantly over the conventional tank-body-shell system requiring 8 to 12 in. for structure, insulation, and purge space.

At launch, a layer of ice on the exterior of the single honeycomb shell, according to the proposers, would serve as insulator. During main engine operation, the ice is expected to break away from the vehicle. The greatest thermal stresses occur during ascent and are caused by the liquid hydrogen on the inside at -423°F and the aerodynamic heating of the outer surface resulting in a temperature as high as 650°F for a delta across the honeycomb sandwich of about 1000°F. During entry the temperature drop across the honeycomb shell was estimated to be only about 200°F at peak heating.

In this single sandwich honeycomb concept, the upper half of the body shell consists of titanium, and the lower half is Rene. Possible disadvantages of the concept are the embrittlement of the Rene in the presence of hydrogen and the sensitivity of titanium to impact in the presence of liquid oxygen. A modification of this concept was proposed in reference 4 in which Inconel 718 was selected. The Inconel is somewhat heavier than the titanium but no tension ties are required, since the tank is round. Another advantage of the Inconel over the titanium and Rene is that it is easily field repaired by brazing. Inconel has good strength up to about 1350°F and good oxidation resistance up to about 1800°F. No joint between dissimilar metals is required on the all-Inconel 718 design; however, a joint is required along a waterline between the titanium and Rene in the design of reference 3.

A possible deterrent to the utilization of the single metallic honeycomb sandwich wall is the high thermal stresses induced during normal operation, and this is the reason for the consideration of other designs. The highest stress found in the all-Inconel 718 tank design occurs during ascent and is caused by the combined effects of tension due to pressure and temperature on the inner face sheet of the sandwich in the circumferential direction. The stress was 170,000 psi compared with a yield of 180,000 psi for the Inconel at cryogenic temperature (ref. 4).

An alternative for a minimum weight tank might consist of a high strength-to-weight composite outer shell equipped with an impermeable liner, such as aluminum, for containment of the propellant (fig. 5). The liners for these tanks are either classed as load sharing or non-load sharing. Many tanks have been built with load sharing liners, but these applications relate to small high pressure (1000 to 3000 psi) designs. Overwraps on these tanks included Kevlar and glass with 2219-T62 aluminum or 301 stainless steel liners (refs. 5-11). Buckling analysis for liners, based on small deflection theory is presented in reference 12 and would be useful for any tank-liner study. Some experimental research has been done on a scaled-down version of a glass overwrapped honeycomb tank intended for use as an expendable tank for the current Shuttle (ref. 9). Much can be learned from this design, even though the tank was not designed for reuse.

AMBIENT AIR EFFECTS ON CRYOGENIC TANKS

In all tank designs, the problems of the presence of ambient air surrounding the tank must be considered. For example, the moisture in the air would condense and freeze on uninsulated tanks containing methane (CH_4), liquid oxygen (LOX), fluorine, or hydrogen (LH2) (fig. 6). For a tank containing LH2, both the oxygen (O_2) and the nitrogen (N_2) would freeze. Any frost buildup in the space between the tank and body shell shown in figure 3, for instance, would be unacceptable because f the vehicle weight increase and possible damage to subsystems. For all of the concepts, any liquefaction or freezing of the O_2 or N_2 in a cryo-pumping process would be detrimental, particularly in a confined space such as a crack in the insulation adjacent to the tank wall. In a multi-functional multi-layered tank such as that proposed, the temperature gradients and integrity of the layers against permeation of ambient air must be such that this cannot occur.

FILAMENT WOUND TANK CONCEPT

In a current study, a filament wound tank with a metallic liner is being analyzed for its potential as a propellant tank for future space transportation vehicles (fig. 5). The tank consists of a graphite composite overwrap on a 2-inch-thick foam-filled organic honeycomb. The liner is fabricated from 2219-T87 aluminum. Reusable surface insulation tiles (RSI) are bonded directly to the outside of the tank. Potential advantages of the configuration over an aluminum tank and separate body shell, or the single metallic honeycomb sandwich, are:

(a) The foam-filled honeycomb is multi-functional, serving as a cryogenic insulator and as a stabilizer to prevent buckling from in-plane compressive loads. This should save weight, since conventional systems such as stringers to carry axial compression loads in the tank can be eliminated.

(b) The thermal protection tile (or reusable surface insulation, RSI) provides some insulation for the cryogenic fluid during ground hold and ascent, reducing the thickness of the cryogenic insulation needed.

(c) The combined tank-body-shell wall system takes up much less moldline volume making the vehicle much smaller.

(d) The composite tanks should not fail catastrophically.

Tank Liner Strain Matching

One of the greatest problems in the design of large low-pressure filament wound metal lined tanks for rocket propellants is the geometric mismatch caused by thermal contraction of the liner in the presence of a cryogenic propellant. One approach is to pre-pressurize the liner and, by design, match the pressure-expansion of the liner to the expected thermal contraction due to temperature. The thermal contraction of the liner in in/in is given by:

$$\varepsilon_t = \alpha(dT) \qquad (1)$$

Where α = Expansion coefficient, in/in ^{o}F
and dT = Difference between ambient and operating temperature, ^{o}F.

The strain in the liner at operating pressure is given by:

$$\varepsilon_s = S/E \qquad (2)$$

Where S = Hoop stress in barrel section of tank, psi

and E = Modulus of liner material, psi

In order to obtain a geometric match for the operating condition, the thermal contraction (strain) must equal the pressure expansion (strain), or:

$$\varepsilon_t = \varepsilon_s \qquad (3)$$

from which

$$dT = S/\alpha E$$

From the above, the allowable temperature drop without liner separation depends on the operating stress in the liner and the modulus and expansion coefficient of the liner material. Therefore, the best liner material, from the standpoint of strain matching, is one that can operate at the highest operating stress (S) and has the lowest $\alpha(E)$ product.

Likely candidates in the forseeable future for main rocket engine propellants cause a geometric mismatch between the liner and overwrap for an allowable pressure strain in an aluminum liner of 0.0024 in/in. (This strain in an aluminum liner corresponds to a 25,000-psi operating stress.)

For this constraint, the thermal contractions compared with the pressure expansion are shown for various propellants in figure 7. The thermal contractions of the liner for various propellants are shown as positive values in order to better identify tank-to-liner gaps for a 25-psi operating pressure and an unrestrained liner.

For example, an aluminum liner within a room-temperature graphitic composite overwrap, if unrestrained, would pull away from the overwrap. The amount of the mismatch for hydrogen storage would be 0.0037 in/in, or the difference between the 0.0061 and 0.0024 in/in values shown in figure 7. This would amount to about a 0.73-in. radial gap between the liner and overwrap for the 32.8-ft diameter on the hydrogen tank used as an example in the study (fig. 8).

If an aluminum liner could be operated at a 45,000-psi stress, methane could be stored without a geometric mismatch. This is based on storage at a temperature near the boiling point of the propellant, which is -259°F. For hydrogen, the required stress for an aluminum liner for strain matching is 61,000 psi for storage at -423°F. The corresponding liner thickness is 0.081 in. The 61,000 psi exceeds the nominal 0.2-percent offset yield by 7 percent but does not exceed the nominal ultimate tensile strength of 69,000 psi. Yielding the liner is a practice sometimes used on tanks with overwrap to work harden the liner and to place it in compression upon completion of the first pressurization cycle.

A matrix of liner materials and liner thicknesses is summarized in Table I for three tank materials and three cryogenic propellants. The liners are stressed for strain matching. The values shown are based on a room temperature of 70°F for the tank (as fabricated) and for storage of the propellant at its boiling point. Also, stresses are hoop values for a 32.8-ft-diameter tank operating at a maximum pressure of 25 psi. Further, the overwrap is assumed not to contract. This is considered to be a reasonable assumption inasmuch as the expansion coefficient is small for a graphite composite; also this material is on the outside of the tank where temperature excursions are small compared with those for the liner. If the composite overwrap does contract, the assumption of no contraction is conservative.

Liner stresses and thickness values shown in Table I satisfy the condition for expansion under pre-pressurization equal to the thermal contraction from the introduction of the cryogenic fluid listed. Considering only the last column in Table I, the aluminum tank wall unit weight based on thickness and material density would be 1.17 psf; the boron/aluminum, 0.93 psf, and the nickel steel liner, 2.0 psf. (For comparison purposes, the average unit weight of the hydrogen tank in the Shuttle expendable External Tank is 3.3 psf. The corresponding LOX tank unit weight is 2.8 psf but it is 3.3 psf when slosh baffles are included. All of the LH2 liners are thinner than the corresponding LOX and CH4 liners because the matching strain assumptions make it necessary to have greater pressure strain to match the greater thermal contraction of the colder hydrogen. Operating the liners at the stresses listed in

Table I for hydrogen storage may be unacceptable for an aluminum liner. The 104,000 psi required for the nickel steel liner is well below the yield listed at 153,000 psi (the ratio of yield to operating stress being 1.47). The yield strength of a composite aluminum may be adequate, but little is known regarding its application to tankage. The matching strain approach, however, is more tenable for storage of the CH_4 and the LOX because of the lower stresses needed to match the lower thermal strains.

The liner problems that might be encountered in the dome areas (where the membrane stresses are nominally one-half the hoop values) are not addressed. Some liner separation from the overwrap may not be detrimental in the dome areas, since the tank is stabilized by compression along the barrel section in the radial direction and by shear in the axial direction, particularly if the tank is fabricated with several hundred psi pre-compression in the liner. The equal-strain, high-operating stress liner represents a somewhat different approach from the lower-operating-stress, high-pre-compression liners.

Tank Liners With Pre-Stress

A second approach to the design of a filament wound tank with a liner is to pre-stress the liner in compression during manufacture. In so doing, when the tank is pressurized, the compression strain must be removed first before the liner reaches a tensile condition. In theory, enough compressive strain can be placed in the liner during fabrication so that there will be no liner-to-overwrap separation when the liner is cooled to the propellant temperature even when the tank is unpressurized. In reality, most liners will buckle when compressed to the matching thermal contraction strain associated with the commonly used cryogenic propellants.

As a compromise solution, some pre-stress is placed in the liner, but not enough to cause buckling. In doing so, the intermediate layer of insulation-filled honeycomb is also placed in compression. This reduces the amount of tensile strain on the insulation during operation and minimizes the likelihood of crack development for a material that is weak in tension. Once in use, the tank is pre-pressurized to the operating condition prior to filling it with the cryogenic propellant. A similar procedure is followed in the current Shuttle for similar, but not identical, reasons. In the Shuttle procedure, the tank is pressured to 26 psi prior to filling to prevent dimpling of the tank at the aft-strut orbiter-to-external tank attachment points. In this approach, then, the liner is pre-stressed in compression and in operation is pre-pressurized prior to filling.

In figures 9 and 10, two fabrication conditions for the tank are shown--one in which no pre-stress was assumed in a 0.10-in liner, and the other in which the liner was pre-stressed in compression to 20,000 psi. A program that is suitable for determining the stresses in a thick-walled body of revolution was used (ref. 13). The overwrap serves two purposes, the reduction in the operating tensile stress in the aluminum liner and the elimination of the tendency for the liner to separate from the other tank wall layers. For example, at an operating pressure of 25 psi and a liner pre-stress of 20,000 psi, the stress in the aluminum liner is about 34,000 psi (fig. 9). Without any pre-stress in the liner, the operating tensile stress in the aluminum is about 46,000 psi. The overwrap used in a test case consisted of 11 layers of graphite/polyimide (fig. 11). In the figure, the 90 fiber orientation refers to the hoop direction. In the analysis all tank layers are assumed to be in contact and bonded.

FRACTURE MECHANICS ANALYSIS

A fracture mechanics analysis was conducted on the aluminum liner. An initial undetected flaw was assumed to exist. This flaw was assumed to be in the form of an internal semi-circular surface crack with a radius of 0.05 in. The fracture mechanics analysis was conducted for both the room temperature and cryogenic environments using the properties for the 2219-T87 aluminum. A discussion of tank flaws and tank life is presented in reference 14.

A computer program entitled NASA/FLAGRO was utilized to determine the fatigue life in the current study (ref. 15). The program provides an automatic procedure for calculating the life of a cyclically loaded structure with defects. The criterion for failure is defined by the growth of the crack to the outer surface of the tank. The loading history on a pre-stressed liner differs from a liner that is only subjected to tension such as the matching strain design. The following analyses apply to liners that are cycled only from zero to a tensile condition. The assumption is conservative for a liner that is subject to full cyclic tension-compression stresses.

In figure 12, the hoop stress versus cycle life is plotted for both cryogenic and room temperatures for the hydrogen tank for a 25,000 psi operating hoop stress. For a 99-in-radius tank, the predicted cycle life of the tank (assuming no scatter in the results) exceeds 10,000 cycles for the room temperature condition. At cryogenic temperature, the cycles-to-leak exceed 100,000. For the 197-in-radius tank, the cycles-to-leak approach 30,000 at room temperature and exceed 400,000 for the cryogenic case. (Note: The 197-in radius, or 32.8-ft diameter, is the dimension of the barrel section of the tank in these studies.) Operationally, the tank walls experience a mixture of cyclic loads at cryogenic, room, and somewhat elevated temperatures prior to launch, and during ascent and entry. Similar data are shown in figure 13 except that tank wall gauge is substituted for hoop stress as the ordinate.

For the 197-in-radius tank, the tank wall gauge based on pressure and allowable stress in the aluminum is 0.197 in. Likewise, the tank wall gauge for the 99-in-radius tank is one thousandth of the tank radius or is 0.099 in. This is due to the somewhat fortuitous selection of 25,000 psi for operation stress in the material and 25 psi for ullage pressure; both values are fairly typical for aluminum tanks for the storage of hydrogen.

The substantial increase in cycle life of the larger tank over the smaller tank is evident in figures 12 and 13. Theoretically, this is achieved with no change in the tank structural fraction because of the relationships between tank wall gauge, volume, area, and weight. In fact, the overall tank should be lighter if the cryogenic insulation is taken into consideration, since tank capacity increases as the cube of dimension, while surface area insulation increases only as the square. Also, the non-optimums should decrease as a percentage of tank weight. One example would be any penetrations in the tank wall required for instrumentation, pressurization systems, or propellant feed. (In these instances, the weight reductions take the form of reductions in the amount of reinforcement required around the tank wall openings.)

If the much greater cycle life for the larger tank shown in figures 12 and 13 is not needed, the added capability could be converted to a weight savings by reducing the gauge on the tank wall (i.e., raising the allowable stress).

LINER CONFIGURATION ALTERNATIVES

The critical compressive stresses for various liners versus diameter-to-liner thickness are shown in fig. 14, taken from reference 5. For a diameter-to-liner thickness ratio of 2000, for the design test case, the D/t ratio corresponds to a constructive wrap compressive strength-to-secant modulus ratio of about 10 (fig. 14). A D/t of 2000 corresponds to a radius(r)/t of 1000 or in one of the examples used, to the ratio 197 in/0.197 in. This ratio remains constant irrespective of tank size as long as material working stress and tank pressure remain the same in the hoop stress formula.

A thin honeycomb sandwich liner could be substituted for a single monocoque load sharing liner. This would enhance resistance to buckling, but the liner weight would increase. Assume two 0.099-in-thick face sheets on a 1/4-in honeycomb core are substituted for a 0.197-in-thick membrane liner. Then the room temperature cycle life of the liner has decreased theoretically from over 28,000 to 12,000 cycles. However, the liner should be fail safe and operational, since the probability of a leak path through both face sheets is reduced. This assumes equal joint reliability in the welding of the 0.099-in-thick material compared with the 0.197-in material. To inspect for possible leakage into the honeycomb sandwich cells, an imaging infrared camera could be used, since thermally hot or cold spots would be indicative of a defective cell.

A second alternative is a non-load carrying liner that is allowed to buckle locally in order to accommodate the mis-match between thermal and pressure induced strains. However, this concept tends to be unsuitable for reusable systems because of the fatigue cracks that develop under cyclic load. An especially complex stress pattern would develop in the vicinity of the barrel-to-dome transition leading to early liner failure.

A third possibility is a thin membrane that is bonded to the composite tank shell. This membrane could conceivably be a metallic-coated organic film with enough elasticity to accommodate any differential in strains between the liner and the composite tank shell. However, no such film is known to exist.

In the previous discussions, a total of five liners have been included: the membrane-strain-matching, the membrane pre-stressed, the thin-honeycomb pre-stressed, the elastic-pre-bonded, and the buckling liners. Some analysis is shown for the strain matching and pre-stressed liners.

WHY CONSIDER FILAMENT WOUND TANKS

There are several reasons for including filament winding as one of the candidate fabrication methods for the propellant tanks on future Earth-to-orbit transports. First, the principal stress directions are known and differ by a factor of two, and the fiber directions can therefore be tailored to minimize material weight--a practice not possible when using isotropic materials. Secondly, tanks fabricated from composites may be lighter because composites can be produced with much higher strength-to-density ratios than metal alloys. Graphitic fibers, for example, are now being produced that have tensile strengths as high as 800,000 psi (ref. 16). A third advantage in using composite filament wound tanks is that they can be designed for leak-before-burst failure criteria. Further, an overwrap can be employed, as cited earlier, taking advantage of its high specific strength to minimize the stresses in a metallic liner and as a means of capturing the cryogenic insulation on the outside of the tank.

The overall weight advantages of the filament wound tank are not readily identifiable, since the weight differences are intricately involved in the overall vehicle and the functions the tank performs--whether containment only, thermal protection, load transmission, or various combinations of the three. Further, there are no fully reusable large low-pressure tanks with which to compare. Another advantage of the overwrap on externally applied cryogenic insulation is that this may be the only means of rendering the insulation reusable. This is achieved by placing the lightweight foam in pre-compression, radially, axially, and circumferentially, so that the tensile strain is much lower than a non-pre-stressed foam. Efforts are being made to develop reusable cryogenic foam insulation. A high density foam panel 2-in thick and 10-in square has been tested for 100 thermomechanical cycles simulating usage on a cryogenic tank for Earth-to-orbit transports (ref.17). The estimated weight of the filament wound tank wall with a 0.197-in liner is 4.10 psf. This is based on the following weight allowances in psf: 0.43 for the graphite composite overwrap, 0.50 for the honeycomb core, 0.33 for the core foam insulation, and 2.84 for the liner. The 4.10 psf value can be compared with the 3.70 psf Shuttle hydrogen tank without insulation or 4.10 psf when the spray-on foam insulation (SOFI) is included.

Filament winding is a rapidly growing industry. The 30-year old process is fast, inexpensive, and proven for making ultralight pressure vessels. Researchers may be able to develop flexible membrane liners that are impervious to hydrogen, making the filament wound tank even lighter than the test case load bearing liner described earlier. As an alternative, the single honeycomb metallic shell walls described in references 3 and 4 may be found to be feasible, if the high stresses induced from thermal gradients can be accommodated.

DESIGN FACTORS OF SAFETY

Traditionally, factors of safety used in the design of structure are based on experience and vary depending upon circumstances of application, lifetime requirements, materials, and other considerations. The factors also allow for some unknowns. Ideally, structure (including tanks) should be designed on the basis of statistical information regarding load history, material properties, and the material thicknesses selected to satisfy an assigned probability for success. The life of a tank liner based on fracture mechanics for a given number of cycles would be one of the inputs. The statistical methods often discussed but seldom applied, are outlined in reference 18. By using statistical methods, unnecessarily large design margins can be avoided, and the possibility of reducing tank weights exists.

Typical factors of safety for reusable structure and pressure vessels are shown in Table II. Typical peak flight dynamic pressures and dynamic pressure angle-of-attack products are shown in Table III. Typical ultimate load factors are shown in Table IV for vertical-takeoff, horizontal landing. These differing environments, for example, the higher loads associated with horizontal versus vertical takeoff, must be taken into consideration when assessing the weights of tanks. Typical operating and limit pressures are shown in Table V. The ideal tank design is one that has a high probability of not failing during the life of the vehicle and, if it does fail, is safe and operational. Another requirement is that the tank must be easily inspectable in order to minimize operation costs. The dual wall tank may provide the solution to both requirements. For example, if one of the face sheets develops a crack and the propellant fills up one of the honeycomb core cells, the second face sheet would prevent the tank from leaking. The vehicle is operational and safe for completion of the mission but must be repaired prior to the next flight inasmuch as there is no redundancy in the tank wall at the failed cell. The failed cell could be identified by an imaging infrared camera as a thermal anomaly.

SUMMARY REMARKS

Some of the design considerations in the development of propellant tanks for future Earth-to-orbit transports have been identified. The potentially lightest vehicle results when the tank is combined to serve also as a body structural shell. A single metallic honeycomb sandwich tank-body-shell combination (to provide containment, insulation, and load carrying functions) appears to be the simplest and lightest concept, but the exceedingly high stresses (primarily thermally induced) may preclude its use. As an alternative, a composite overwrap on a metallic liner with an intermediate honeycomb layer may provide a system with greater redundancy. For this type of tank, the development of the technology for liners is required, and construction of large filament winding machinery may be necessary, accompanied by the manufacture of a tank, with all the elements in place in order to prove the concept. Overall, the filament wound tank concepts appear to offer prospects for success in developing lightweight durable main propellant tankage for future Earth-to-orbit transports.

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Table I. Liner Stresses and Thicknesses For Equal Thermal-Pressure Strains

Material	Operating Stresses, kpsi CH4	LOX	LH2	Thicknesses, in CH4	LOX	LH2
Aluminum	45	46	61	.110	.107	.081
Boron/Aluminum	50	56	74	.100	.090	.068
Nickel Steel	40	78	104	.123	.064	.048

Table II: DESIGN FACTORS OF SAFETY

Item	Factor of Safety* Proof	Yield	Ultimate	Buckling
Ground Handling Equipment	2.5	3.0	4.0	--
Vehicle (i.e., adapters, fins, and structure)	1.1	1.15	1.4 to 1.5	1.5
Flight Systems				
Under internal pressure				
Reusable propellant tanks	1.5	1.65 to 1.95	2.0 to to 2.5	1.5
Expendable Tanks	1.25	1.40	1.70	--
Solid Rocket Motor Cases				
Metallic	1.1	1.15	1.5	1.5
Fiber glass	1.1	--	1.3	1.5
Pressure Tubing	2.5	3.0	4.0	--

*The ratio of the stress in the material at proof testing, yield, ultimate, or buckling condition to the limit stress expected when the material is in use.

Table III. Typical Flight Environments

Conditions	Vert. Takeoff (Rocket)	Horizontal Takeoff (Rocket)	Horizontal Takeoff (Airbreathing)
Max. dynamic pressure (Q), psf	650	1200	1800
Max.Q-alpha product, psf-deg	3000	4000	6000

Table IV. Ultimate Load Factors
(Vertical Takeoff Horizontal Landing)

Mission Phase	Factor Nx	Factor Ny	Factor Nz
Ascent	4.5	0.7	-1.05
Entry/Cruise	0.75	1.5	3.75/-1.5
Landing	1.5/-1.2	-1.0/0.75	3.75

Table V. Shuttle Tank Pressures

Type of Pressure Vessel	Pressure, psi Lim. Operating	Pressure, psi Upper Structural
Main Tanks		
LOX 2219 T87	26	40
LH2 2219 T87	37	40
Fuel Cell Dewars		
LOX (Inconel 718)	950	1050
LH2 (Aluminum-2219)	285	335
Pressurization Systems		
Helium Spheres	4,875	7,268

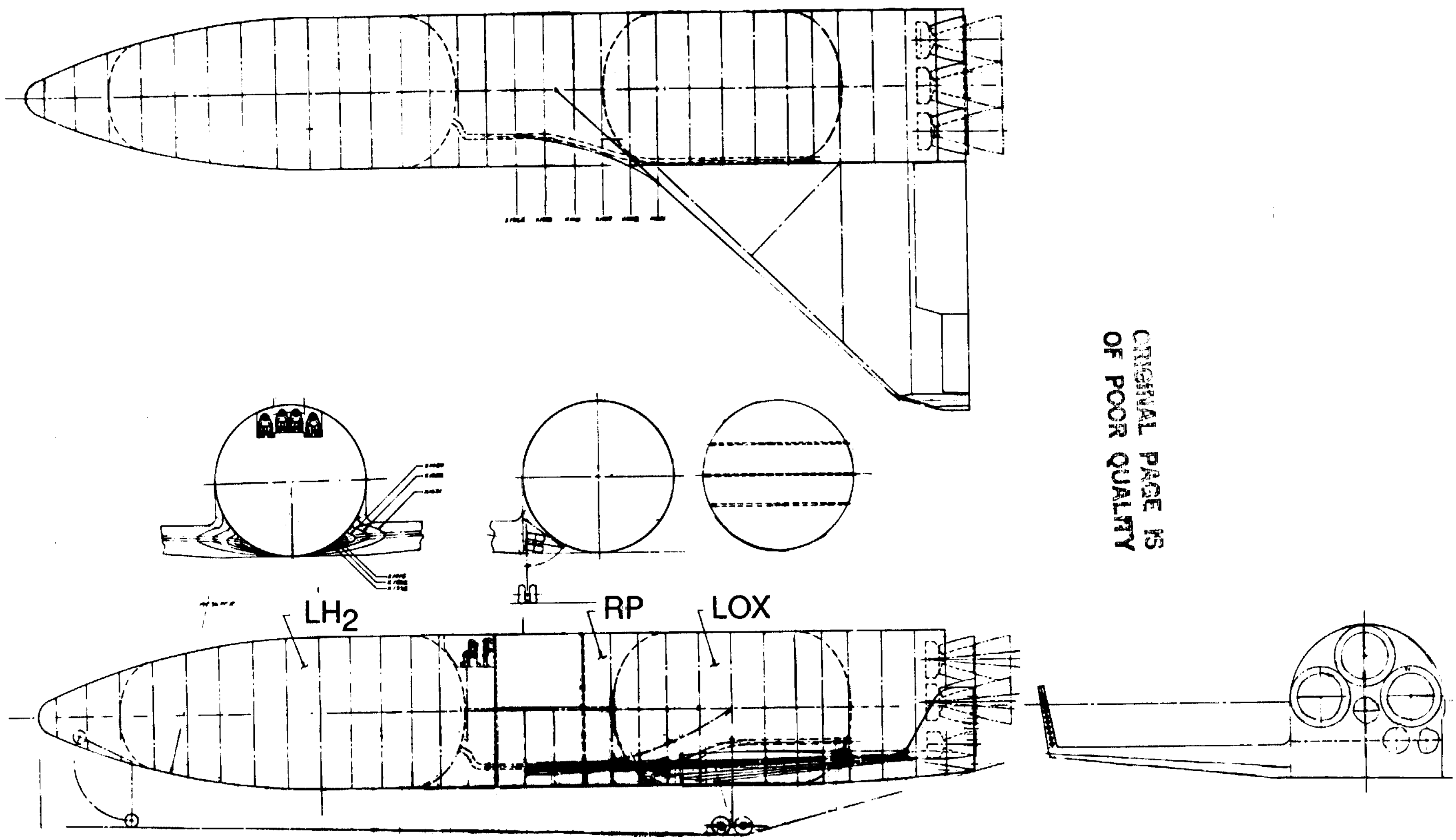

Figure 1. Inboard profile an advanced Earth-to-orbit transport concept.

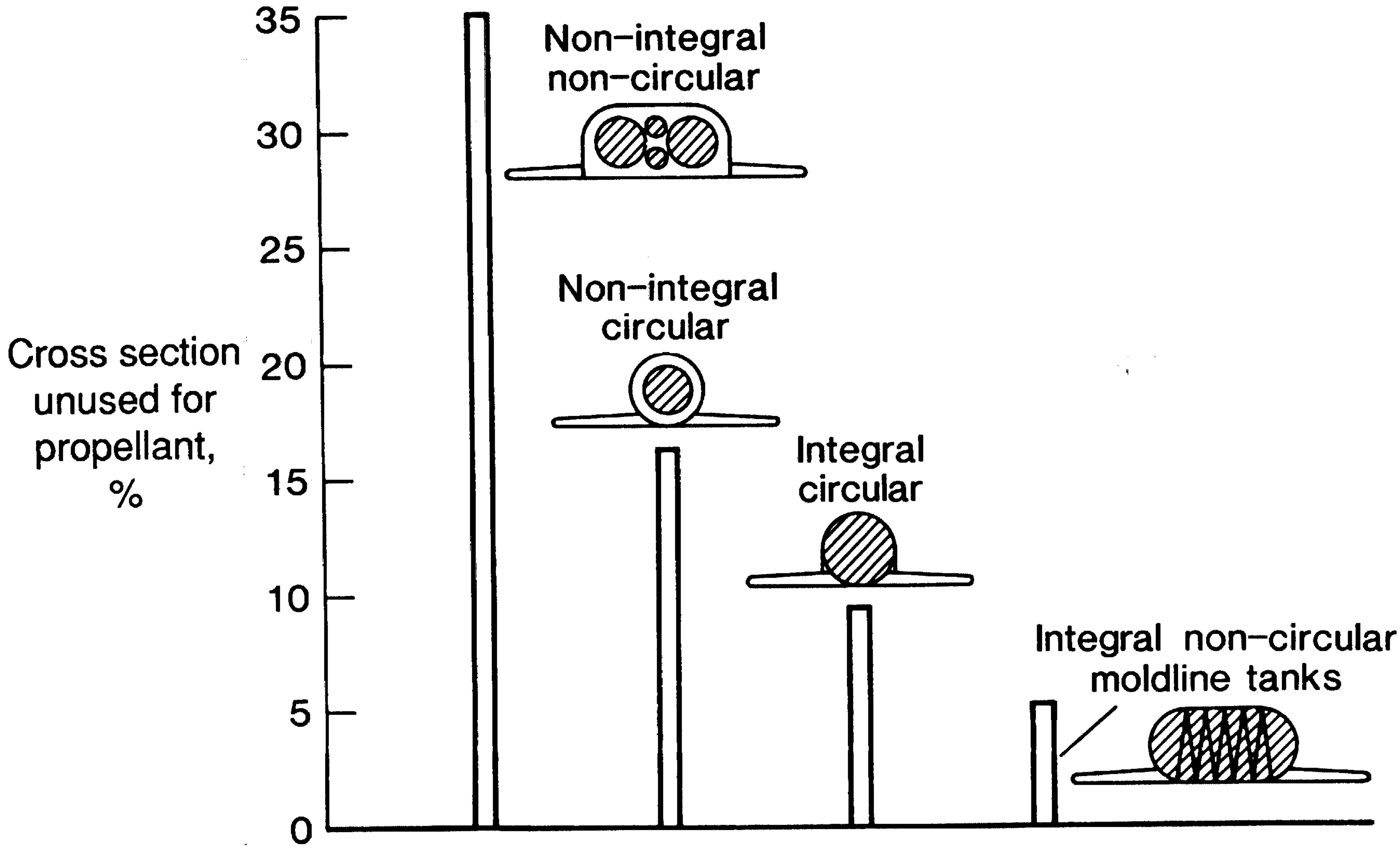

Figure 2. Portion of cross section not used for propellant for four transport designs.

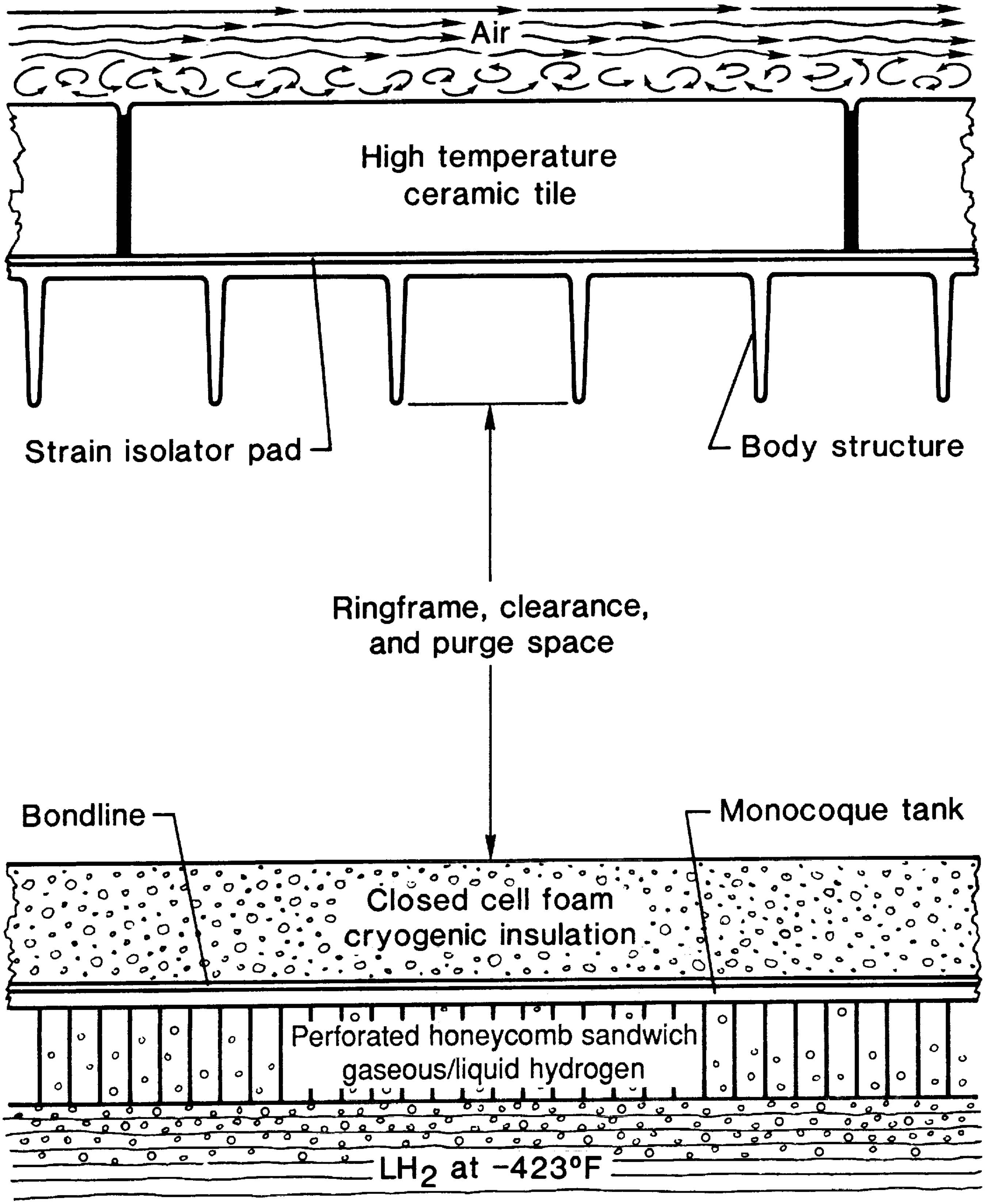

Figure 3. Conventional body-shell-tank cross section.

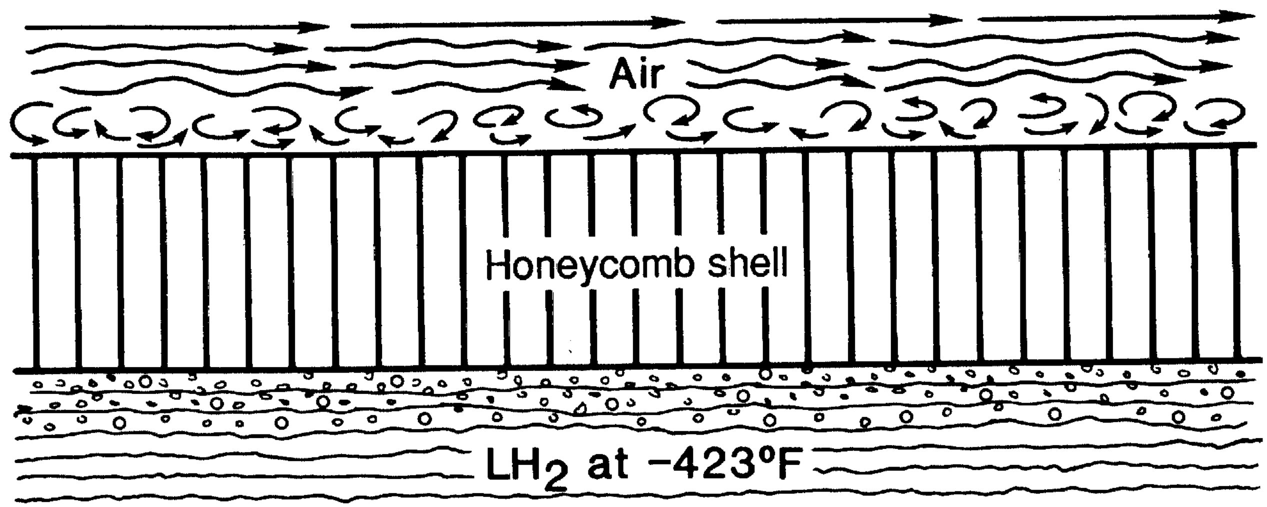

Figure 4. Single metallic honeycomb sandwich body shell.

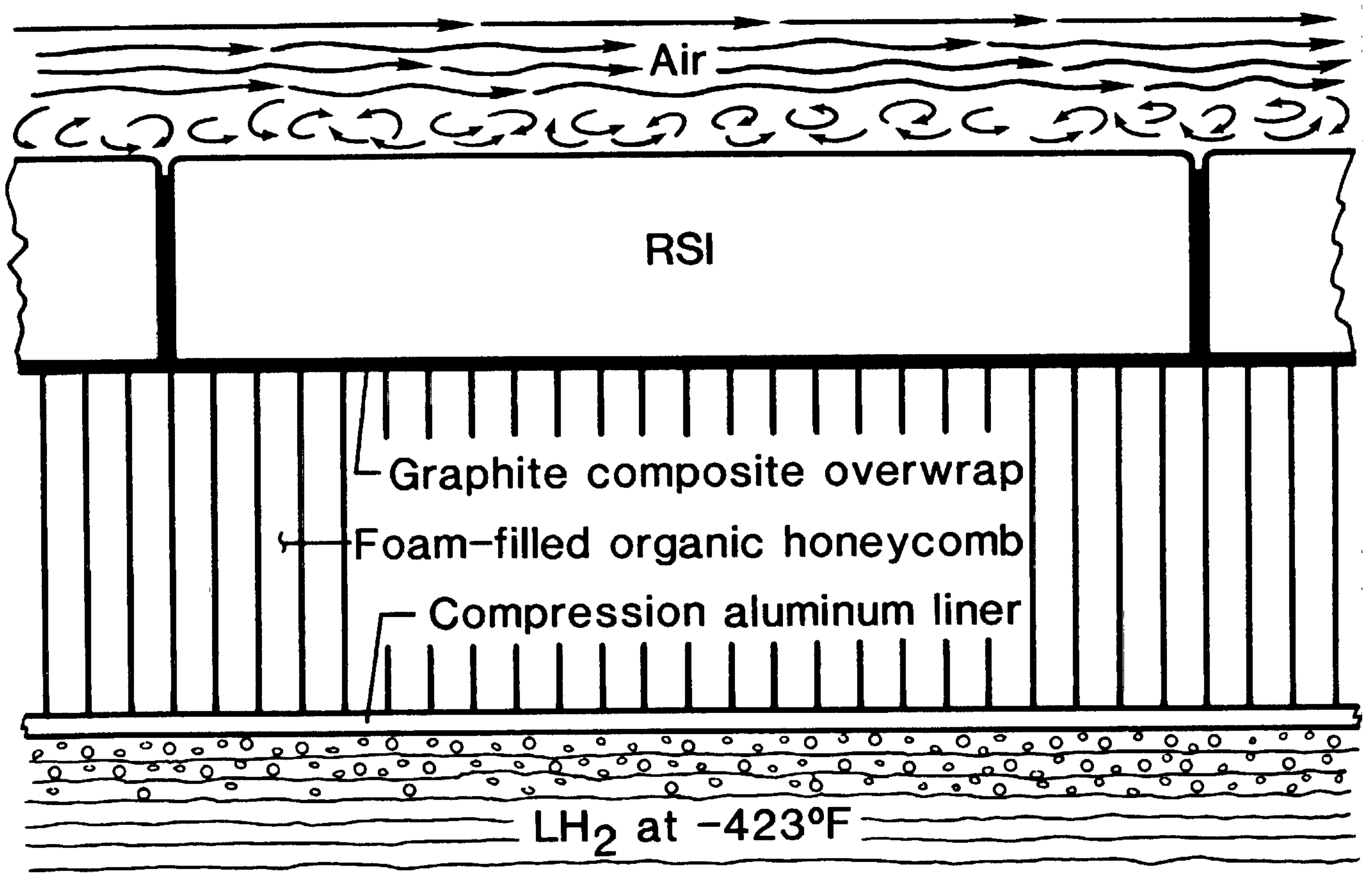

Figure 5. Filament wound tank with metallic liner.

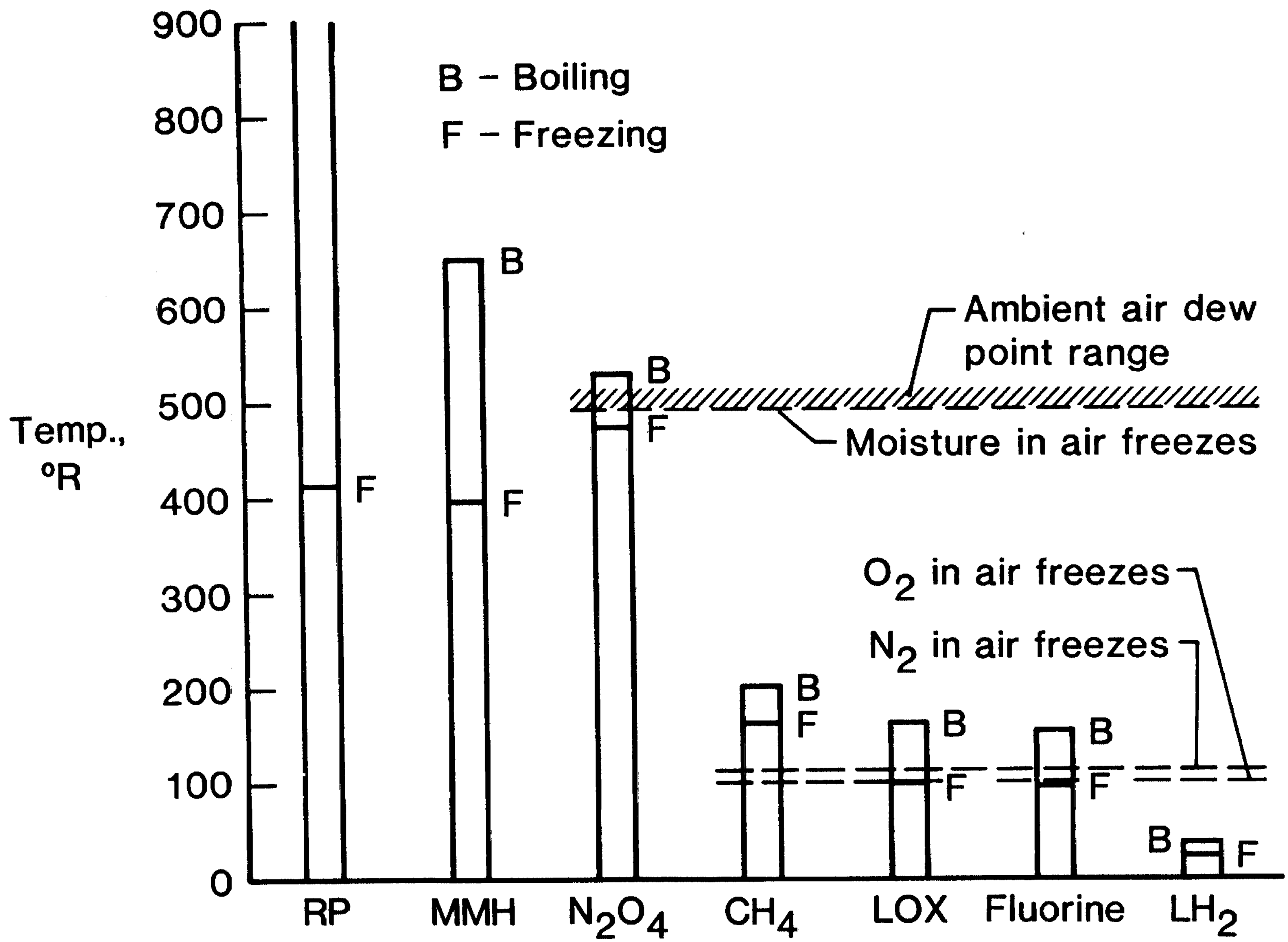

Figure 6. Freezing and boiling points for several propellants.

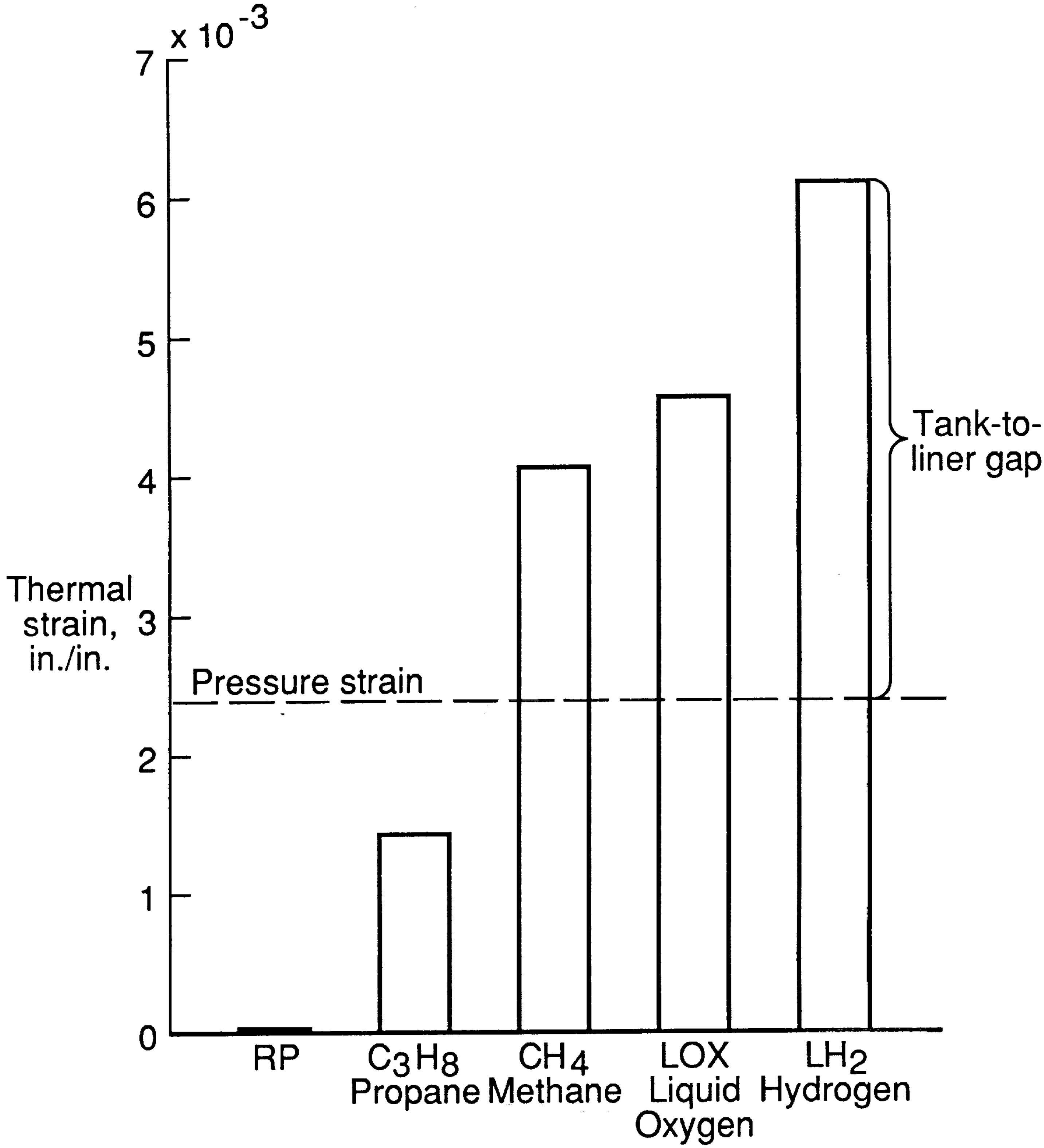

Figure 7. Thermal and pressure strain comparisons for 25 psi tank operating pressure.

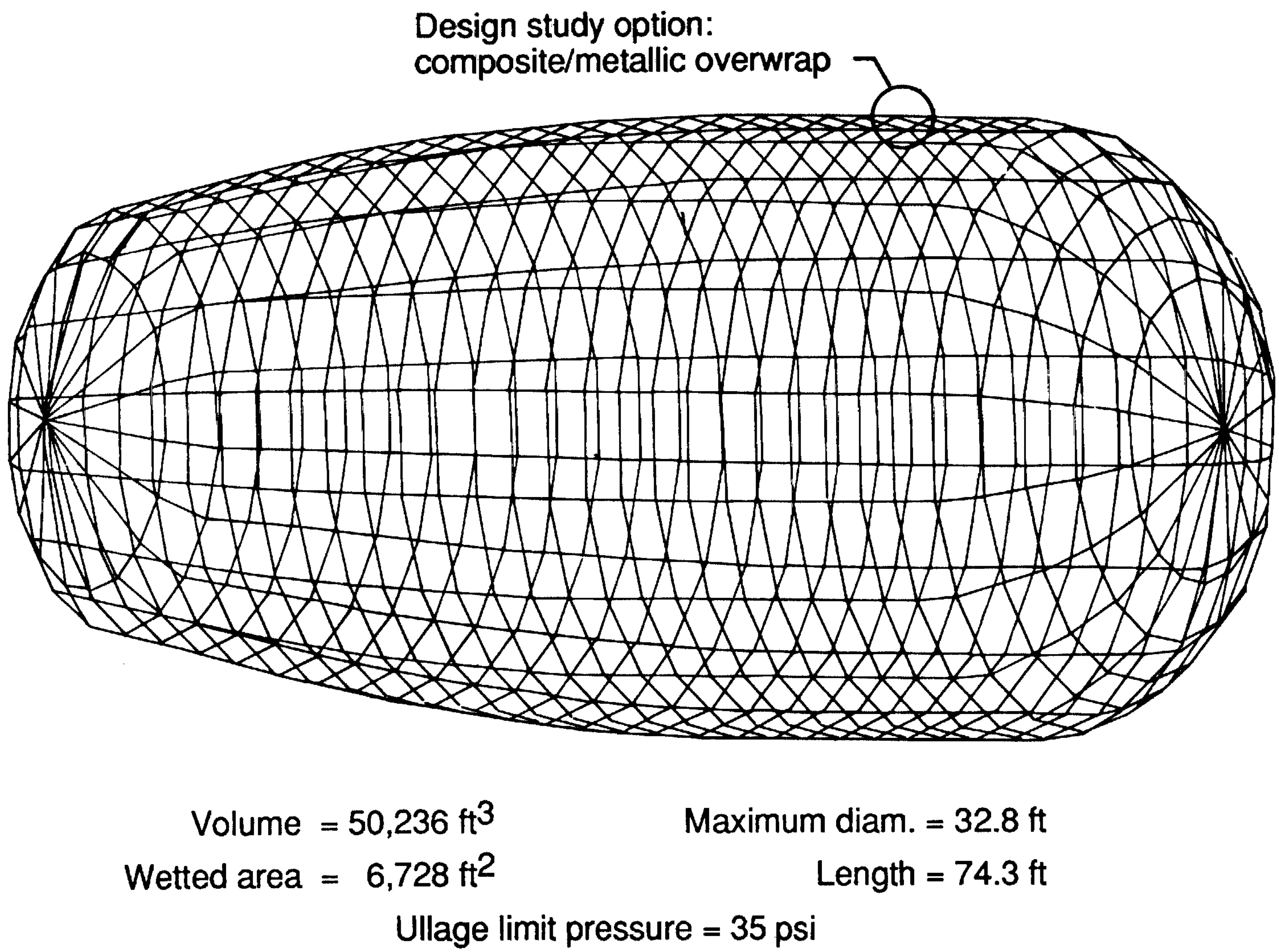

Figure 8. Finite element model of forebody hydrogen tank.

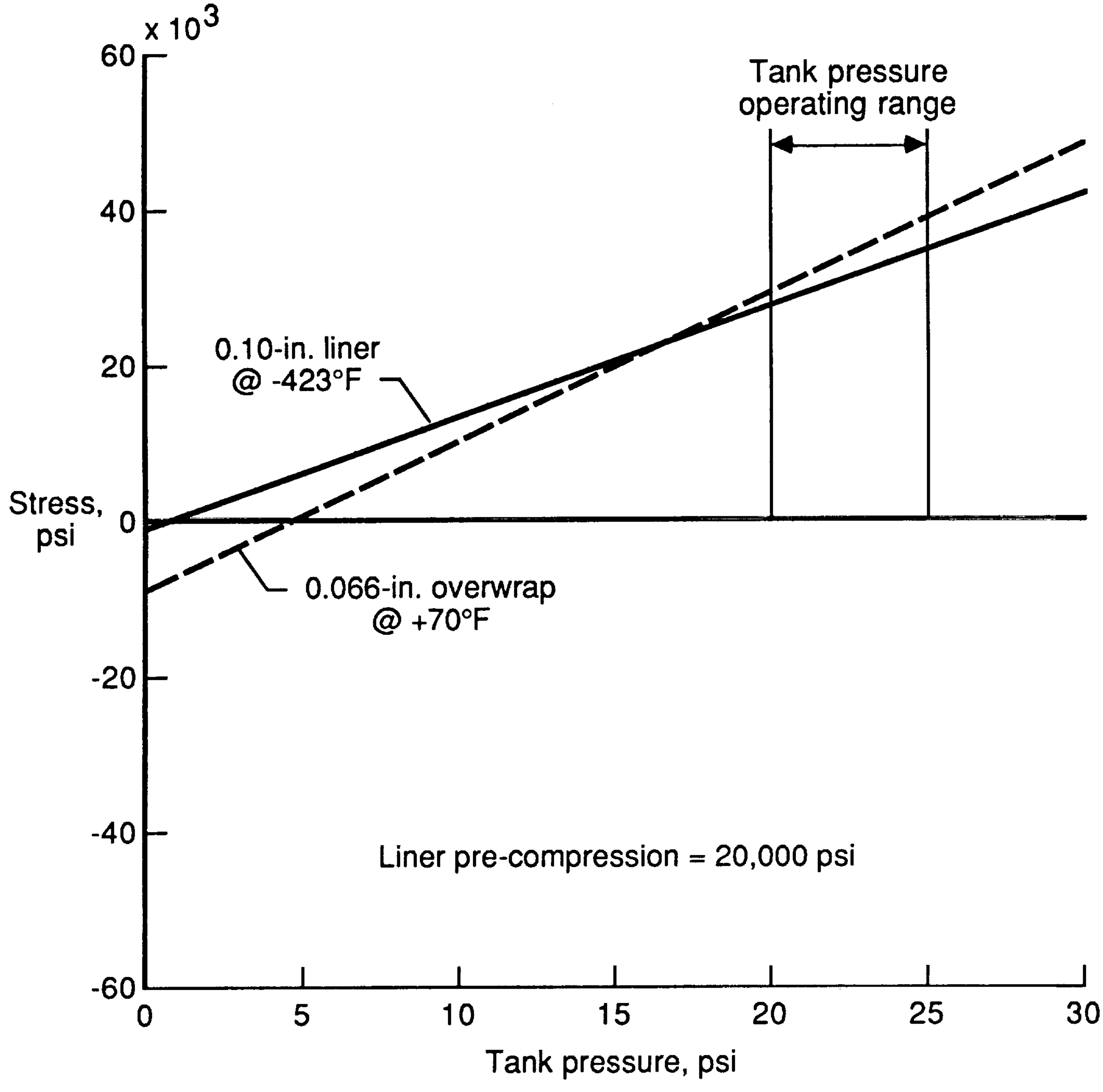

Figure 9. Stress versus tank pressure for pre-stressed liner.

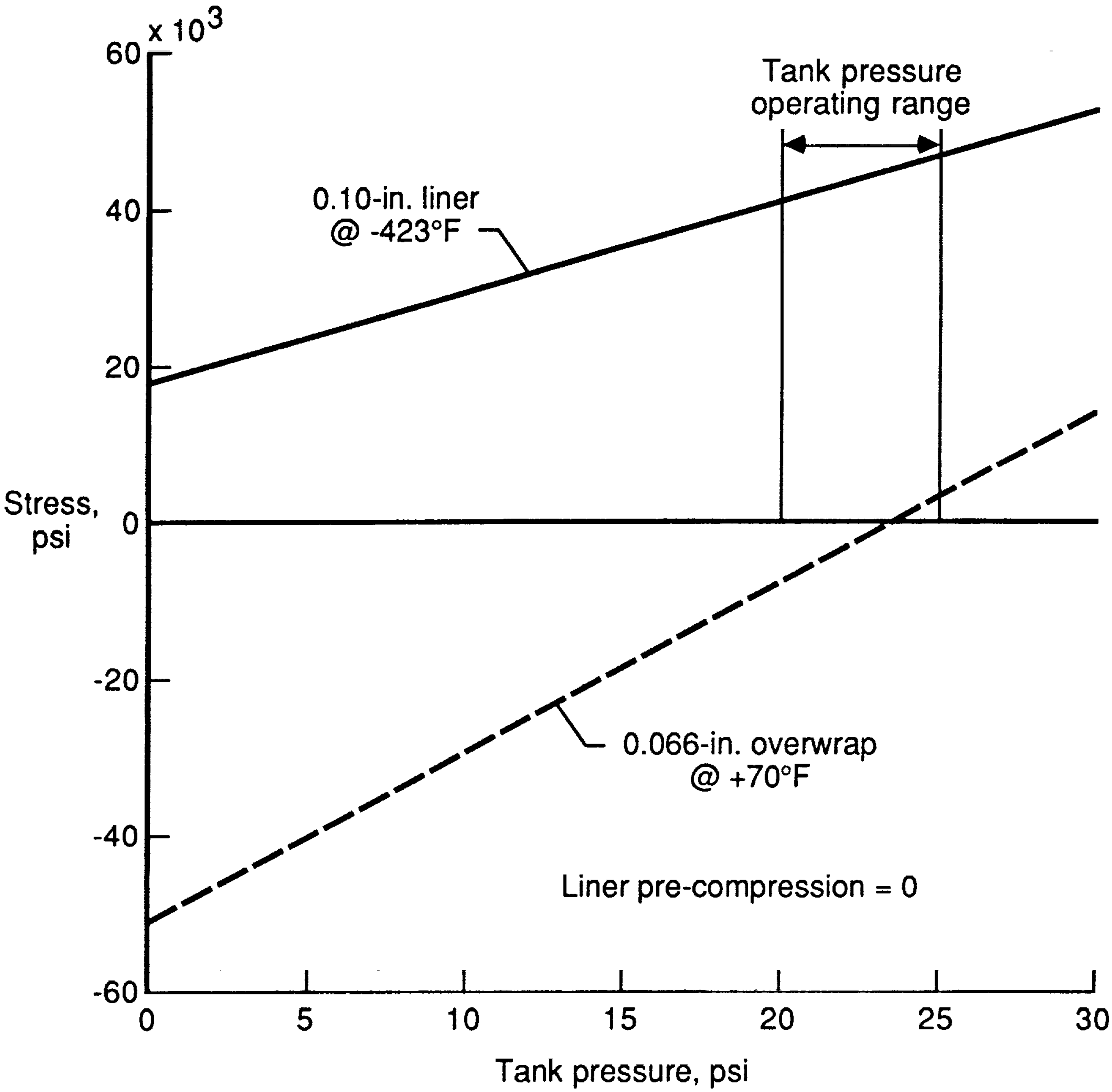

Figure 10. Stress versus tank pressure for zero pre-stress liner.

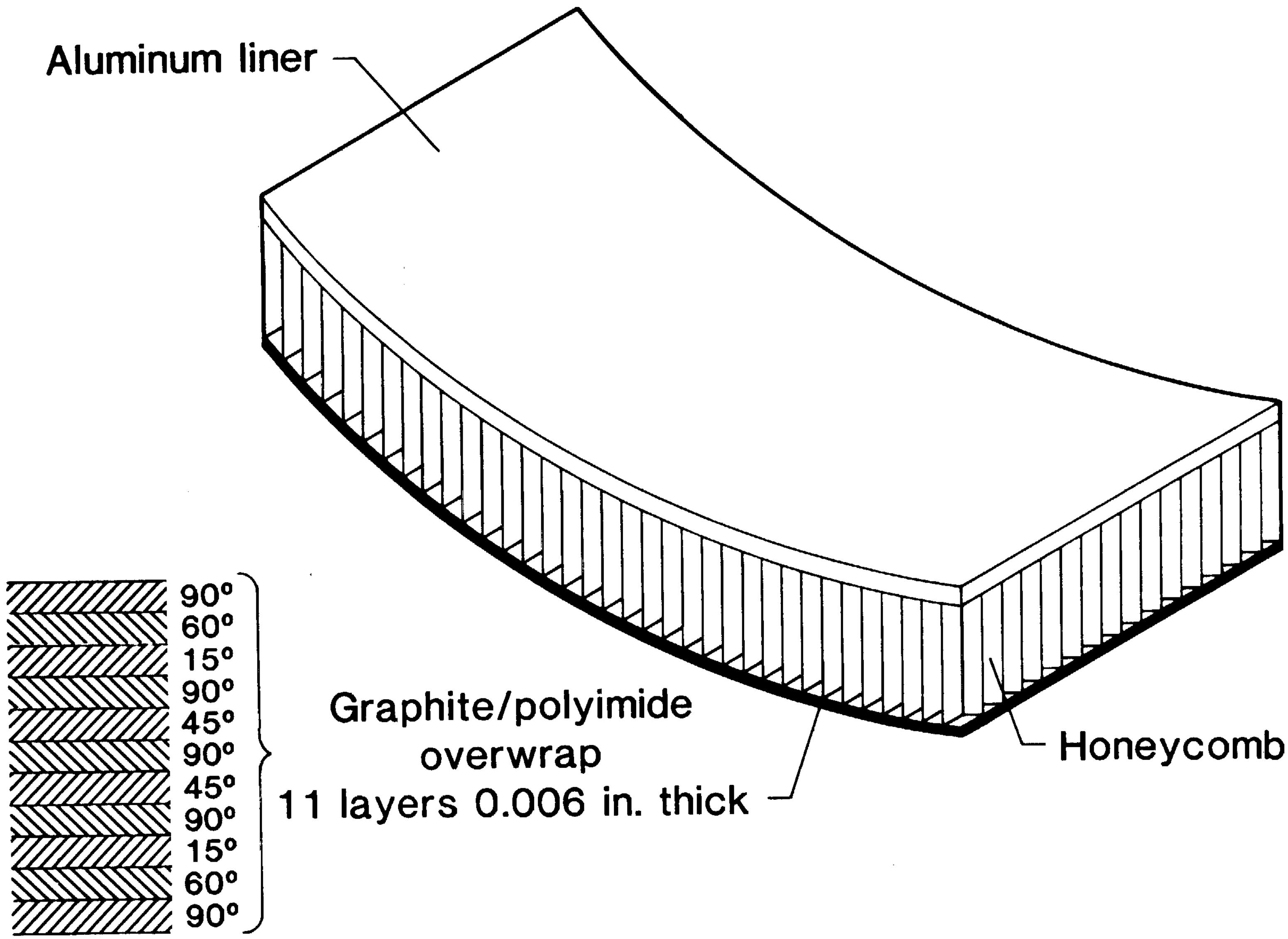

Figure 11. Filament wound tank wall element.

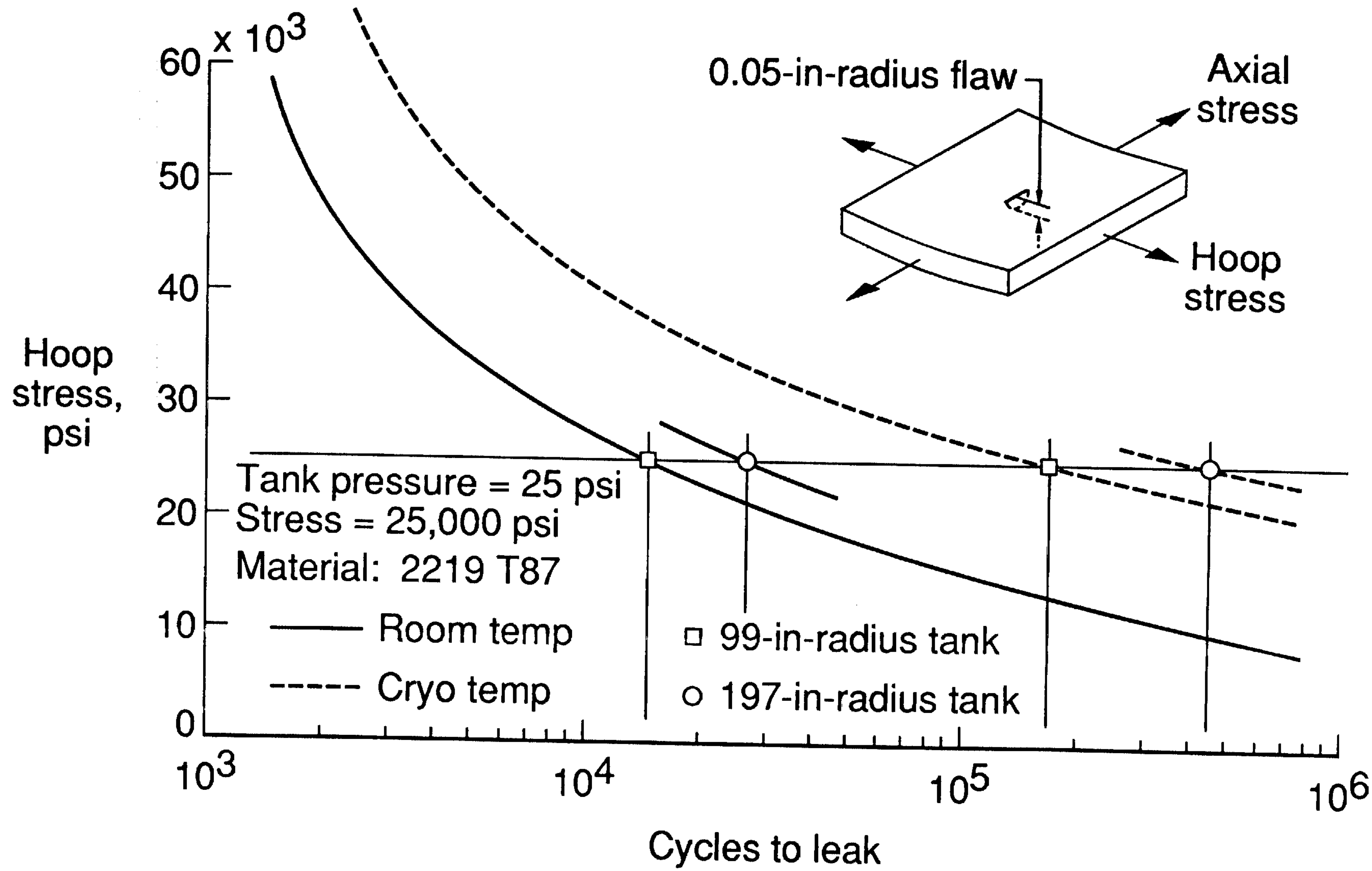

Figure 12. Hoop stress versus cycles-to-leak for an aluminum liner.

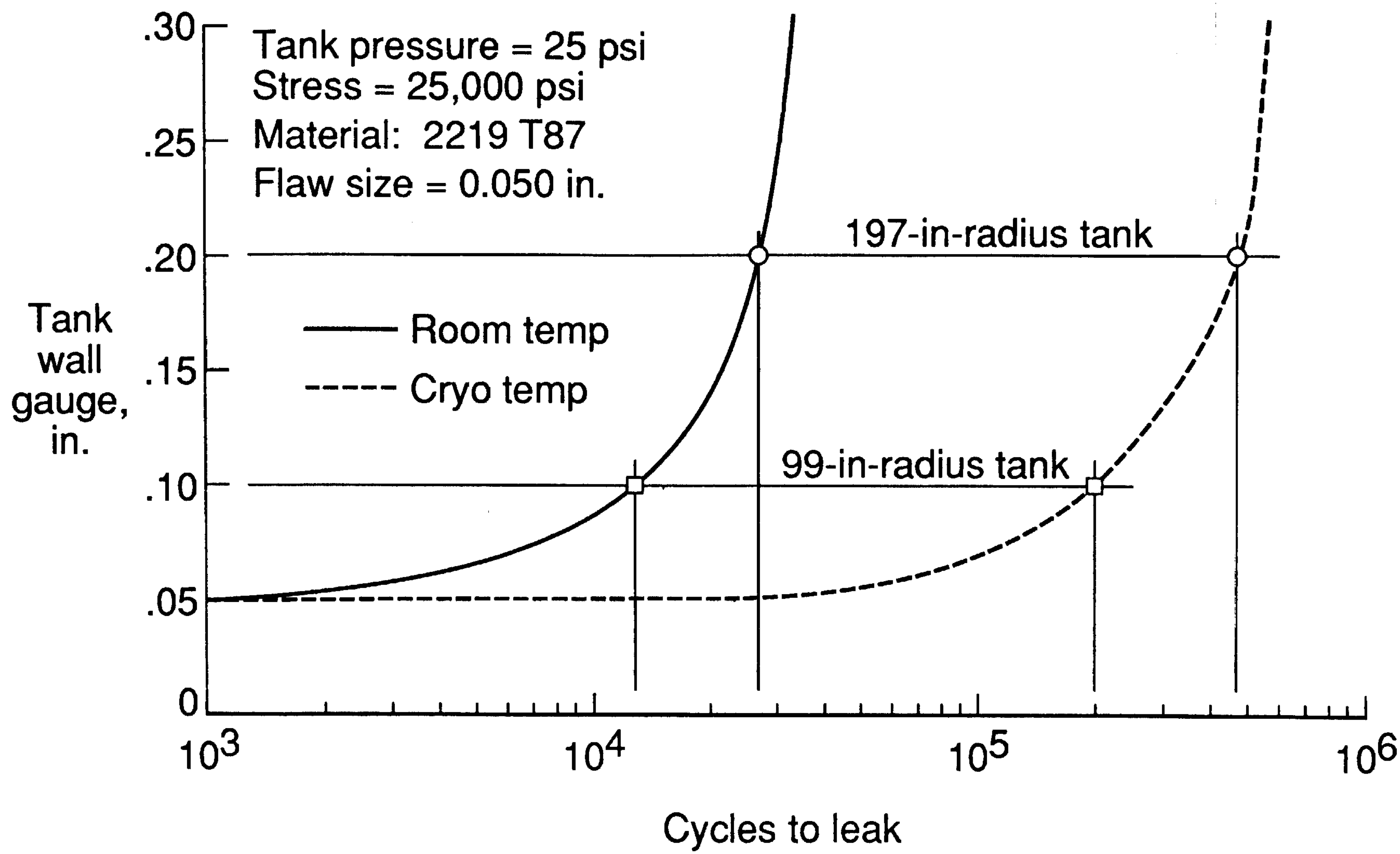

Figure 13. Tank wall gauge versus cycles-to-leak.

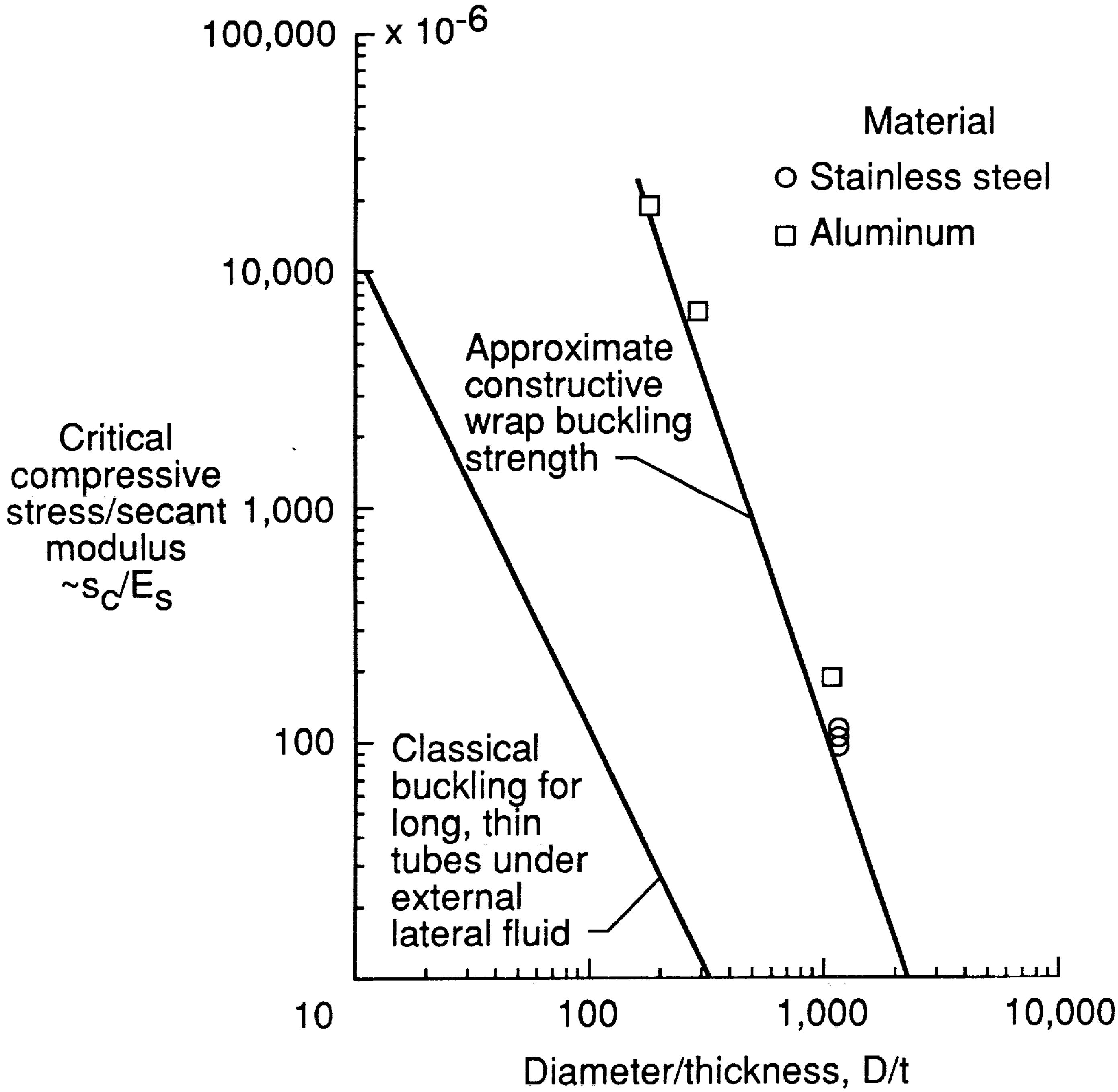

Figure 14. Compression strength versus tank D/t ratio.

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15. Supplementary Notes

16. Abstract
For future Earth-to-orbit transport vehicles, reusability and lighter weights are sought for the main propellant tanks. In order to achieve these goals, a filament wound tank with a metal liner and an intermediate layer of foam-filled honeycomb is proposed. A hydrogen tank is used as an example. In order to accommodate the mismatches in the expansion of liner and overwrap, a design is proposed wherein the liner is configured so that the extension of the liner under pressure matches the expected contraction of the same liner due to the presence of a cryogen. In operation, the liner is pressurized at a rate such that the pressure strain just matches the contraction due to the decrease in temperature. As an alternate design approach, a compressive pre-stress is placed in the liner such that the liner will not separate from the overwrap at operating conditions. A finite element program is used to show stresses in the liner and overwrap for various tank pressures for the pre-stressed liner concept. A fracture mechanics analysis is made of the liners to determine tank life. The tank concept shown has a similar unit weight to the Shuttle external hydrogen tank, but the filament wound tank is expected to be reusable. Various design considerations related to the integration of the propellant tanks into a future transport vehicle are discussed.

17. Key Words (Suggested by Author(s))
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