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COMPARATIVE STUDY OF FUSELAGE TANKS FOR LIQUID-METHANE-FUELED SUPERSONIC AIRCRAFT

by Rene E. Chambellan and William A. Bevevino

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ABSTRACT

Three designs of flight-weight nonintegral tanks, capable of gage pressures of 15 or 30 psi (10.8 or 20.7 N/cm^2), were studied. Two void spaces representative of a forward and an aft fuselage segment were selected. Ratios of tank weight to contained fuel weight range from 0.0110 to 0.0482 and volumetric efficiencies range from 75 to 95.4 percent. Tanks studied are thin-walled pressure vessels of titanium or nonmetallic fabric constrained to an envelope by structural elements internal to the tank.

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SUMMARY

Several designs of lightweight, pressurized, nonintegral tanks for storing liquid methane in the fuselage of a supersonic aircraft were studied. Three types of tank structures were compared: (1) membrane tanks made of a titanium alloy, (2) modified semimonocoque tanks composed of internal webs supporting a pressure-tight skin, all made of a titanium alloy, and (3) filamentary restrained, membrane tanks of either a titanium alloy or a nonmetallic fabric where the outer skins are restrained, respectively, by wires or threads attached to the opposite skin. Two storage spaces of nearly equal volume were assumed as typical of (1) a forward space whose cross section is a segment of a circle, and (2) an aft space whose cross section is an isosceles trapezoid.

Designs were compared by volumetric efficiency (ratio of tank volume to volume of space into which tank is fitted) and tank weight fraction (ratio of tank weight to contained fuel weight). Volumetric efficiencies ranged from 75 to 95.4 percent and tank weight fractions from 0.0110 to 0.0482. These values do not account for insulation, supports, fittings, and reinforcements.

No particular tank design studied was found to be superior in both volumetric efficiency and tank weight fraction. The modified semimonocoque tank with flat heads yielded the highest volumetric efficiency (95.4 percent) for design gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2) for either storage space. The lowest tank weight fraction (0.0110) was obtained with the titanium, single-lobe, unidirectional filamentary restrained membrane tank, applied to the aft storage space, for a design gage pressure of 15 psi (10.3 N/cm^2). Application of the latter tank design to the forward fuselage space is impractical because the resulting volumetric efficiency would be too low.

INTRODUCTION

Two factors that are important in determining the feasibility of using liquid methane as a fuel for supersonic cruise aircraft are the tank weight and the volume penalties associated with the storage of this low-density cryogenic fuel aboard the aircraft. The investigation reported herein for the design of pressurized, nonintegral, fuselage tanks is a continuation of a prior study of wing tanks (see ref. 1).

The mission analyses for supersonic transport aircraft, reported in reference 2, established the fact that the use of liquid methane as a fuel offers a potential for significant improvements in payload and direct operating cost when compared with aircraft using kerosene fuels. Methane burns well in engine combustors and provides desirable heat-sink properties for high-speed aircraft, but its low temperature and density as a liquid create storage problems aboard the aircraft. A major problem associated with the use of liquid methane in vented tanks is the avoidance of boiloff as the aircraft increases altitude and the pressure on the liquid is reduced. Elimination of boiloff can be accomplished by the use of tanks capable of withstanding an internal gage pressure of at least 1 atmosphere (1×10^5 N/m^2), so that the pressure within the tanks at altitude will be no less than that at ground level when the tanks are filled with fuel. Additional pressure capability can be provided in the tank design to account for increased fuel pressure due to heat absorption.

Since the density of liquid methane is approximately one-half that of kerosene fuels, all unallocated volume in the aircraft would probably have to be used for fuel storage. The study in reference 1 was of the relatively more difficult problems of the storage of a cryogenic fuel in the wings of the aircraft. The results obtained from the work reported in reference 1 indicate that the weights (excluding insulation weight, tank supports, tube fittings, and localized structural reinforcements) of nonintegral pressurized wing fuel tanks, of designs similar to those described herein for use in the fuselage, could be as low as $2\frac{1}{2}$ percent of the stored fuel weight. Since these weights are low enough to realize the benefits of methane as a fuel for supersonic cruise aircraft, the investigation has been continued to evaluate the weights and volumetric efficiencies of several types of pressurized nonintegral tank designs that could be used in the aircraft fuselage. That portion of the assumed supersonic aircraft fuselage, which is considered to be available for fuel storage, has been approximated by two typical void shapes, each with a constant cross section, a length of 63 inches (1.6 m) and approximately equal volume (see fig. 1). The results of this investigation of fuselage tanks for storing liquid methane are reported herein. The three types of tank designs studied are:

(1) Conventional membrane tanks (hereinafter called membrane tanks) where the loads in the tank skin are predominantly tensile (see fig. 2)

(2) Modified semimonocoque tanks (hereinafter called semimonocoque tanks) composed of an array of parallel perforated sheets covered by a pressure-tight skin (see figs. 3 to 6)

(3) Filamentary restrained membrane tanks (hereinafter called filament tanks) where the outer skins of either metal or sealed nonmetallic fabric are restrained by wires or threads attached to the opposite skin (see figs. 7 to 9)

The characteristics used as the basis for comparison of the tanks investigated were the volumetric efficiency and the ratio of tank weight to contained fuel weight (tank weight fraction) for tank internal gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2).

ANALYTICAL PROCEDURES

Assumptions

The following assumptions were made for this study:

(1) The fuselage storage void space typical of the forward section of the fuselage is as shown in figure 1(a), and the space typical of the aft section is as shown in figure 1(b).

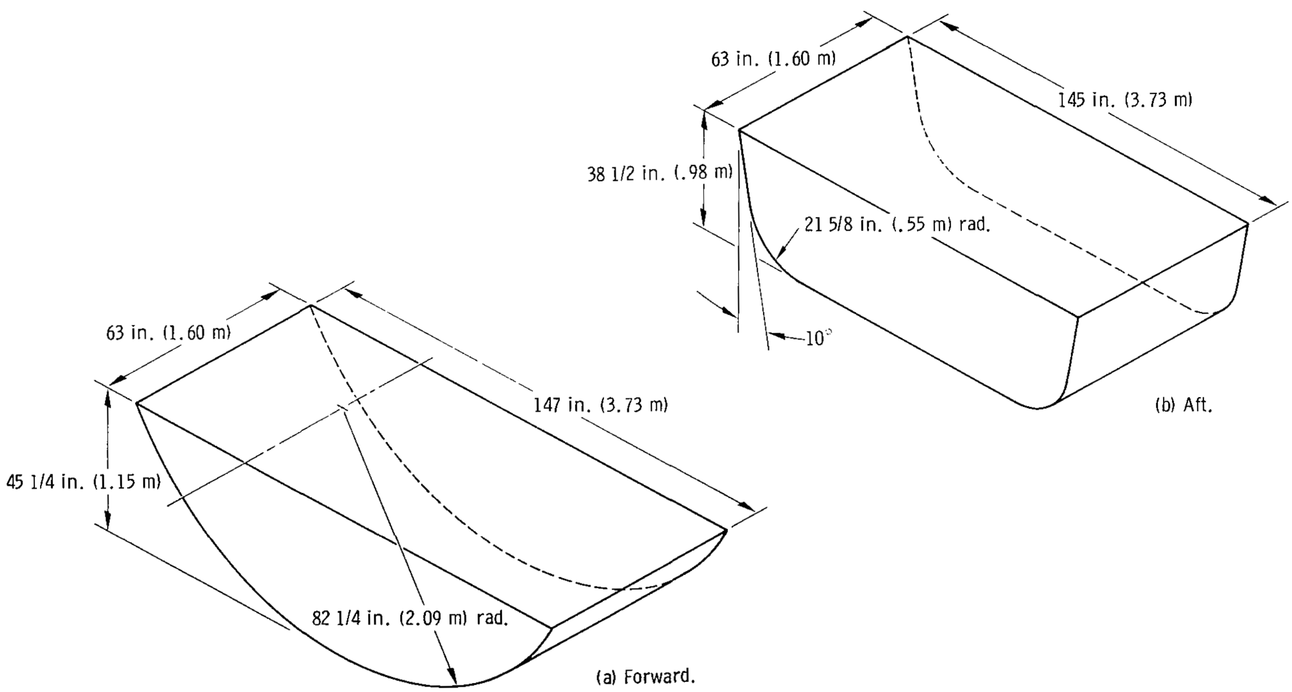


Figure 1. - Typical storage void space in fuselage.

(2) The two levels of tank internal gage pressure considered are 15 and 30 psi (10.3 and 20.7 N/cm^2).

(3) The tank material is a titanium alloy with mechanical properties at room temperature as follows:

Yield stress, psi; N/cm^2. . . . . .150 000; 103 000
Shear yield stress, psi; N/cm^2 . . . . .90 000; 62 100
Specific weight, $lb/in.^3$; kg/cm^3. . . . . 0.160; 0.443
Modulus of elasticity, psi; N/cm^2. . . . . 17.0×10^6; 11.7×10^6

(4) The allowable working stress is one-third of the material yield stress.

(5) The material thickness for metallic parts is no less than 0.010 inch (0.0254 cm).

(6) Insulation material does not reinforce the tanks and in the calculations of volumetric efficiency the volume required for insulation is not considered.

(7) The effect of tank supports, line fittings, and localized structural reinforcements on tank characteristics are neglected.

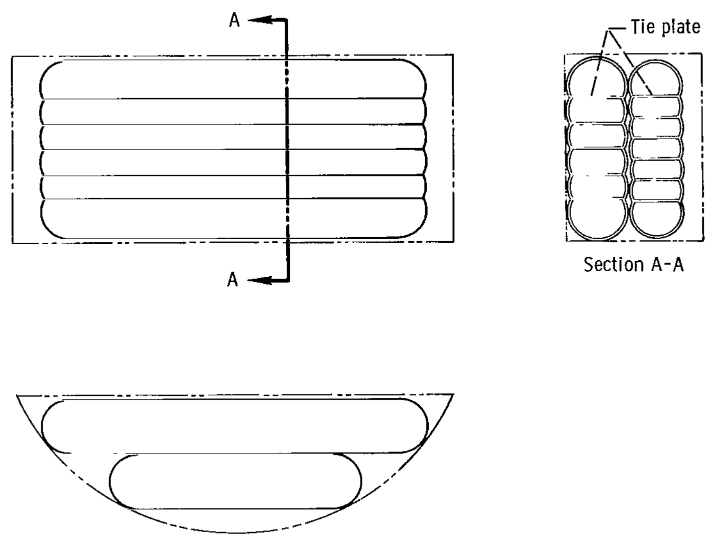
(8) The characteristics for the nonmetallic filament tanks were calculated from empirical data furnished by a manufacturer.

Structural Methods

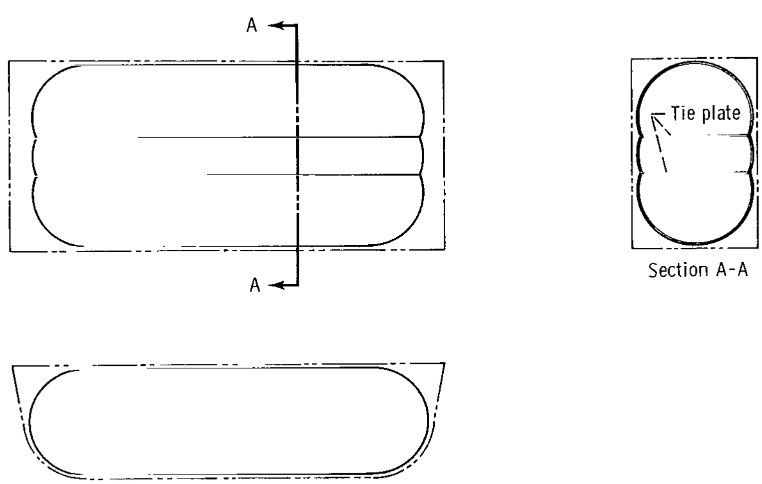
Membrane tanks. - The elements of these tanks are subjected to tensile loads primarily. The tie plates (see fig. 2) are perforated so that the average stress in the tie plate (not accounting for stress concentration at the holes) is made equal to the stress in the tank wall. The stresses are calculated according to membrane theory. For the detailed description of the analysis see reference 1, appendixes B and E.

Semimonocoque tanks. - For these designs (see figs. 3 to 6), the tank skin located between the perforated inner sheets was analyzed as a membrane clamped along two edges (see appendix C of ref. 1). The spacing of the perforated sheets is such that the tank skin located between them is stressed to the allowable limit. The primary stress in these sheets is tensile when the tank is pressurized. These sheets are analyzed as plates having a uniformly distributed inplane loading along the periphery. The inner sheets are perforated to save weight and bring the working stress up to the allowable limit.

Filament tanks, metallic. - These tanks have four basic structural elements: (1) the tie filaments, (2) the end closure shells, (3) the plate ties (in the multilobe configuration), and (4) the side panels (see figs. 7 to 9). The details of the analytical approach is identical to that found in appendix B of reference 1. The filament and plate ties carry inplane tensile loads only, and the end closures carry the pressure loads as membranes. The



(a) Two multilobe tanks for fuselage forward storage void space.



(b) One multilobe tank for fuselage aft storage void space.

Figure 2. - Membrane design.

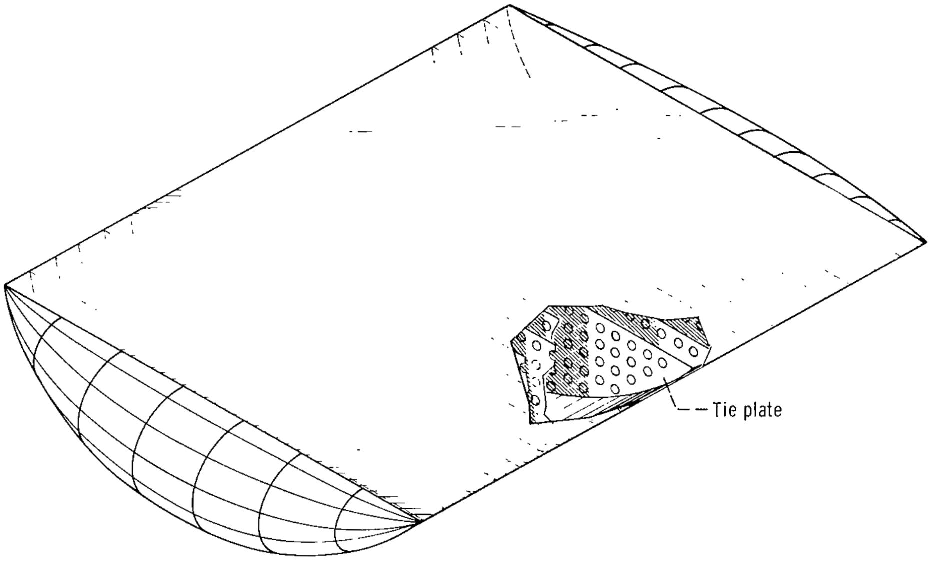


Figure 3. - Modified semimonocoque tank with curved heads for fuselage forward storage void space.

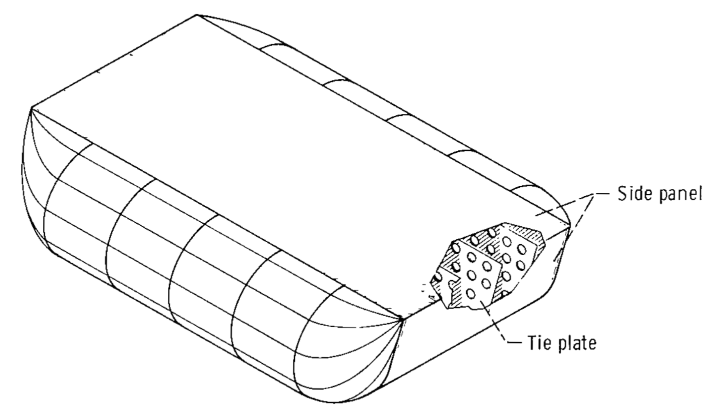


Figure 4. - Semimonocoque tank with curved heads for fuselage aft storage void space.

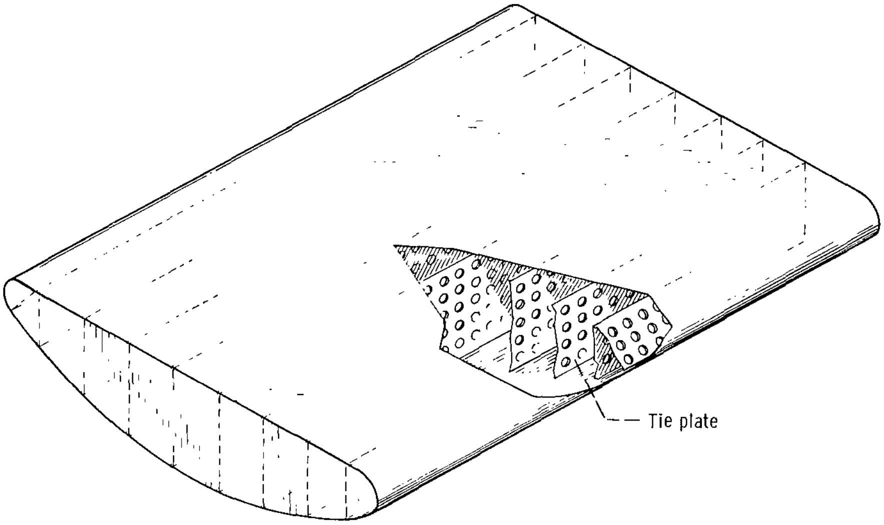


Figure 5. - Modified semimonocoque tank with flat heads for fuselage forward storage void space.

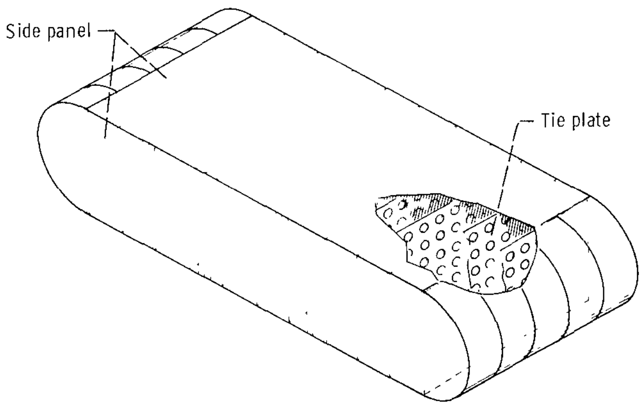
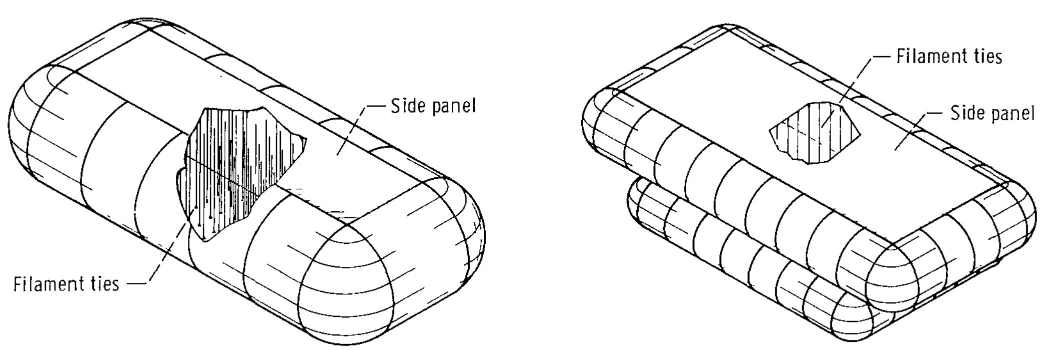


Figure 6. - Semimonocoque tank with flat heads for fuselage aft storage void space.

stresses in the flat side panels were calculated on the assumption that they were divided into contiguous square plates, subjected to a uniform pressure on one side, and restrained at the corners by the tie filaments and inplane tensile loads on all four edges.

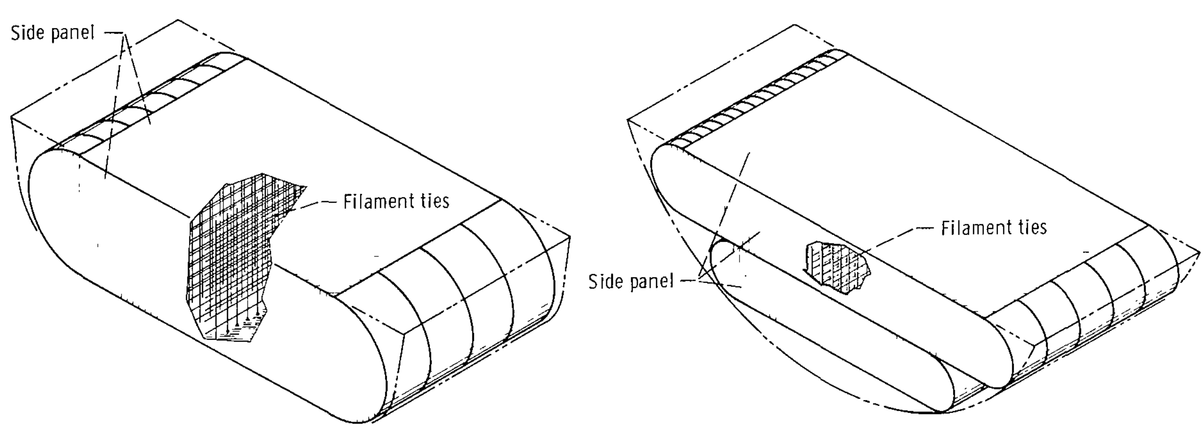
Filament tanks, nonmetallic. - These tanks (see figs. 7 and 9(a)), similar to the unidirectional metallic tanks, have the fabric outer skins sealed with an elastomeric compound and are designed on the basis of empirical data developed by a manufacturer of this type of tank.



(a) One lobe; fuselage aft storage void space.

(b) Two-lobe; fuselage forward storage void space.

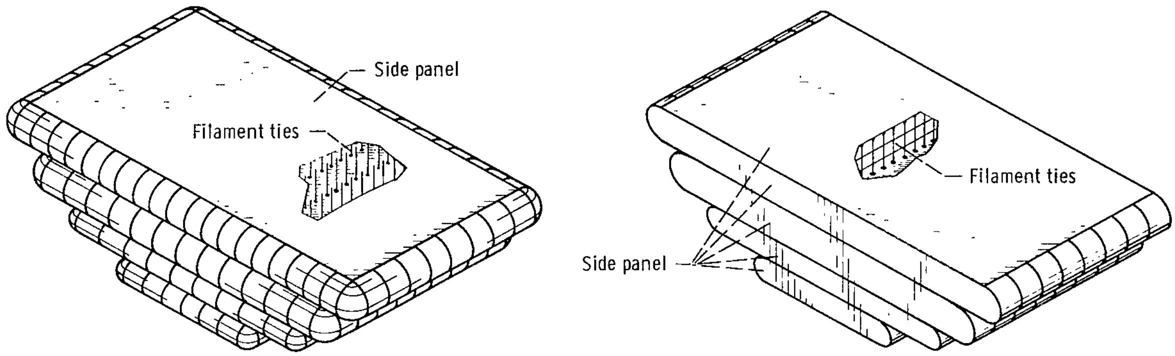
Figure 7. - Unidirectional, filament tank.



(a) One lobe; fuselage aft storage void space.

(b) Two-lobe fuselage forward storage void space.

Figure 8. - Bidirectional filament tank.



(a) Unidirectional. (b) Bidirectional.

Figure 9. - Four-lobe filament tank for fuselage forward storage void space.

RESULTS AND DISCUSSION

Tank Characteristics

In this study, several types of nonintegral fuel tanks, designed for the storage of liquid methane in the fuselage of a supersonic cruise transport aircraft, were investigated. For each design, two tank characteristics were determined for the comparison of the various tanks. The characteristics determined were volumetric efficiency and the ratio of tank structural weight to contained fuel weight (tank weight fraction). Volumetric efficiency is defined as the ratio of the tank volume available for fuel storage to the volume of the fuselage storage void space. The tank weight fraction is the ratio of the tank structural weight (exclusive of supports, line fittings, localized structural reinforcements, and insulation) to the weight of liquid methane that would be contained with zero ullage.

The fuselage segment of a typical supersonic cruise transport that might be used for fuel storage does not have a constant cross section along the fuselage; therefore, two typical storage void spaces of approximately equal volume were selected as representative for this study. The cross section of the forward storage void space is a segment of a circle with dimensions as shown in figure 1(a). The aft storage void space cross section is an isosceles trapezoid with the bottom corners rounded off, as shown in figure 1(b). Each void space is 63 inches (1.6 m) long. The characteristics determined for selected tank designs, adapted to the two storage void spaces and for design gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2) are shown in table I and figure 10.

TABLE I. - COMPARISON OF VARIOUS TANK TYPES FOR TYPICAL STORAGE VOID SPACES

Tank type	Tank gage pressure		Forward storage void space				Aft storage void space				
	psi	N/cm^2	Volumetric efficiency, percent	Tank weight, lb	Tank weight, kg	Tank weight fraction	Volumetric efficiency, percent	Tank weight, lb	Tank weight, kg	Tank weight fraction	Figure
Membrane, two tank multilobe configuration	15	10.3	77.0	76.3	34.6	0.0221	----	-----	----	-------	2(a)
	30	20.7	77.0	76.3	34.6	0.0221	----	-----	----	-------	
Membrane, one tank multilobe configuration	15	10.3	----	-----	----	------	75.8	58.1	26.4	0.0159	2(b)
	30	20.7	----	-----	----	------	75.8	65.5	29.7	0.0183	
Semimonocoque with curved heads	15	10.3	75.0	40.5	18.4	0.0120	75.0	45.4	20.6	0.0126	3 and 4
	30	20.7	75.0	44.7	20.3	0.0133	75.0	51.4	23.3	0.0142	
Semimonocoque with flat heads	15	10.3	95.4	63.2	28.7	0.0148	95.0	67.7	30.6	0.0148	5 and 6
	30	20.7	95.4	89.5	40.6	0.0210	94.9	90.6	41.0	0.0198	
One-lobe, unidirectional, filament	15	10.3	----	----	----	------	79.7	42.2	19.2	0.0110	7(a)
	30	20.7	----	----	----	------	79.7	53.8	24.4	0.0140	
Nonmetallic, one-lobe, unidirectional, filament	15	10.3	----	----	----	------	79.7	99.5	45.0	0.0258	7(a)
	30	20.7	----	----	----	------	79.7	185.8	84.0	0.0482	
Two-lobe, unidirectional, filament	15	10.3	77.8	60.3	27.4	0.0173	----	-----	----	------	7(b)
	30	20.7	77.8	69.5	31.5	0.0199	----	-----	----	------	
Nonmetallic, two-lobe, unidirectional, filament	15	10.3	77.8	74.5	33.8	0.0219	----	-----	----	------	7(b)
	30	20.7	77.8	141.8	64.4	0.0406	----	-----	----	------	
One-lobe, bidirectional, filament	15	10.3	----	-----	----	------	93.7	73.1	33.1	0.0162	8(a)
	30	20.7	----	-----	----	------	93.5	113.0	51.2	0.0250	
Two-lobe, bidirectional, filament	15	10.3	83.9	77.0	34.9	0.0205	----	-----	----	------	8(b)
	30	20.7	83.9	106.2	48.2	0.0282	----	-----	----	------	
Four-lobe, unidirectional, filament	15	10.3	87.1	84.0	38.1	0.0215	----	-----	----	------	9(a)
	30	20.7	87.1	97.0	44.0	0.0248	----	-----	----	------	
Four-lobe, bidirectional, filament	15	10.3	92.2	87.5	39.7	0.0211	----	-----	----	------	9(b)
	30	20.7	92.1	118.9	53.9	0.0288	----	-----	----	------	

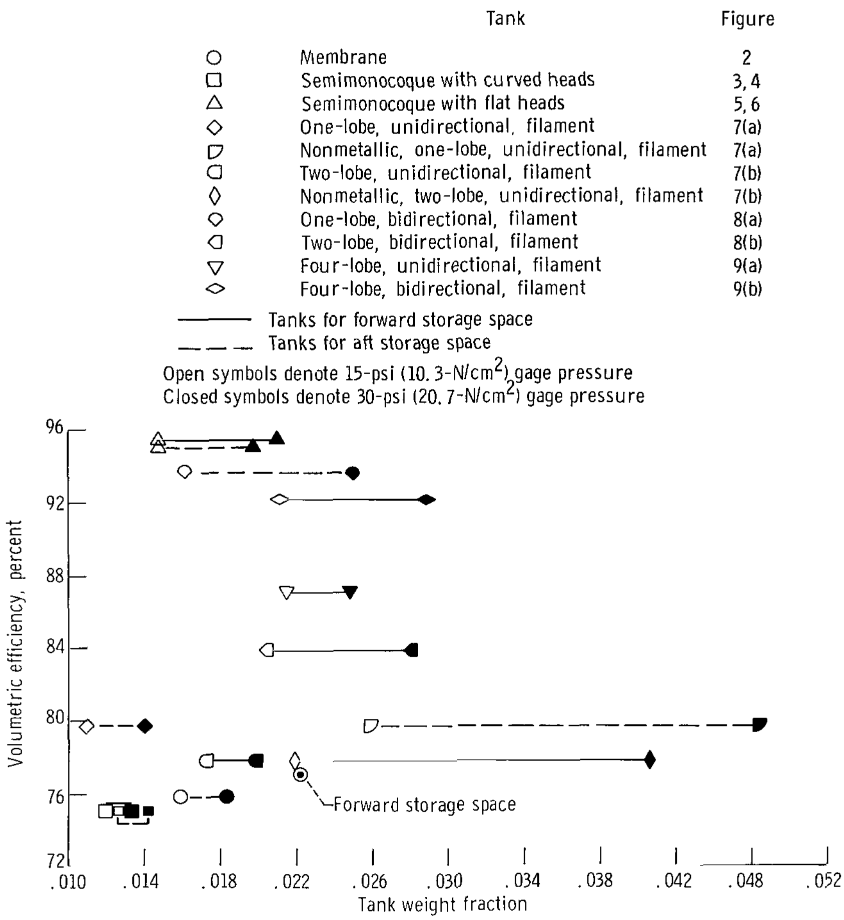


Figure 10. - Comparison of various tank designs based on volumetric efficiency and tank weight fraction for two tank pressures.

Membrane Tank

Two configurations of the conventional membrane design (see fig. 2) were used in an effort to utilize the forward and aft storage void spaces effectively. Many other combinations or schemes can be developed; however, those presented herein appear to be the most practical. The forward storage void space is the more difficult one to fill. Here, two separate multilobe tanks were used, resulting in a volumetric efficiency of 77 percent (see table I) for the combination. The aft storage void space is more readily utilized since it is more prismatic in shape. In this void, a single multilobe tank was used yielding a volumetric efficiency of 75.8 percent. Comparison of storage void space utilization shows that the forward space yielded a volumetric efficiency 1.2 percentage points higher than did the aft space. The penalty for applying these tanks to these differently shaped spaces becomes more apparent when the tank weight fractions are compared. The tank weight fractions are 0.0221 and 0.0159 for the forward and aft tankage, respectively, for a tank design gage pressure of 15 psi (10.3 N/cm^2). For a tank design gage pressure of 30 psi (20.7 N/cm^2), the corresponding tank weight fractions are 0.0221 and 0.0183.

Semimonocoque Tanks

Investigation of the applicability of semimonocoque tanks (see figs. 3 to 6) to the specific storage void spaces revealed that the flat-head and curved-head tanks have volumetric efficiencies averaging 95.2 and 75 percent, respectively, for either tank design pressure level. Tank weight and tank weight fractions proved to be pressure dependent, with the flat-head design being more sensitive. For either storage void space, when the design gage pressure is increased from 15 to 30 psi (10.3 to 20.7 N/cm^2), the percentage increase in tank weight fraction of the flat-head and curved-head design averaged 38 and 12 percent, respectively.

Filament Tanks

The investigation of the applicability of filament tanks to the forward and aft storage void spaces showed that the unidirectional, one-lobe filament tank with tank weight fractions of 0.0110 and 0.0140, corresponding to design gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2), is the lightest of all the filament designs considered for either storage space.

Examination of the relation between tank characteristics and pressure shows that here, too, volumetric efficiency is insensitive to pressure, but that the tank weights and tank weight fractions are dependent on the pressure. For the multilobe, metallic, unidirectional, filament tanks in either void space, the increase in tank weight fraction is about 15.2 percent for a change in gage pressure from 15 to 30 psi (10.3 to 20.7 N/cm^2). For the one-lobe, metallic, unidirectional, filament tank in the aft storage void space, the increase in tank weight fraction is 27.3 percent for the same increase in pressure. In this case, the greater sensitivity of this characteristic for an increase in design pressure is the result of an increase in tie filament size and cylindrical end closure skin thickness in order to maintain stresses at the allowable value.

In the case of the multilobed, metallic, bidirectional, filament tanks in the forward storage void space, the increase in tank weight fraction averaged 37.1 percent for the same change in pressure. In the aft storage void space, only one bidirectional tank design was studied and it yielded a corresponding increase of 54.4 percent in this characteristic. The corresponding increase in tank weight fraction for the nonmetallic, unidirectional, filament tank is 85.3 percent for the forward storage part and 86.8 percent for the aft storage void space. This increase is based on empirical weight estimates from a manufacturer and followed from the requirement for a heavier fabric and more sealant at the higher pressure. The specific strengths of the nonmetallic fibers in the fabric and ties, that is, the ratio of tensile strength to specific weight, are considerably greater than those of the metals (in some cases by a factor of 3). Therefore, it seems possible that weights of the fabric tank could be reduced through a concerted development effort where the fibers are used more effectively and sealant requirements are reduced. Comparisons of the filament-type tank designs made from titanium or sealant-impregnated nonmetallic fabrics indicate that the nonmetallic designs have higher tank weight fractions than their titanium counterparts by 26.6 and 104 percent for the forward storage void space and by 135 and 244 percent for the aft storage void space at design gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2), respectively.

Volumetric Efficiency and Tank Weight Fraction Relation

Comparisons of data in table I and figure 10 show that, in general, the tank weight and tank weight fraction increase with design pressure. This result should be anticipated, since, at higher pressures, more structural material is required to maintain the tank stresses within the allowable limit. However, the volumetric efficiency is relatively insensitive to tank design pressure, since the volume of additional tank structural material is small compared with volumetric capacity of the tank. The only exception to a change in weight for an increase in design pressure is the membrane design in the two-tank, multilobe configuration applied to the forward storage void space.

Further comparisons of results shown in table I and figure 10 show that, for identical types of tank design, no definite superiority in terms of volumetric efficiency and tank weight fraction can be realized for either storage void space. This tends to indicate that the type of tank design, rather than the shape of the storage void, has the greater influence on volumetric efficiency, if reasonable tank configurations are used. The best tank designs are indicated in the upper left portion of figure 10 and the less attractive designs in the lower right portion. Probably the best compromise design is the semimonocoque tank with flat heads, possessing the highest volumetric efficiency (95.4 percent) and a relatively low tank weight fraction. The tank weight fractions for this tank range from 0.0148 to 0.0210 compared with the range of 0.0110 to 0.0142 for the one-lobe, unidirectional, filament and semimonocoque tanks with curved heads, which have the lowest tank weight fractions for gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2), respectively.

A comparison of the results of this study with a similar study for wing tanks (ref. 1) shows that the range of volumetric efficiencies for wing and fuselage tanks is similar in magnitude, but the tank weight fractions for the fuselage tanks are approximately one-half those for the wing tanks at either design pressure. Also, as was concluded for the wing tank study (ref. 1), no specific type of tank design is best with respect to both volumetric efficiency and tank weight fraction. When there is inadequate storage volume for fuel and redesign of the aircraft is necessary, detailed tank designs, aircraft range, and payload analyses must be made to determine necessary compromises between tank weight and volumetric efficiency.

CONCLUDING REMARKS

In this study, three types of tank designs were considered for the storage of liquid methane in the aircraft fuselage. These tank designs were adapted, where possible, to both the forward and aft storage void spaces. The transverse cross section, assumed for the forward void, resembles a segment of a circle, and the aft void, an isosceles trapezoid. The types of tank design considered are (1) a membrane tank, where the loads in the tank skin result in membrane stresses, (2) semimonocoque tanks, which are composed of an array of perforated parallel sheets covered by a pressure-tight skin, and (3) filament tanks, where the outer skins of either metal or sealed nonmetallic fabric are restrained by wires or nonmetallic threads, respectively, attached to the opposite skin.

This comparative study of the utilization of storage void spaces illuminated several important facts.

The only configurations which are considered practical for installation in either the forward and aft storage void spaces are the membrane, semimonocoque, and the bidirectional, filament tanks. For these configurations, the volumetric efficiency was essentially insensitive to the shape of the voids.

Volumetric efficiencies ranged from 75 to 95.4 percent, where the lowest value was obtained for the semimonocoque tank with curves heads, ana the highest value was obtained for the semimonocoque with flat heads.

No specific type of tank design is best with respect to both volumetric efficiency and the ratio of tank weight to contained fuel weight (tank weight fraction) at tank gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2). However, at the lower pressure level, the semimonocoque tank with flat heads, fitted to the forward storage void space, has the highest volumetric efficiency (95.4 percent) and a tank weight fraction (0.0148) which is next to the lowest, and therefore, appears to offer a potentially successful type of design.

The tank weight and tank weight fraction of most tank designs increased when the design internal gage pressure was increased from 15 to 30 psi (10.3 to 20.7 N/cm^2). The membrane-type configuration for the forward storage void space is an exception to this trend because of the assumption that the wall thickness must be no less than 0.010 inch (0.0254 cm); the result is very conservative stress levels at the lower pressure and stresses below the design allowable limit at the upper pressure.

The volumetric efficiency, for the design gage pressure range of 15 to 30 psi (10.3 to 20.7 N/cm^2), is essentially independent of pressure level.

The lowest tank weight fraction was obtained with a metallic, one-lobe, unidirectional, filament tank adapted to the fuselage aft storage void space. The tank weight fractions were found to be 0.0110 and 0.0140 with a volumetric efficiency of 79.7 percent for tank gage pressures of 15 and 30 psi (10.3 and 20.7 N/cm^2), respectively. These tanks have cylindrical end closures and two flat opposed faces restrained by filament ties. For the forward storage void space, a semimonocoque tank with curved heads was the lightest, with tank weight fractions of 0.0120 and 0.0133 at the lower and upper design pressure, respectively.

The nonmetallic filament tanks, made from a sealant impregnated polymer fabric, are heavier than their titanium metal counterparts. However, the volumetric efficiencies are essentially independent of the tank material for either pressure level. For the forward storage void space, a double-lobe, unidirectional, filament tank design using nonmetallic fabric materials had tank weight fractions 26.6 to 104 percent greater than the metallic design, for tank gage pressures of 15 to 30 psi (10.3 to 20.7 N/cm^2), respectively. Tank weight fractions for the aft storage void space in a nonmetallic, single-lobe, unidirectional, filament tank were 135 to 244 percent greater than for the corresponding metallic design at the lower and upper design pressures, respectively.

Comparison of the results of this study with those reported in reference 1 for nonintegral wing tanks reveals that the range of volumetric efficiencies for wing and fuselage tanks are similar, but the tank weight fraction for fuselage tanks is about one-half that of wing tanks at either design pressure.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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