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REUSABLE LH_2 TANK TECHNOLOGY DEMONSTRATION THROUGH GROUND TEST

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Abstract

The paper presents the project plan to demonstrate, by March 1997, the reusability of an integrated composite LH_2 tank structure, cryogenic insulation, and thermal protection system (TPS). The plan includes establishment of design requirements and a comprehensive trade study to select the most suitable Reusable Hydrogen Composite Tank system (RHCTS) within the most suitable of 4 candidate structural configurations. The 4 vehicles are winged body with the capability to deliver 25,000 lbs of payload to a circular 220 nm , 51.6 degree inclined orbit (also 40,000 lbs to a 28.5 inclined 150 nm orbit). A prototype design of the selected RHCTS is established to identify the construction, fabrication, and stress simulation and test requirements necessary in an 8 foot diameter tank structure/insulation/TPS test article. A comprehensive development test program supports the 8 foot test article development and involves the composite tank itself , cryogenic insulation, and integrated tank/insulation/TPS designs. The 8 foot diameter tank will contain the integrated cryogenic insulation and TPS designs resulting from this development and that of the concurrent lightweight durable TPS program. Tank ground testing will include 330 cycles of LH_2 filling, pressurization, body loading, depressurization, draining, and entry heating.

Background

The reusable cryogenic propellant tank systems are a most critical technology development. SSTO program viability depends on achieving the promise of lightweight and reusability within acceptable development and operations cost goals. All cryogenic tank systems successfully flown (S-II , S-IV, and Shuttle External Tank) have been expendable. SSTO stringent weight requirements; robustness; and affordable DDT & E and operations costs magnify the development challenge. The key concerns of this challenge are listed in Figure 1.

- Cyclic life of the cryogenic tanks and lines
- Sealing capability of the cryogenic tanks, feed lines, and penetrations (emphasis on composite LH2 tank)
- Adequate tank structure robustness for mission flexibility
- Cyclic life suitability of the insulation and adhesive bond to the tank
- Avoidance or acceptable minimization of frost formation in the TPS
- Adequate TPS durability for future NASA-established environmental requirements (wind/drain, etc.)
- Ease of repair or replacement of insulation and TPS and ease of repair of the tank wall
- Inspectability of adhesive bond lines, insulation, TPS, and tank structure.
- Use of IHM (Integrated Health Monitoring) methods

Figure 1 Key RHCTS Concerns to be Resolved

Design Requirements

SSTO systems requirements such as payload weight, size, altitude and inclination, geometry, and return weight; flight rates, reliability, operability, responsiveness, mission duration, initial operational capability, operational life cycle, launch and landing sites, ferry capability, design margins, mission completion assurance, ferry and cost are defined .

The appropriate safety factors and design criteria are established. Requirements are defined by mission phase from on the pad rollout, prelaunch, ascent, on-orbit stay, entry, to landing. Trajectories (dispersions) are defined for aeroheating and aerodynamic pressures definitions. Tank maximum relief, peak operating, and minimum regulator pressures are defined with particular attention to reduction of pressure upon entry to orbit. Dynamic factors and acoustics are predicted. Environmental conditions of wind/rain flight conditions, and on-orbit environmental conditions including the appropriate NASA micrometeoroid/debris models are included. Other requirements may surface such as for IHM, for damage tolerance, and for damage avoidance during fabrication, and will be included as appropriate. A preliminary example of such requirements is shown in Table 1.

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Requirement Parameter	Qualification of Limit Value	Ultimate Safety Factor
Differential pressure		
• Maximum relief valve pressure	34 psig (on pad to MECO)	
• Minimum regulator valve pressure	28 psig (on pad to MECO)	1.4
• Maximum tank pressure	6.0 psig (orbit insertion to landing)	
• Minimum regulator valve pressure	2.0 psig (orbit insertion to landing	
Temperature during fueling		
• LO_2 tank wall	From -300°F	
• LH_2 tank wall	From -423°F	
• TPS-to-insulation bond line	No lower than -180°F	
Body loads		
• Peak KSC wind-on pad/unfueled	1% probability of exceedance of peak wind speed in 2 weeks	
• Peak KSC wind-on pad/fueled	1% probability of exceedance of peak wind speed in 1 day	
• Frost	Frost to be negated or minimized to be less than TBD	
• Lift-off KSC wind	1% probability of exceedance of peak wind speed in 1 hour	1.4
• Flight loads-lift-off to MECO	Nx 1.25 to 4.0 g (to be verified in program). Ny and Nz to be determined in study. Local air pressures up to 6.0 psi and vent pressure = 1.0 psig	
• Entry maneuver loads	2.5-g maneuver-vent pressure = -1.0 psig	
• Main gear landing	10-fps sink speed. Nz at gear. 4.0-g rotational acceleration	
• Nose gear slap - down landing	Nz at nose gear 4.0-g rotational acceleration w = 11 deg/sec	
On-orbit environment		
• On-orbit micrometeoroid or debris environment	NASA JSC postulated models for orbit and altitude	0.5% probability of critical impact (to be verified in program)
• On orbit-temperature	+170°F to 280°F	
Entry heating		
• Entry heat rates	In regime of 0.10 to 11.3 Btu per square feet per second	
• Entry heat loads	In regime of 500 to 9,000 Btu per square foot (to be verified in program)	
• Outer face of Rohacell surface	Temperature not to exceed 400°F	
• Tank wall temperature	Temperature not to exceed 250°F	

Table 1 - Example of requirements that drive an integral RHCTS

Candidate SSTO vehicle Configurations

The four candidate tri-propellant SSTO vehicle configurations are shown in Figure 2. Configurations No. 1 and No. 2 place the payload bay between the cryogenic tanks. The LH_2 tank is forward in configuration 1 and aft in Configuration 2. Configurations No. 3 and No. 4 , respectively, place the payload bay forward and aft of the tanks. The major pros and cons of each configuration for integral tank designs are:

• No. 1 - Expected lightweight, most difficult ascent control , complex wing attachment design.

• No. 2 -Expected heaviest weight , best ascent control, complex wing attachment design.

• No. 3 - Expected lightest weight, difficult ascent control , complex wing attachment design, worst payload in/out c.g... excursion, added design risk and operations with common bulkhead.

• No. 4 - Expected heavy weight, adequate ascent control, simplest wing attachment , least payload in/out c.g. excursion, worst payload acoustic environment, added design risk and operations with common bulkhead.

The common bulkheads are compression -stable designs using 2 face sheets (honeycomb sandwich core) between the LO_2 and LH_2 propellants. For safety a GSE purge system senses any LO_2 or LH_2 leakage into the honeycomb sandwich core during prelaunch.

Trade Study Options

The design options shown in Table 2 are included in the trade study . The wing attachment is simplified for Configuration No. 2 with a non-integral tank. A discussion of the trade options is:

• Integral vs non-integral composite hydrogen tanks - Integral hydrogen tanks are expected to have less structure weight but can represent increased design, stress and thermal analysis complexity if chines and the wing are attached. All these attachments penetrate the insulation. The non-integral tank represents a more simpler classical pressure vessel behavior with only penetration of the insulation at its end supports and has much better protection from on-orbit debris impact.

• Insulation arrangement - The most promising designs are shown in Figure 3. Figure 4 outlines the reasons for not investigating internal insulation. Figure 5 outlines the pros and cons between the two insulation location options.

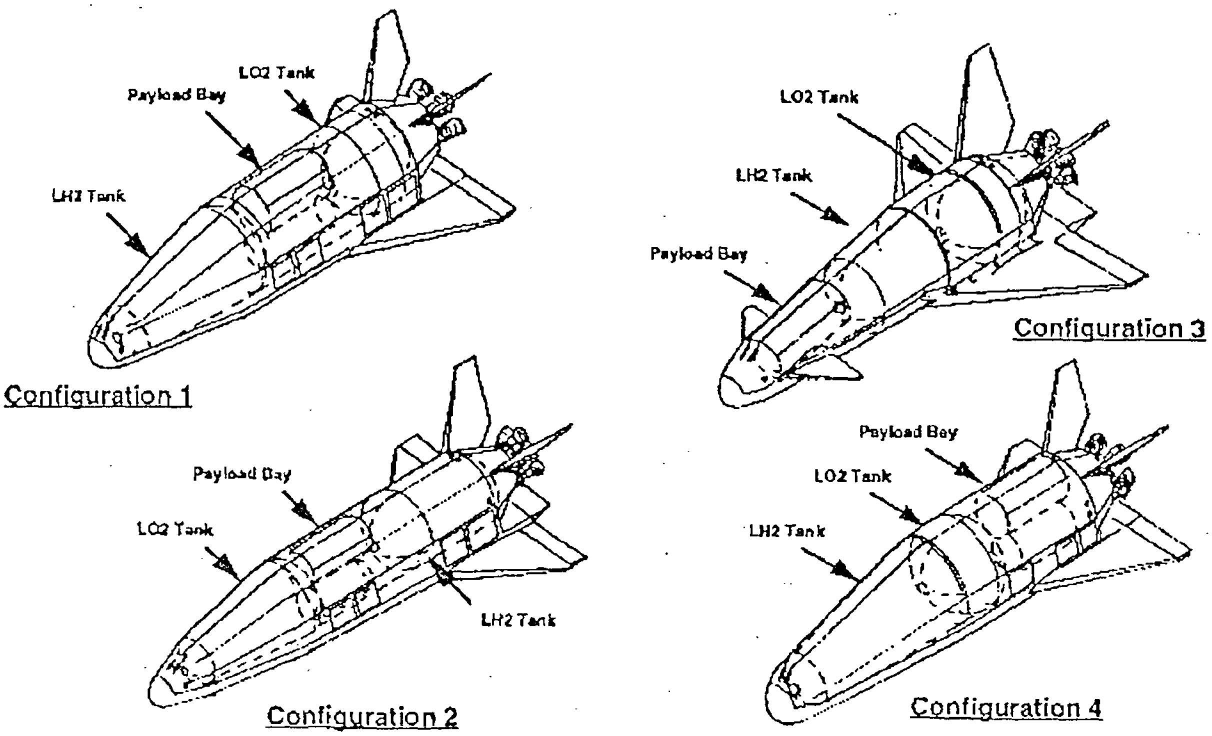


Figure 2. Four candidate SSTO vehicle configurations are studied

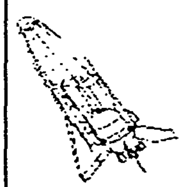
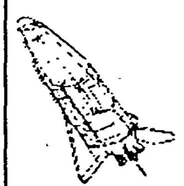
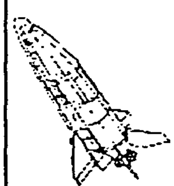
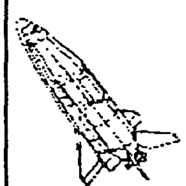
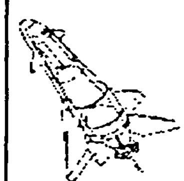
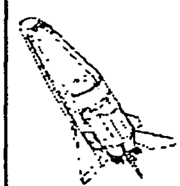
Design Options	Configuration 1A Forward LH tank 	Configuration 1B Forward LH Tank 	Configuration 2A Forward LO tank 	Configuration 2B Forward LO Tank 	Configuration 3 Common Bulkhead 	Configuration 4 
Integral or Non-integral Tanks	Both tanks are integral	Non-integral LH tank Integral LO Tank	Both tanks are integral	Non-integral LH tank Integral LO Tank	Both tanks are integral	Both tanks are integral
Wing Attachment *	LO Tank Thrust Structure	LO Tank Thrust Structure	LH Tank Thrust Structure	Fuselage Thrust Structure	LO Tank Thrust Structure	Into Payload Bay Unpressurized Structure
LH Tank Cryo Insulation	External to skin/str core of sandwich	External to skin/str core of sandwich	External to skin/str core of sandwich	External to skin/str core of sandwich	External to skin/str core of sandwich	External to skin/str core of sandwich
Composite Fuselage	None external to LH tank	Gr/BMI external to LH tank	None external to LH tank	Gr/BMI external to LH tank	None external to LH tank	None external to LH tank
TPS on LH Tank	PBI, TABI, AETB	PBI, TABI, AETB, C/Sic Multipost	PBI, TABI, AETB	PBI, TABI, AETB, C/Sic Multipost	PBI, TABI, AETB	PBI, TABI, AETB
Chines	minimum to maximum size	minimum to maximum size	minimum to maximum size	minimum to maximum size	minimum to maximum size	minimum to maximum size

Table 2 These trade study options are studied

• Wing attachment variations - The reasons for not attaching to the tank are discussed above. However, the option of attaching to the thrust structure may represent increased wing weight. Attachment to the fuselage in configuration 2 avoids the foregoing but may have the heavier tank and fuselage design associated with a non-integral tank. A potential concept for wing attachment for Configurations 1 to 3 is shown in Figure 6. Configuration 4 is the best option for wing attachment and avoids the weight penalty of fairing structure that is in Configurations 1 to 3.

• Chines - The reasons for not attaching chines to composite tanks are discussed above. Attachment to an LO2 metal tank requires the chine design to accommodate the three dimensional contraction of the tank, due to fueling, and hence increased design complexity. However the chines enhance aerodynamic stability and can be used to route utilities along the vehicle.

Each of the options listed in Table 2 will be analyzed to the necessary level of detail in order to select the most suitable structural configuration.

Trade Selection Process

A traceable selection process will be used to identify the most suitable vehicle configuration . Within this configuration is the most suitable RHCTS. Selection criteria are established. A dictionary explicitly defines the criteria and a rating and point system is established. The system is on spread sheets to permit team iteration and review of scoring. This information will be used in the decision process in conjunction with experience driven judgment. This method was successfully used in the AMLS Task 5 TPS Study Contract, SSD93D0310.

Prototype RHCTS design and analysis

A prototype composite design of the most suitable RHCTS design will identify the construction, fiber placement (by Hercules) fabrication process, laminate ply orientations and thicknesses, and stresses that need to be simulated in the 8 foot diameter tank test article. Fiber placement is an automated fabrication process for high-performance composite structures with complex shapes. With fiber placement, the entire cylinder and both end bulkheads (less access manhole and sump) are placed in one continuous operation. The design goal is to have the stringers and frames in place during the fiber placement process.

Tank interface loads are obtained from a finite element model of the most suitable SSTO vehicle structural configuration and applied to an FEM of the prototype RHCTS.

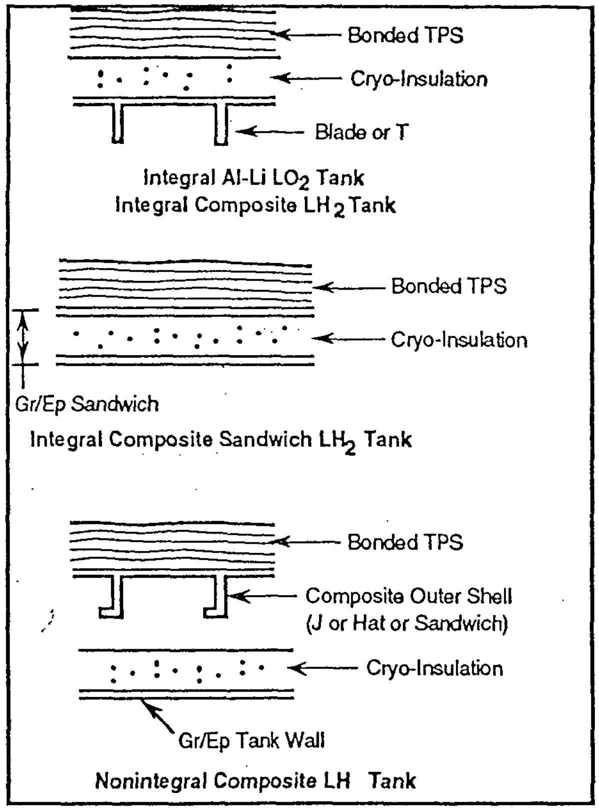


Figure 3 - Most Promising Tank/Insulation Arrangements

- Visual inspection from inside the tank during off-line maintenance is precluded
- Sealing around pressurization system and internal subsystem supports is required. High risk/high cost
- Micrometeoroid/debris resistance is not provided, unlike external insulation
- Particles collecting at the engine inlet screen is a risk
- Sealing around the attachments for slosh baffles in LO2 tanks is a high-cost/high-risk design
- The significant weight savings with Al-Li at 423°F is not realized

Internal insulation in a nonintegral composite tank with end frames is also expected to be a high-risk/high-cost design

Figure 4 - Reasons for not Developing Internal Insulation

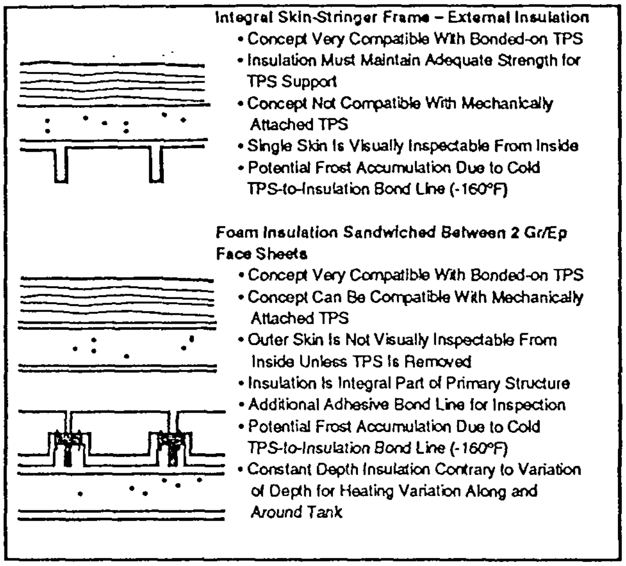


Figure 5- In-depth trade study will identify the Most suitable of these designs

Replication of design details such as frame splices will be provided. Particular attention is paid to discontinuity stresses at stringer/frame intersections, bulkhead to cylinder mating diameters, and penetrations. These are regions where acceptable increases in margins of safety may be considered for added robustness.

Development Test Plan

The development test plan is arranged in four tasks. NASA/MSFC and Rockwell SSD are jointly responsible for all of these tasks. The tasks are:

• Task 1 - Composite Tank, Feed Lines, and Penetrations Development - Rockwell's NAAD/Tulsa is responsible to SSD for this development and is supported by the Hercules Advanced products Division .

• Task 2 - Reusable External Cryogenic Insulation Development

• Task 3 Integrated tank/insulation/TPS development - (SSD's joint Lightweight/durable TPS development task with NASA/Ames supports this task)

• Task 4- Life Cycle Testing of 8 foot diameter Integrated tank/Insulation/TPS test article

Each of these developments are discussed further as follows:

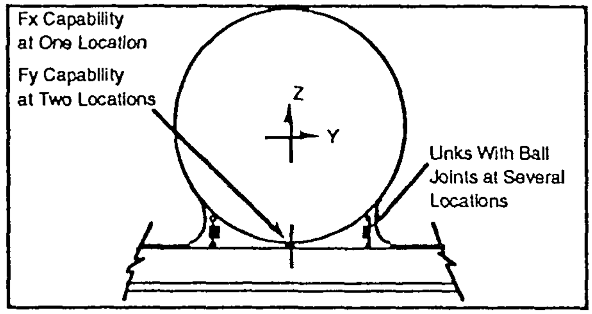


Figure 6 - Wing Attachment Concept

Task 1 -Composite Tank, Feed Lines, and Penetrations Development -

Table 3 illustrate the major features of the technology development plan for the composite tank. The plan incorporates coupon, small component, and large component tests as shown in the table.

The development will investigate the suitability of IM7/977-2 and low-temperature curing material systems to avoid the need to build a large autoclave for the prototype design and to facilitate potential repairs.

Manufacturing development evaluations will be performed to assess and reduce the risk of scale-up for materials/processes, such as fiber placement, low-temperature cure resins, and in-situ consolidated materials. Bench tests will evaluate processing considerations.

Development tests to investigate the compatibility of composites with LO_2 will be demonstrated through bottle testing and in the presence of such ignition sources as rapid depressurization, frictional heating, particle impact, and electrical energy. The relative success will determine any further effort.

An 8-ft-diameter tank such as that shown in Figure 7 is selected because it can demonstrate all the manufacturing processes and can be cyclic tested to 330 cycles by March 1997. The stresses in the prototype tank are simulated by a higher differential pressure in the 8-ft tank. A finite-element model, will be used to assure simulation of stresses with the prototype design.

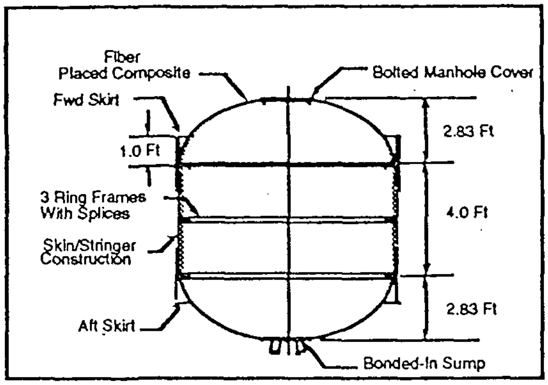


Figure 7 - Preliminary Concept for Scale Test article of prototype RHCTS

Task 2 - Reusable Cryogenic External Insulation Development.

Our approach is based on external insulation. The trade study will include insulation sandwiched between composite skins.

Rohacell is a promising candidate cryogenic insulation on the basis of preliminary test results in which we characterized five different foams and successfully cyclic tested (ten cycles) the integrated design suitability of advanced flexible reusable surface insulation (AFRSI) blankets on Rohacell foam on an aluminum skin. In these tests, the aluminum was exposed to liquid nitrogen (-320°F) and then the AFRSI to radiant heating (1,030°F) with the top of the foam insulation limited to 400°F. These tests demonstrated the promise of polymethacrylimide (Rohacell) insulation and urethane and room temperature vulcanize (RTV) adhesives and the potentially low level of frost formation. We also learned that polyimide (Fluocore) and polyisocyanurate (NCFI) were not reusable to 400°F.

Table 4 builds on this experience and illustrates the insulation characterizations and then the characterizations as attached to composite skins.

Task 3 - Integrated tank/insulation/TPS component development

The development tests to verify the suitability of insulation and TPS integration is shown in Table 5.

Task 4- Life Cycle Testing of 8 foot diameter integrated tank/Insulation/TPS test article

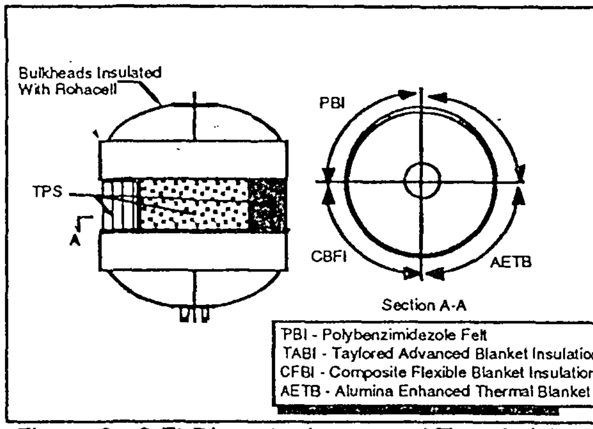


Figure 8 - 8 Ft Diameter Integrated Test Article

Figure 8 illustrates the preliminary concept of the integrated tank/insulation/TPS test article. The tank contains the selected insulation/TPS on the cylinder and, only insulation on the bulkheads. Each tank cylinder will contain 25 ft^2 each of PBI, TABI, CBFI, and AETB tiles.

The test article will be tested to 330 cycles of fueling, pressurization, body loads, depressurization, draining, and radiant heating. This is the number of cycles anticipated for ten flights per year for 30 years. It assumes one cycle every flight except every tenth flight, which may be two cycles. Leak detection will be determined by *bagging at appropriate test intervals.* At the conclusion of the tests the test article will be *placed on a shaker table to verify insulation* support of the TPS. Investigations are currently *underway to determine the feasibility of foam* blocks to minimize fueling and draining time.

Chine attachment loads may be included depending on the trade study results. The radiant heat loads are applied to verify insulation and adhesive life. With a 400°F limit on insulation, studies have shown the tank wall temperature does not exceed 250°F. At 250°F, composite material degradation is expected to be insignificant but is verified by the test.

Nondestructive Inspection/Evaluation and Integrated Health Management (IHM).

Table 6 summarizes the IHM development plan. Rockwell SSD is responsible for the development and application of IHM for the reusable cryogenic propellant tank system. This effort will establish inspection period predictions and ascertain the validity of appropriate NDE/NDI and health management techniques.

The objective is to identify the most cost-effective life cycle approach for fault detection and accommodation. Emphasis is on technologies that provide wide-area coverage, automation, remote sensing, and maintenance on demand. Maintenance on demand will preclude the need for extensive test and checkout operations for every flight and is achieved by a combination of ground and in-flight monitoring techniques that identify failed components and/or impending failures. A model will be created to estimate structural element inherent reliability and to predict remaining operational life.

Table 3 Composite Material Tests For Composite Tank Dev.

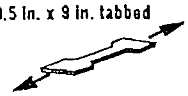
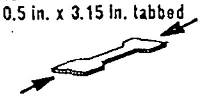
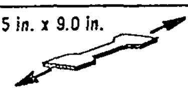
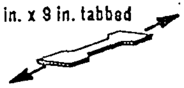
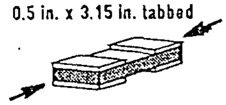
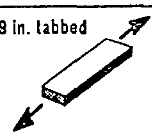
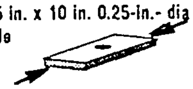
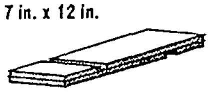
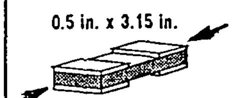
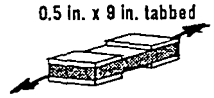
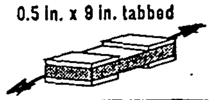
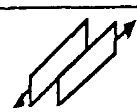
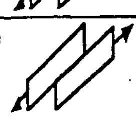
Test Item	Test Objective	Test Article Description	Replicates		Test Description	Instrumentation	Test Spec
			-423F	RT			
A	Screen four materials for tensile properties	0.5 in. x 9 in. tabbed 	3 Specimens x 4 materials = 12	3 Specimens x 4 materials = 12	Tensile strength and modulus	Instrumentation Per specification	NASA 1142 B.6
B	Screen four materials for compression properties	0.5 in. x 3.15 in. tabbed 	3 Specimens x 4 materials x 2 tests = 24	3 Specimens x 4 materials x 2 tests = 24	Compression strength and modulus	None	NASA 1142 B.7
C	Permeability screening of four materials	2.5 in. dia. 	3 Specimens x 4 materials = 12		Specimens will be tested with LH_2 with representative shell layup	None	ASTM D284-424 D1434
D	Screen four materials for effects of impacts	7 in. x 12 in. 	3 Specimens x 4 materials = 12	3 Specimens x 4 materials = 12	Res. compr. after damage induced by impact	Instrumentation Per specification	NASA 1142 B.11
E	Thermal cycling screening of four materials	0.5 in. x 9.0 in. 	3 Specimens x 4 materials = 12	3 Specimens x 4 materials = 12	-423°F to 250°F for LT with residual tension	Instrumentation Per specification	NASA 1142 B.6
F	Tension strength and modulus Preliminary properties data base	0.5 in. x 9 in. tabbed 	6 Specimens x 2 batches = 12	6 Specimens x 2 batches = 12		Instrumentation per specification	NASA 1142 B.6
G	Compression strength and modulus Preliminary properties data base	0.5 in. x 3.15 in. tabbed 	6 Specimens x 2 batches x 2 tests = 24	6 Specimens x 2 batches x 2 tests = 24		Instrumentation per specification	NASA 1142 B.7
H	In-plane shear Preliminary properties data base	1 in. x 9 in. tabbed 	6 Specimens x 2 batches = 12	6 Specimens x 2 batches = 12		Instrumentation per specification	SACMA SRM-788
I	Open-hole compression Preliminary properties data base	1.5 in. x 10 in. 0.25-in.- dia hole 	6 Specimens x 2 batches = 12	6 Specimens x 2 batches = 12		None	NASA 1142 B.10
J	Compression after impact Preliminary properties data base	7 in. x 12 in. 	6 Specimens x 2 batches = 12	6 Specimens x 2 batches = 12		Instrumentation per specification	NASA 1142 B.11
K	Compression interlaminar shear Preliminary properties data base	0.5 in. x 3.15 in. 	6 Specimens x 2 batches = 12	6 Specimens x 2 batches = 12		None	NASA 1142 B.8
L	Durability screening	0.5 in. x 9 in. tabbed 		3	Two-lifetime Spectrum load, residual tension	Strain Gauges	NASA 1142 B.7
M	Thermal cycling screening	0.5 in. x 9 in. tabbed 	3		-423°F to 250°F for one LT with residual tension	Strain Gauges	NASA 1142 B.7
N	Screen 6 materials for shear strength	1 by 9 	3 Specimens x 6 materials = 18	3 Specimens x 6 materials = 18	Lap shear	None	ASTM D1002
O	Preliminary properties data base	1 by 9 	3 Specimens x 2 materials x 2 batches = 12	3 Specimens x 2 materials x 2 batches = 12	Lap shear	None	ASTM D1002
P	Preliminary properties data base	1 by 12	3 Specimens x 2 materials x 2 batches = 12	3 Specimens x 2 materials x 2 batches = 12	T Peel	None	MMM-A-132

Table 3(con't) Composite Material Tests For Composite Tank Dev.

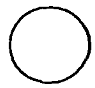
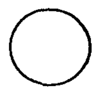
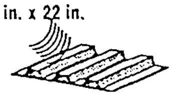
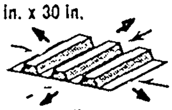
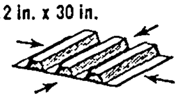
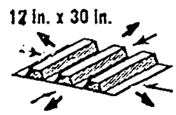
Test Item	Test Objective	Test Article Description	Replicates -300F	Replicates RT	Test Description	Instrumentation	Test Spec
Q	Determined composite thermodynamic compatibility with LO_2	1.5 dia. 	3 Specimens x 6 materials = 18	3 Specimens x 6 materials = 18	Character. in LO_2 in presence of rapid depressur., friction particle impact, and elec. energy	Strain guage monitoring	None
R	Characterize compatibility of Gr/Ep in presence of LO_2	1.5 dia. 	3 Specimens 2 batches = 6	3 Specimens 2 batches = 6	Standard LO_2 compatibility test	None	None
S	If material are LO_2 compabile, characterize selected material. Cyclic strength and cyrogenic applications	Test coupons 0.05 in. and 0.10 in. thick. In plane. Coupons represntative of 0- and 90-° orientations. Coupons fabricated with process planned for large tank	6 Specimens 2 batches 3 orientations 2 thicknesses 3 or 4 tests = 288	6 Specimens 2 batches 3 orientations 2 thicknesses 3 or 4 tests = 288	3 to 4 test types: tensile test at RT after (1) as-fab., not cycled; (2) low cycle fatigue at RT for 300 cycles; (3) thermal cycle -300°F to 250°F for 100 cycles; (4) if any effect of thermal cycles, (2) + (3) combined	Conventional strain instrumentation. Record permeability in LO_2 for test 3 (before and after test)	NASA 1142 B.6
T	Verify acoustic fatigue strength of a thin-skin panel	22 in. x 22 in. 		3 Specimens	Sonic fatigue defects over 1 LT @ 150 db Residual tension	Strain guages	
U	Verify structural stability of a critical segment	30 in. x 30 in. 	2 Specimens	2 Specimens	Evaluate panel instability under combined load	Strain guages	
V	Verify Y-joint load transfer and strength capability	6 in. x 15 in.	2 Specimens	2 Specimens	Check Y-joint load transfer	Strain guages	
W	Develop feed line and feed line attachment designs for tank penetration, elbows, and bellows attachments	Two feed lines with elbows and attachments for bellows and attachment to tank	2 Specimens		Evaluate Feedline pressure capability with LH_2 100 cycles	None	
X	Evaluate stiffened panel damage tolerance	12 in. x 30 in. 		3 Specimens 2 impact levels = 6	Impact & test reidual strength in 4 point bend, 2 LT	Strain guages	
Y	Verify biaxial tension load capability of full-scale structure	12 in. x 30 in. 	1 each		100, fill with pressurize and drain (100 cycles)	Strain guages	
Z	If LH_2 permeability is excessive in above tests, investigate techniques to provide metal (or other) coating on the exterior of the tank wall	2.5 in. dia. cut from 12 x 12 inch Gr/Ep panel 	2 each of 2 configurations		Apply coating to panel, inspect, cut coupons, check permeability, cycle test, and check permeability	None	
AA	Develop repair techniques for damage to tank wall	Tank wall panels with induced damage (representative of debris impact) 12 x 24	2 each of 2 designs		Repair damaged design and impose -423°F cryogenic environment and cyclic test 20 times. Test to failure	Strain guages	
BB	For selected material, verify fiber placement approach to fabrication of shell tank cylinder, domes, and skirts	Half wall thickness of 8-ft-dia. Gr/Ep tank with a small number of stringers and frames	1 each		Perform process verification testing	Biaxial strain	
CC	Fabricate, proof, test, inspect 8-ft-dia. tank. Simulation of prototype stresses and manufacturing is essential	8-ft-dia. tank with end domes, manholes in one dome, skin-stringer, cyl. attach skirt, and fill and drain lines	1 each		Fill with water, record leakage and inspect tank.	Strain Guages	

Table 4 Cryogenic Insulation Tests For Composite Tank Dev.

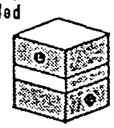
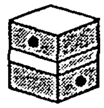
Test Item	Test Objective	Test Article Description	No. of Test Articles	Test Description	Instrumentation
A	Characterize static strength and stiffness of 3.2- and 6.0-pcf Rohacell foams	Rohacell test coupons for tension, compression, and shear strength and stiffness tests	6 each for 3 strength tests for 3 temperatures for 2 densities for a total of 108	Determine static strength of 400°F, RT, –423°F	Load cells, LVDT, required and COD gauges as
B	Characterize static strength and stiffness of spray-on or pour-on foam (2 foams)	*Foam test coupons for* tension, compression, and shear strength and stiffness tests	*6 each for 3* strength tests for 3 temperatures for 2 *foams for a total of* 108	*Determine static* strength at 400°F, RT, –423°F	*Load cells*, LVDT, and COD gauges as required
C	Characterize residual strength of Rohacell 3.2- and 6.0-pcf foams after thermal cycling	Rohacell test coupons for tension, shear, and compression tests	6 each for 3 strength tests for 2 densities for a total of 36	Determine residual strength after exposure to 20 thermal cycles at –423°F to 400°F	Load cells, LVDT, and COD gauges as required
D	Characterize strength of joints between Rohacell *blocks (Rohacell 6.0 pcf)* before and after thermal cycling	Rohacell test coupons containing bonded *adhesive joint* between blocks 	6 each for 3 strength tests, 2 conditions for a *total of 36*	Determine cyclic strength after exposure to 20 thermal *cycles at –423°F to 400°F*	Load cells, LVDT, and COD gauges *as required*
E	Characterize residual strength of foam after thermal cycling	Test coupons for cyclic tension, shear, and compression tests	6 each for 3 strength *tests for a total of 18*	Determine residual strength after cycle exposure to 20 thermal cycles-423°F to 400°F	Load cells, LVDT, and COD gauges as required
F	Characterize thermal properties of two selected foams	Two selected foam 8-in. dia. x 2-in. thick samples. Rohacell to have urethane adhesive bonded joint	3 each of 2 foams and 3 each of 2 joined foams for a total of 12	Determine thermal conductivity and specific heat at vacuum, ambient, and one intermediate pressure for three temperatures (–423°F, RT, 400°F)	Thermocouples
G	Down-select and develop process and specifications for adhesive bonding of selected foam to tank wall skins	N/A	N/A	N/A	N/A
H	Characterize static strength of urethane adhesive bonding of selected foam to Gr/Ep *skins*	Foam and skin test coupons for tension test 	6 each of Gr/Ep skins for 3 temperatures for a total of 18	Determine static strength at 250°F, RT and –423°F	Load cells, LVDT, and COD gauges as required
I	Characterize the residual strength of urethane adhesive bonding of selected foam to Gr/Ep skins. Note any cryopumping	Foam and skin test coupons for tension test	6 each of Gr/Ep skins for a total of 6	Determine residual strength upon cyclic exposure to 20 thermal cycles at -423°F to 250°F	Load cells, LVDT, and COD gauges as required
J	Develop methods for repair and replacement of selected foam and verify thermal performance	12 in. x 12 in. panels of Gr/Ep with damage	4 each for a total of 4	Repair two and replace two panels of each *material*	Therocouples
K	Develop methods of sealing foam around tank line penetrations	N/A	N/A	N/A	N/A
L	If system trades result in wing attachment to tank, verify suitability of sealing design around penetration	Full-scale link attach clevis, simulated tank stud, short link, and skin with insulation in enclosure simulating actual condition	1	Determine magnitude of frost and boil-off and design implications	Thermocouples

Table 5 TPS Tests For Composite Tank Dev.

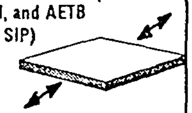
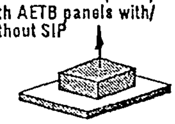
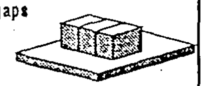
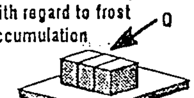
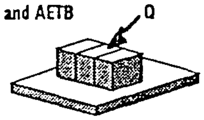
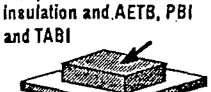
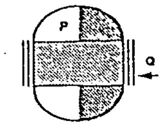
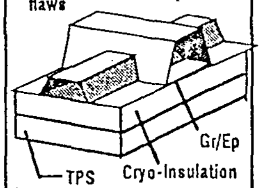
Test Item	Test Objective	Test Article Description	No. of Test Articles	Test Description	Instrumentation
A	Verify if SIP is required between AETB and foam insulation	12-in. x -12-in. panels of Gr/Ep-stiffened walls, Rohacell, and AETB (without SIP) 	Two each for a total of 2	Apply in-plane longitudinal tension and compression at RT to achieve 5 mils of strain. Cycle 20 times	Strain gauges
B	Determine the strength suitability of the selected cryoinsulation and TPS bond line	12-in. x -12-in. panels of stiffened Gr/Ep foam (joint filler as required) with AETB panels with/ without SIP 	Two each of every combination for a total of 4	Wet tank wall with LH_2, drain, and apply peak heat load. Repeat for 20 cycles. Perform pull test on TPS	Thermocouples at both bond lines—4 per panel, total of 16
C	Determine magnitude of frost accumulation	12-in. x -12-in. panels of Gr/Ep tank walls, selected foam (joint filler as required), PBI and TABI with end-to-end butting, AETB panels with gaps 	Two each of every combination for a total of 6	Wet Gr/Ep with LH2 in KSC-simulated humid environments. Weigh panel before and after exposure	Thermocouples at both bond lines—8 per panel, total of 96
D	Determine the effect of frost contained in the TPS during entry heating—AOA	Three of the worst panels with regard to frost accumulation 	Three	Expose panels with frost to reentry heat load. Visually inspect test panels after test	Thermocouples at 4 points
E	Only if frost accumulation is significant, characterize frost avoidance of silicone rubber film with embedded nichrome wires and one alternate method	12-in. x -12-in. panels of the three design combinations with worst frost accumulation 	Three each of two frost avoidance methods for a total of 6	Wet tank wall with LH_2 in KSC-simulated humid environments. Weigh panels before and after exposure	Thermocouples at both bond lines—8 per panel, total of 48
F	Characterize thermal performance	12-in. x -12-in. panels of Gr/Ep tank walls, selected foam (joint filler as required), PBI, TABI, and AETB 	Two each of every combination for a total of 6	Wet tank wall with LH_2, drain, and apply predicted ambient atmosphere and concurrent peak heat loads	Thermocouples at both bond lines—9 per panel
G	On-orbit debris impact preliminary testing	6-in. x -6-in. Gr/Ep panels tank walls, insulation and PBI, AFRSI, and AETB 	Three each of each configuration, three projectile a total of 27 types per panel for	Expose panels to ballistic firing of aluminum spheres	None
H	Determine the tank wall damage from simulated on-orbit debris impact with TPS	6-in. x -6-in. panels of Gr/Ep tank walls, insulation and AETB, PBI and TABI 	Three types TPS three specimenseach, 2 wall thicknesses, 2 insulation thicknesses, and 2 TPS thicksesses for a total of 72	Expose panels to ballistic firing of aluminum spheres	None
I	Verify repair and replacement of TPS/ insulation techniques developed separately in Task 4 and TA-3	12-in. x -12-in. panels of Gr/Ep tank walls, insulation and other with joint filler as required, with PBI, TABI, and AETB panels 	Four each of every combination for a total of 24	Induced repairable damage to half the panels, then repair. Induce damage requiring replacement, then replace. Perform selective mechanical and thermal properties tests	None

Table 6 NDI/NDE/IHM Methods For Composite Tank Dev.

Test Item	Test Objective	Test Article Description	No. of Test Articles	Test Description	Potential Instrumentation
A	Cryopumping, leakage, flaws/cracks, debonds, TPS integrity, water content	Integrated Subscale • Insulation • 4-ft Al tank • Selected TPS 	1 test article from TA 3	Evaluate IHM technologies at system level under cryogenic loads. Drive out system requirements before entering detailed component tests	Thermograpy, shearograph, ultrasonics, acoustic energy, radiography, fiber optics
B	Evaluate preferred sensor & technologies to detect Gr/Ep delaminations and Insulation/TPS debonds	30 in. x 30 in. insulated Gr/Ep panel with injected flaws  	1	Apply technologies to detect Gr/Ep delaminations and insulation/TPS debonds under tension loads	Thermography, shearography, ultrasonics, acoustic energy, radiography, fiber optics, laser based ultrasonics
C	Detect flaws/cracks, damage, growth in Y-joint using preferred advanced sensors	6 in. x 15 in. Y-Joint Gr/Ep	1	Characterize coverage techniques for flaw assessment and growth rate under loads	Thermography, shearography, ultrasonics, acoustic energy, radiography, fiber optics, laser based ultrasonics