Executive Summary

Structural Arrangement Trade Study

Reusable Hydrogen Composite Tank System (RHCTS) and Graphite Composite Primary Structures (GCPS)

Cooperative Agreements NCC8-39 and NCC1-193

March 14, 1995

Prepared for:
NASA
Marshall Space Flight Center
Langley Research Center
Ames Research Center
Briefing Objectives

To present the Trade study process, requirements used, analysis performed, and data generated

To present the derived Conclusions and Recommendations

Through understanding of the above arrive at NASA/RI cooperative team joint decisions pertaining to TA 1 and TA 2 future structural developments
Agenda

Trade Study Objective
Requirements
Operability Features
Subsystems Supporting Analysis
Structural Arrangement Options
Selection Process
Conclusions and Recommendations
Trade Study Objectives

Determine the most suitable vehicle structural arrangement and structural materials applications recognizing:

The most suitable vehicle structural arrangement contains the most suitable Major Structures, i.e., Hydrogen and LO Tankage concepts, Intertank, wing and Thrust Structure concepts

Consider other potential technology development needs

On the basis of the foregoing recommend the Major Structures for continuing development in TA 1 and TA 2
Major Requirements/Guidelines Direct Trade Study

Requirements
- Satisfy the National Launch needs
  - Space Station Missions
  - Deliver and return payloads/crews to and from 220 nmi circular/51.6° orbit
- Provide high degree of reliability and passenger safety per flight
- Acceptable cost
- Environmentally acceptable (EPA standards, etc.)

Assumptions
- Capable of delivering/returning 25,000 lb to/from Space Station
- Payload Bay Volume: 15 x 30 ft
- Mission Duration: 2 to 7 days
- Airframe Life: 100 missions/20 years
- OMS Delta V Budget: 1,100 ft/s
- RCS Delta V Budget: 110 ft/s
- Cross Range: 1,100 nmi
- Capable of withstanding rainstorm on launch pad
- Dry Weight Growth Margin: 15%
- Autonomous operations (ground and flight)
- Parallel, off-line processing of payloads
  - Standardized interfaces
- Off-line regularly scheduled depot maintenance

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
24 Configuration Structural Arrangement Options Studied

**1A Separate Tanks**
-1, 3 Skin-stringer LH tank
-2, 4 Sandwich LH Tank
-3, 4 Wing not attached to LO Tank

- Fwd LH Tank
- Mid Payload Bay with one RP Tank
- Aft LO Tank
- Shell Thrust Structure

**2A Separate Tanks**
-1, 3 Skin-stringer LH tank
-2 Sandwich LH Tank
-3 Wing not attached to LH Tank

- Fwd LO Tank
- Mid Payload Bay with one RP Tank
- Aft LH Tank
- Shell Thrust Structure

**3A Common Bulkhead**
-1 Skin-stringer LH tank
-2 Sandwich LH Tank
- Front Payload Bay with four RP Tanks

- Fwd LH Tank
- Aft LO Tank
- Shell Thrust Structure

**4A Common Bulkhead**
-1 Skin-stringer LH tank
-2 Sandwich LH tank

- Fwd LH Tank
- Aft LO Tank
- Aft Payload Bay with one RP Tank
- Truss Thrust Structure for -1
- Shell Thrust Structure for -2

1B-1 and 2B-1 have non-integral (floating) LH tanks. All LO tanks are integral, skin-stringer-frame construction.

NASA - ROCKWELL/SSD - NORTHRUP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
Wide Range of Structural Materials/TPS Options Studied

1A-1
Intertank Option 11
AFRSI or TABI
AFR 700 - Polyimide HC Core

< 550 F

1B-1 and 2B-1
Non-Integral Tank Option 7
AFRSI or TABI
AFR 700 - Polyimide HC Core
IM7/977-2

< 550 F
< 250 F

2A-1
Intertank and Wing Option 10
CSIC Panels
Mechanically Attached
AFR 700 - Polyimide HC Core

< 550 F

Intertank, Wing, Tail and Control Surfaces Option 11
AFRSI, TABI or AETB
AFR 700 - Polyimide HC Core

< 550 F

Wing Option 12
CSIC Panels
Mechanically Attached
AFR 700 - Polyimide HC Core

< 1200 F

Control Surface Option 14
CSIC Panels
Mechanically Attached
TMC Blackglas

< 1200 F

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
Vehicle Design Incorporates Operability Features

Vehicle Utilizes "Clean Pad" (No Tower) Approach

JOINTLESS TANK ELIMINATES POTENTIAL LEAKS

SIMPLE PL CANISTER (3 TYPES) WITH HORIZONTAL LOADING

TPS PLACED OUTSIDE TANKS TO EASE TANK WALL INSPECTIONS

8 HINGED DOORS IN ENGINE FAIRINGS FOR SUBSYSTEMS ACCESSIBILITY

MODULAR RCS SYSTEMS USE SAME PROPELLANTS AS MPS

Structure Designed to Maximize Ease of Inspection

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
Study Addressed Key Structural Design Details

<table>
<thead>
<tr>
<th>LH Tank Y-Joint Concept for Sandwich Cylinder</th>
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<tr>
<td><img src="image1" alt="Diagram of LH Tank Y-Joint Concept" /></td>
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<tr>
<th>Solid Laminate Filler</th>
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<td>Foam Filler</td>
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<td>Rohacell Core</td>
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<th>Wing Attachment to LH Tank - High Design Risk</th>
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<td><img src="image2" alt="Diagram of Wing Attachment" /></td>
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<tr>
<th>ADHESIVE BOND LINE</th>
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<tr>
<td>WING ATTACH FITTING</td>
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<tr>
<td>SEAL PLYS</td>
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<tr>
<td>CRES INSERT</td>
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<tr>
<td>KEENBERT</td>
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<tr>
<td>TANK SKIN</td>
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Chine Support Avoids Penetration of Tank

| ![Diagram of Chine Support](image3) |

<table>
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<tr>
<th>TANK</th>
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<td>SKIN</td>
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NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
Study Addressed Key Structural Design Details (con't)

Potential Common Bulkhead Joint Concept

<table>
<thead>
<tr>
<th>Weld</th>
<th>Tangent Point</th>
<th>Closeout Plate</th>
<th>Sealer Plys</th>
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<td>17.8</td>
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Gr/Ep Fiberboard Over Y-Joint

He Purge Channel

"Waffle" Grid

Butt Weld Inner Face

Drilled Passages

Adhesive Bond Outer Face Sheet

Thrust Structure Hold Down Concept

Latch Assy

GSE

1.0 Clearance

Skin/Wing

Thrust Structure

Fairing for Access to Propulsion System

Base Holddown Fitting (11 Pcs)

Thrust Post Longerons (6 Pcs)

Aft Skirt Assy

Modular RCS System (2 Pcs)

Note: Not to Scale

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
1A-1 and 1A-1 Intertank Option 11 Have Lowest Vehicle Gross Fueled Weights

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
1. DESIGN AND PRODUCTION EFFORT - 10%
   a. Certification Effort - 3%
   b. Verification Effort - 3%
   c. Producibility Effort - 2%
   d. IHM Effort - 2%

2) MISCELLANEOUS WEIGHTS - 6%
   a. Primary Structure Weight - 2%
   b. TPS Weight - 1%
   c. Total Dry Weight - 3%

3) GROSS FUELED WEIGHT - 14%
   a. Gross Fueled Weight Sensitivity - 14%

4) PROPELLION INTERFACE - 6%
   a. Number Of Feed Line Penetrations - 1.5%
   b. Number Of Propellant Suction Lines - 1.5%
   c. Ease Of Slop Baffle Integration - 1.5%
   d. Ease Of Tank Cleaning - 1.5%

5) VEHICLE CONTROLLABILITY - 9%
   a. Ascent Controllability - 3%
   b. Hypersonic Controllability - 3%
   c. Subsonic Controllability - 3%

6) ON PAD OPERATIONS - 12%
   a. Pressurization/Fueling Flexibility - 3%
   b. Sub-Systems For On-Pad Operations - 3%
   c. Systems Requiring Disconnects - 3%
   d. Facilities - 3%

7) MAINTENANCE OPERATIONS - 18%
   a. Wide Area Coverage Inspection - 4%
   b. Localized Area Coverage Inspection - 2%
   c. Accessibility - 1%
   d. Number Of Inspection Points - 2%
   e. Re-Waterproofing - 1.5%
   f. Sustained Personnel - 1.5%
   g. Turn Around Time - 3%
   h. Facilities - 1.5%
   i. Equipment Requirements - 1.5%

8) SAFETY - 15%
   a. Probability of Tank Penetration - 6%
   b. Tank Rupture Due To Debris Impact - 4%
   c. Number of Fracture Critical Parts - 2%
   d. Probability of LH/LLO Contact - 1%
   e. Amenability to IHM - 2%

9) DEVELOPMENT RISK - 10%
   a. Structural Design Risk - 3%
   b. TPS Design Risk - 3%
   c. Technology Development - 4%

10) COST
    a. DDT&E Cost
    b. Operations Cost
    c. Production Cost
    d. Life Cycle Cost
    e. Cost Per Flight
Certification Effort - (Qualitative evaluation) - The candidate vehicle options are rated according to the perceived effort of analysis, development testing, and demonstration testing required for certification of structure and TPS. Certification refers to only the design and is achievable without fabrication of a vehicle.

Certification (Low Is Best)

Ranking (High Is Best)

NASA - ROCKWELL/SSD - NORTHRUP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
1A Options Received Best Scores Due To High Ranking In Nine Key Areas

- Design and Production Effort
- Miscellaneous Weights
- Gross Fueled Weight
- Propulsion Interface
- Vehicle Controllability
- On Pad Operations
- Maintenance Operations
- Safety
- Development Risk

NASA - Rockwell/SSD - Northrop/Grumman - Rockwell/NAAD/Tulsa - Hercules
Cost Estimates Favor 1A-1 But 2A-1 and 3A-1 Are Only Slightly Higher in Cost

![Graph showing normalized acquisition cost and annual operations cost for various structural configurations. The graph compares normalized production cost (Prod Cost Normalized), DDT&E cost (DDT&E Normalized), and operations cost (Ops Cost Normalized). The configurations are labeled as follows: NASA, ROCKWELL/SSD, NORTHROP/GRUMMAN, ROCKWELL/NAAD/TULSA, and HERCULES.]
1A Has Most Suitable Structural Arrangement

1A Separate Tanks

- Fwd LH Tank
- Mid Payload Bay with one RP Tank
- Aft LO Tank
- Shell Thrust Structure

2A Separate Tanks

- Fwd LO Tank
- Mid Payload Bay with one RP Tank
- Aft LH Tank
- Shell Thrust Structure

- Lowest Current Vehicle Gross Weight - Best 1A is 107,000 lbs lower than 2A-1 and 228,900 lbs lower than 2A-3
- Lowest Vehicle Cost and best in Evaluation
- On pad prepressurization of Hydrogen tank is not required like in 2A
- Hydrogen Tank has no mechanical penetrations (except manhole) - No wing or fairing attachments
- Hydrogen Tank has lowest skirt Y-joint loading - Significant design advantage
- Avoidance of Wing supports into LO Tank is most easily achieved with small wing glove - Avoidance of LH tank attachment with 2A requires long glove

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
3A Common Bulkhead Design Is Prohibitive Risk - Attractive With Intertank Design

- 3A-1 - Gross Vehicle Weight is currently only 42,115 heavier than 1A-1 but Common bulkhead design (Al-Li LO tank to Composite LH tank is excessive risk)

- 3A - Common bulkhead design for Composite LH and LO tanks reduces 3A Vehicle weight and design risk - This is significant development effort

- 3A Modified with Intertank has Gross Vehicle Weight is 140,000 lbs heavier than 1A-1 but should be more controllable

- 3A Modified has LH tank with no wing or fairing attachments
4A-1 - Gross Vehicle Weight is 241,600 lbs heavier than 1A-1 but Common bulkhead design (Al-Li LO tank to Composite LH tank is excessive risk)

- 4A - Common bulkhead design for Composite LH and LO tanks reduces 4A Vehicle weight and design risk - This is significant development effort

- Cost is higher than 1A-1

- 4A - Expected advantage of avoidance of wing attachment to cryogenic tankage is achievable with 1A and 3A

- 4A - Highest exposed tank surface for debris impact
Preliminary Tri-Propellant Assessment Indicates That Option 1A is Marginally Controllable and Option 2A is Stable and Controllable

- Ascent TVC moment authority with single engine-out to:
  - Balance aerodynamic moment
  - Provide trajectory control
  - Provide dynamic stability
  - Remove errors from C. G. tracking, engine installation, thrust vector misalignment, aero- uncertainties, Nav & control sensors and actuator errors
- Projected angle-of-attack < 5 degrees for both configurations, assuming nominal is zero.
- Configuration 1A is marginal in control effectiveness for no engine-out and no system errors conditions. Pitch plane cg-tracking TVC gimbal angle is from 1.5 to 3.64 degrees. Trajectory and disturbance recovery require 4.2 degrees. Engine-out and other errors sources account for 1.5 degrees. Est. Max. is +/-7.5 degs. Actuation rate is at least 12 deg/sec.
- Configuration 2A is stable and controllable TVC gimbal requirement is within +/-6 degrees.
2A Wing Attach Shear Fitting Minimizes Normal Loads
2A Wing Attachment to Skin-Stringer LH2 Tank Has High Design Risk

- Potential leak path in adhesive between frame & skin.
- Heavy frames at wing attachment causes high normal load between skin & frames - potential for bending induced adhesive peel failures in stringers.
- High transverse CTE of composite vs CRES presents potential for cracking around insert.
- Requires hand laying of seal plys after insert installed in frame.
2A Wing Attachment to Sandwich Tank Has High Design Risk But Reduced Mfg. Risk & Leakage Potential

- Heavy frames at wing attachment causes high radials load between skin & frames - potential for frame flange peel
- Wing fitting attaches to longeron imbedded in sandwich; design adequacy depends on load shearing from longeron to inner facesheet and thru adhesive to frame cap
- No penetrations of inner face - no leakpaths (for concept shown)
- Improved producibility over skin-stringer design

NASA - ROCKWELL/SSD - ROCKWELL/NAAD/TULSA - HERCULES
2A Option Represents High LH Tank Structural Design Risk

- Wing attachment to LH tank avoids weight penalty of long glove to avoid tank

- Wing attachment to tank presents significant potential leakage concern and high radial tension loads across cobonded skin to frame interface (838 lb/in instead of 300 lb/in for 1A design)

- Wing attachment fitting loads result in cross ply tension loads- worst loading for composites

- Numerous wing to tank attachments reduce cross ply tension loads but represent increased heat shorts

- All the above is significant risk in view of current LH tank development schedule

- Alternative to avoid attachment to LH tank represents 228,900 gross vehicle weight penalty

Proceed with technology development to 1A option - Avoid wing attachment design pending completion of control analyses by March 27, 1995

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES
Non-integral Tank May Be Most Likely Design for Strict Adherence to Debris Impact - Lowest Risk Design

No option satisfies no penetration probability requirement in regime of .99. Current weight penalty of non-integral tank may be negated for strict adherence to this requirement.

Advantages of non-integral design are:

- Non-integral tank - Loss of pressure is not expected to be critical to vehicle survival - burst pressure issue applies to both
- Cryogenic insulation is not exposed to 400 F - Other insulations possible
- Avoidance of criticality of Y-joint technology development

Technology development requirements of non-integral tank are enveloped by integral tank design.

Designs to required debris impact have significant increases in skin thickness - reduced limit stresses, and radial tension loads.

Recommendation - Do not include debris impact requirement into development of hydrogen tank - Pursue investigation of debris impact requirements and solutions.

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA - HERCULES

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Option 1A (LH tank forward, integral tank, payload at midbody) is most suitable structural arrangement

- Option 1A marginally controllable
- Option 2A stable and controllable

Option 2A Wing attachment to composite LH tank has high design risk

Common bulkhead designs represent prohibitive risk

Non integral tank can be most suitable design for strict adherence to current debris impact
Development Recommendations

• Proceed with development of integral 1A Hydrogen tank - Development to encompass integral and non-integral LH tank

  Above development is also applicable to 3A (with intertank) Hydrogen tank and 1B-1 non-integral tank with short skirts (Avoidance of penetrations)

• Proceed with development of 1A Intertank - Lowest loads provide design with fabrication challenge

• Proceed with development of 1A Wing with supports straddling LO Tank

• Proceed with 1A Conical Shell Thrust Structure - will have highest gimbal forces

• In any future NRA composite LO tank efforts proceed with 1A LO tank development based on wing attachments straddling the LO tank

• Proceed with refinement of 1A Finite Element Model
Development Recommendations - Cont’d

Stay with Gr/BMI unpressurized structures

Use of AFR 700 on Intertank, Wing, Wing control surfaces and Tail results in essentially the same gross vehicle weight as Gr/BMI for Space Station mission

Design to 1100 nm polar AOA will increase TPS weight with AFR 700 design

Operations reductions are small because of small reductions in TPS surface area

Use of TMC, and Blackglas protected by CSic TPS, as necessary, represented significant vehicle weight increase

CSic TPS repair, and replacement time savings are offset by increased inspection and waterproofing hours

All material variations from Gr/BMI with blanket TPS represent TA 2 schedule risk