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
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.

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Wide Range of Structural Materials/TPS Options Studied

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

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

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

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

Wing Option 12
CSIC Panels (Mechanically Attached)
< 1200 F
TMC

Control Surface Option 14
CSIC Panels (Mechanically Attached)
< 1200 F
TMC: Blackglas

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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

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Study Addressed Key Structural Design Details

LH Tank Y-Joint Concept for Sandwich Cylinder

Solid Laminate Filler
Foam Filler
Rohacell Core

Wing Attachment to LH Tank - High Design Risk

ADHESIVE BOND LINE
WING ATTACH FITTING
TANK FRAME
SEAL PLYS
CRES INSERT
KEENSERT
TANK SKIN

Chine Support Avoids Penetration of Tank

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Study Addressed Key Structural Design Details (con't)

Potential Common Bulkhead Joint Concept

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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<tbody>
<tr>
<td>Weld</td>
<td></td>
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<tr>
<td>Tangent Point</td>
<td></td>
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<tr>
<td>Closeout Plate</td>
<td></td>
</tr>
<tr>
<td>Gr/Fibrobornd Over Y-Joint</td>
<td></td>
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<tr>
<td>Sealer Plys</td>
<td></td>
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<tr>
<td>AL-U/Machined &quot;Waffle&quot; Grid</td>
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<tr>
<td>He Purge Channel</td>
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<tr>
<td>Drilled Passages</td>
<td></td>
</tr>
<tr>
<td>Butt Weld Inner Face</td>
<td></td>
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<tr>
<td>Adhesive Bond</td>
<td>Outer Face Sheet</td>
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</tbody>
</table>

Thrust Structure Hold Down Concept

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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<tbody>
<tr>
<td>Latch Assy</td>
<td></td>
</tr>
<tr>
<td>Clearance</td>
<td>1.0</td>
</tr>
<tr>
<td>Skin/Winglet</td>
<td></td>
</tr>
<tr>
<td>Thrust Structure</td>
<td></td>
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</tbody>
</table>

Fairing for Access to Propulsion System

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Base Hold-down Fitting</td>
<td>(11 Pics)</td>
</tr>
<tr>
<td>Thrust Post Longeron</td>
<td>(6 Pics)</td>
</tr>
<tr>
<td>Alt Skirt Assy</td>
<td></td>
</tr>
<tr>
<td>Modular RCS System</td>
<td>(2Pics)</td>
</tr>
</tbody>
</table>

Note: Not to Scale

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1A-1 and 1A-1 Intertank Option 11 Have Lowest Vehicle Gross Fueled Weights
### 1. DESIGN AND PRODUCTION EFFORT - 10%
- Certification Effort - 3%
- Verification Effort - 3%
- Producibility Effort - 2%
- IHM Effort - 2%

### 2) MISCELLANEOUS WEIGHTS - 6%
- Primary Structure Weight - 2%
- TPS Weight - 1%
- Total Dry Weight - 3%

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

### 4) PROPULSION INTERFACE - 6%
- Number Of Feed Line Penetrations - 1.5%
- Number Of Propellant Suction Lines - 1.5%
- Ease Of Slosh Baffle Integration - 1.5%
- Ease Of Tank Cleaning - 1.5%

### 5) VEHICLE CONTROLLABILITY - 9%
- Ascent Controllability - 3%
- Hypersonic Controllability - 3%
- Subsonic Controllability - 3%

### 6) ON PAD OPERATIONS - 12%
- Pressurization/fueling Flexibility - 3%
- Sub-Systems For On-Pad Operations - 3%
- Systems Requiring Disconnects - 3%
- Facilities - 3%

### 7) MAINTENANCE OPERATIONS - 18%
- Wide Area Coverage Inspection - 4%
- Localized Area Coverage Inspection - 2%
- Accessibility - 1%
- Number of Inspection Points - 2%
- Re-Waterproofing - 1.5%
- Sustained Personnel - 1.5%
- Turn Around Time - 3%
- Facilities - 1.5%
- Equipment Requirements - 1.5%

### 8) SAFETY - 15%
- Probability of Tank Penetration - 6%
- Tank Rupture Due To Debris Impact - 4%
- Number of Fracture Critical Parts - 2%
- Probability of LH/LO Contact - 1%
- Amenity to IHM - 2%

### 9) DEVELOPMENT RISK - 10%
- Structural Design Risk - 3%
- TPS Design Risk - 3%
- Technology Development - 4%

### 10) COST
- DDT&E Cost
- Operations Cost
- Production Cost
- Life Cycle Cost
- Cost Per Flight
1a. 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.
Top Level Results

<table>
<thead>
<tr>
<th>Trade Option</th>
<th>TOP LEVEL RESULTS</th>
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<tbody>
<tr>
<td></td>
<td>COST</td>
</tr>
<tr>
<td>1A-1</td>
<td>0</td>
</tr>
<tr>
<td>1A-2</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: The table above shows the distribution of weighted scores for different categories, with 1A-1 and 1A-2 being compared against each other. The categories include cost, development risk, safety, etc., each with a specific weight percentage.
1A Options Received Best Scores Due To High Ranking In Nine Key Areas

SSTO

- DESIGN AND PRODUCTION EFFORT
- MISCELLANEOUS WEIGHTS
- GROSS FUELED WEIGHT
- PROPULSION INTERFACE
- VEHICLE CONTROLLABILITY
- ON PAD OPERATIONS
- MAINTENANCE OPERATIONS
- SAFETY
- DEVELOPMENT RISK

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Cost Estimates Favor 1A-1 But 2A-1 and 3A-1 Are Only Slightly Higher in Cost

- Normalized Acquisition Cost
- Normalized Annual Operations Cost

Structural Configurations

<table>
<thead>
<tr>
<th>NASA</th>
<th>ROCKWELL/SSD</th>
<th>NORTHROP/GRUMMAN</th>
<th>ROCKWELL/NAAD/TULSA</th>
<th>HERCULES</th>
</tr>
</thead>
</table>

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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 - A 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
3A Common Bulkhead Design Is Prohibitive Risk - Attractive With Intertank Design

- 3A-1: Gross Vehicle Weight is currently only 42,115 lbs 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.

[Diagram of 3A Common Bulkhead with labels: Front Payload Bay with four HIP Tanks, Fwd LH Tank, Aft LO Tank, Shall Thrust Structure]
4A Common Bulkhead Design Represents Prohibitive Risk

4A-1 - Gross Vehicle Weight is 241,600 lbs heavier than 1A-1 but Common bulkhead design (AI-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

Option 1A
LOX Tank
Aft, at Max Q

500 1000 1500 2000

Min (Lcp/Lc) = 0.13

\[ \text{Marginal overall GN&C System Performance} \]

Lcp= 4.5 ft, at alpha = 4 deg.

Gimbal point

Lc = 34.1 ft

\[ \text{Lcp= aero moment arm} \]
\[ \text{Lc = control moment arm} \]

Option 2A
LOX Tank
Forward, at Max Q

500 X-cg 1000 1500 2000

Min (Lcp/Lc) = 0.73

\[ \text{Lcp= 70.8 ft, at alpha = 4 deg.} \]

Gimbal point

Lc = 96.3 ft

\[ \text{Lcp= aero moment arm} \]
\[ \text{Lc = control moment arm} \]

- 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.

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2A Wing Attach Shear Fitting Minimizes Normal Loads

LOCAL BUILDUP

ATTACH FITTING

LOAD PATH

INSULATION

SHEAR ATTACH'S

TANK FRAME

WING LINK

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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

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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

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Conclusions

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

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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