Advanced Transportation System Studies

Technical Area 3

Alternate Propulsion Subsystem Concepts
NAS8-39210
DCN 1-1-PP-02147

Tripropellant Comparison Study
Task Final Report
DR-4
October 1995

MSFC/Rocketdyne
Contents

• Introduction

• Summary

• Engine Technical Groundrules

• Weight Estimating Procedure

• Weight Estimate Example

• Choice of Weight Baseline

• Cycle Options and Turbopump Arrangements

• Configuration Choices

• Operating Parameter Determination

• Engine Weights and Vehicle Performance

• Engine Cycle Margins

• Conclusions
Introduction
Alternate Propulsion Subsystem Concepts NRA
Option 2 Status

- September 1994 — December 1995
  - Task 1 — Tripropellant Comparison Study
    - $200K
    - Final Briefing October 1995
    - Task Final Report Available
      - Final Briefing Plus Additional Backup
      - Gary Johnson (205) 544-0636
  - Task 2 — Reliability, Maintainability, and Operability Assessment
    - $50K
    - Performed by Rockwell/SSD
    - NASA/MSFC Point-of-Contact
      - Jack Lehner (205) 544-4253
  - Task 3 — Parametric Rocket Engine Cost Modeling
    - $90K
    - RLV Operations Cost Model
    - Parametric Engine Cost Model — Extended Version
    - Due December 1995
Alternate Propulsion Subsystem Concepts NRA
Tripropellant Comparison Study
Study Objective

• Unbiased, Consistent Data to Draw Out the Inherent Performance Oriented Differences, Benefits and Issues
  • Bipropellant and Tripropellant
  • Engine Implementations
Summary
Tripropellant Comparison Study
Conclusions

• For Newly Designed Engines, Using the Same Groundrules and Technology

• No Significant Differences in Vehicle Dry Weight Performance Between Tripropellant and Bipropellant Engines
  • < 3% Across Chamber Pressure Range 2,000-5,000 psi
    • Bipropellant Engine Slightly Better
  • Single Chamber and Bell Annular Tripropellant Configurations Similar in Vehicle Performance (< 1%)

• Much Larger Vehicle Performances Differences Within Any One Engine Configuration Due to Operating Point and Design Choices
  • Mixture Ratio
  • Chamber Pressure
  • Nozzle Exit Pressure
  • Power Cycle
  • Coated versus Uncoated Materials
  • Welded versus Cast

• FFSCC Has Significantly Higher Available Margins Than Staged Combustion Cycle (SCC)
  • For Both Bipropellant and Tripropellant Engines
    • Differences More Pronounced for Tripropellant Engines
  • Inherent Engine Weight Difference ~ 2-5%
    • Favors SCC
    • Applies if Coated Ox Side Or Improved Ox Resistant Materials
  • Strongly Supports the Value of Ox Resistant Material Technology Programs
Engine Technical Groundrules
Tripropellant Comparison Study
Study Objectives

- Produce an "Apples-to-Apples" Comparison of Tripropellant versus Bipropellant Engines for the SSTO Application
  - Option 3 Vehicle
- Isolate the Effects of Tripropellant versus Bipropellant from the Incidentals of Design Implementation
  - Use the Same Design Groundrules
  - Use the Same Design Practices
  - Include the Same Technologies
- Produce Consistent Bipropellant and Tripropellant Databases Usable for Future Efforts
  - Other Evaluations
  - Other Vehicles
  - Other Applications
  - Support – Other Design Factors
    - Mission Evaluations
Tripropellant Configurations

Annular

Single Chamber

O₂

H₂

RP
Tripropellant Comparison Study

Engine Groundrules

- Sea Level Thrust – 421,000 lbf
- Fixed Bell Nozzle
- $\eta_{cstar}$
  - $O_2/H_2 - 0.995$ (@ MR = 6.0)
  - $O_2/RP - 0.97$ (@ MR = 2.6)
  - $O_2/H_2/RP - 0.993$ (@ MR = 4.4)
    - At 6% $H_2$
- Step Loss
  - $O_2/H_2$ as Inner Chamber
    - 1 percent
  - $O_2/H_2$ as Outer Chamber
    - 1 percent
- Mixing Loss for Separate $O_2/H_2$ and $O_2/RP$ Streams
  - $O_2/H_2$ as Inner Chamber
    - 1 percent
  - $O_2/H_2$ as Outer Chamber
    - 1 percent
- Individual Thruster Interaction (Annular)
  - 0.985
- Engine Life
  - Number of Missions 60
  - Missions Between Overhauls 20
LOX/RP-1 Turbine Nozzle Area Change Characteristics

Fractional Area Change per 100 seconds

Inlet Temperature, °R

MK 10 (35 inch) Turbine Nozzle Area Change

MK 4 Turbine Nozzle Area Change

TA3-0958
Tripropellant Comparison Study
Material Groundrules

- Pumps
  - Al for H₂
  - Inco 718 for O₂ and RP
- Turbines
  - RIM-D1 or Astroloy (Rotor), Thermo-Span (Housing) for H₂ Rich Gases
  - Haynes 214 or Inco 718 for O₂ Rich Gases
  - Inco 718 for RP Rich Gases
    - Astroloy for Rotor if Needed for AN₂ Capability
- Most H₂ Side Components – Thermo-Span
- Most O₂ Side Components – Haynes 214
- Most RP Side Components – Al or Ti
- Injector and MCC Liner – NARloy
- MCC Closeout – Ni/Co
- Nozzles
  - A286 Tubes
  - Ti Honeycomb Jacket
- Silicon Carbide Reinforced Al
  - Thrust Cone and Gimbal Bearing
  - H₂ Valve Bodies
- Composite with Steel Bushings
  - Gimbal Actuator Attach Bracket, Support Struts for Turbomachinery
Tripropellant Comparison Study
Lessons Learned from Previous Tasks

- From Previous Bipropellant and Tripropellant Efforts
  - Competitive Chamber Pressure $\geq 2,000$ psi
  - Very High Pressures Possible for Some Closed Cycles but No Vehicle Improvement Above $\sim 5,000 - 6,000$ psi
  - Performance Penalty for Open Cycles in Mode 2 is Excessive
  - There is an Optimum $P_e$ for a Fixed Nozzle
    - May Differ With Chamber Type
  - Minimal or No Engine Weight Penalty for Lower Turbine Inlet Temperatures
- Most Important Performance Parameters
  - Sea Level Thrust/Weight
  - Mode 2 Vacuum $I_{sp}$
  - Mode 1 Vacuum $I_{sp}$
Advanced Low Cost Engines
SSTO Performance
Effect of Fuel Turbine Inlet Temperature

FFSCC

Vehile Empty Weight, lbm

25K Payload
220 NMI, 51.6°
15% Weight Margin in Vehicle Code

Aggressive Weight Set

Previous Task Results

Locus of Maximum Chamber Pressure Versus Turbine Inlet Temperature

Chamber Pressure, psi

TA3-0910a
Effect of Turbine Temperature on SSTO Performance

- Current Task Results
- New CONSIZ Version
- New, More Detailed Engine Weight Codes
- Same Shapes and Relationships as Previous Task Results

**Bipropellant FFSCC**

Vehicle Empty Weight, lbm

<table>
<thead>
<tr>
<th>Chamber Pressure, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1,000</td>
</tr>
<tr>
<td>2,000</td>
</tr>
<tr>
<td>3,000</td>
</tr>
<tr>
<td>4,000</td>
</tr>
<tr>
<td>5,000</td>
</tr>
<tr>
<td>6,000</td>
</tr>
<tr>
<td>7,000</td>
</tr>
</tbody>
</table>

25K Payload
220 NMI, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

- Uncoated (1150/1100)
- Uncoated (1700/1500)
- Coated Ox Side (1150/1100)
- Coated Ox Side (1700/1500)

TA3-0995g
Effect of Sea Level Engine T/W on SSTO Performance

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
Access to Space Vehicle

Bipropellant Engines
- T/W = 90
- T/W = 80
- T/W = 70

Vehicle Empty Weight, Ibm

Chamber Pressure, psi
SSTO Performance
Specific Impulse Sensitivities

Relative Impacts:
Vacuum Mode 2 – 3.40
Vacuum Mode 1 – 2.63
SL Mode 1 – 1.00
SL Mode 2 – 0.00

Baseline – 193,931 lbm
CONSIZE May 1994
Tripropellant @ 4,000 psi

Vehicle Dry Weight Improvement, lbm

Delta Specific Impulse, sec
Chamber Pressures to be Examined

- $2,000 \leq P_c \leq 6,000$ psi
- Need not examine low $P_c$'s nor the ultimate power limit $P_c$

Use minimum turbine inlet temperatures that are necessary

- Consider exit gas properties
- Consider pump discharge pressures
# Tripropellant Comparison Study
## Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Chamber Tripropellant</th>
<th>Bell Annular Tripropellant</th>
<th>O₂/H₂ Bipropellant</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR (T/C), O₂/H₂; O₂/RP</td>
<td>5.0-7.5; 2.6-3.0</td>
<td>5.0-7.5; 2.6-3.0</td>
<td>5-12</td>
</tr>
<tr>
<td>Thrust Split</td>
<td>—</td>
<td>Optimize</td>
<td>—</td>
</tr>
<tr>
<td>H₂ Flow (Mode 1/Mode 2)</td>
<td>Optimize</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mode Switch</td>
<td>Optimize</td>
<td>Optimize</td>
<td>Optimize</td>
</tr>
<tr>
<td>Pₖ, psi</td>
<td>2,000 – 6,000</td>
<td>2,000 – 6,000</td>
<td>2,000 – 6,000</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Single Fixed</td>
<td>Single Fixed</td>
<td>Single Fixed</td>
</tr>
<tr>
<td>Pₑₓit</td>
<td>Optimize One Point Then Fix</td>
<td>Optimize One Point Then Fix</td>
<td>Optimize One Point</td>
</tr>
<tr>
<td>Sea Level Thrust, lb₉</td>
<td>421,000</td>
<td>421,000</td>
<td>421,000</td>
</tr>
<tr>
<td>Tₑₚₜₜ (Closed Cycles)</td>
<td>Lowest That Works</td>
<td>Lowest That Works</td>
<td>Lowest That Works</td>
</tr>
<tr>
<td>Tₑₚₜₜ (GG)</td>
<td>1900 °R</td>
<td>1900 °R</td>
<td>1900 °R</td>
</tr>
</tbody>
</table>
Tripropellant Comparison Study
Weight Estimating Procedure
Alternate Propulsion Subsystem Concepts
Weight Estimating Procedure

- Engines Reflect a Modest Set of New Technologies
  - All Mid-Term or Nearer
  - Not Very Aggressive in Terms of Materials for Weight Reduction

- New Technologies Used in Engines Resulting From Trade Studies
  - Jet Pump Low Pressure Pumps
  - SLIC™ Turbopumps Where Possible
  - Propellant Duct Gimbal Accommodation on Vehicle Side
  - Laser Igniter
  - EMA Valves
  - Materials
    - Al for H₂ Pump
    - Silicon Carbide Reinforced Al
      - Thrust Cone and Gimbal Bearing
      - H₂ Valve Bodies
    - Composite with Steel Bushings
      - Gimbal Actuator Attach Bracket, Support Struts for Turbomachinery
    - Ti Honeycomb Nozzle Jacket
    - Ni/Co Main Combustion Chamber Closeout
Alternate Propulsion Subsystem Concepts
Weight Groundrules

Materials

- All Material Properties Used are Guaranteed Minimums (Except Al for H₂ Pump)
- 1.2 Limit Load on Pressure then 1.25 on Yield at Operating Temperature
  - More Conservative Than 1.5 on Ultimate
  - Usually More Conservative Than 1.2 Limit Load Followed by 1.5 on Ultimate
  - Most Conservative Method for Materials Used in This Design
- Nozzle Tubes
  - Single Up-pass
  - Nozzle Entrance Mass Flux = 3.0 lbm/(sec-in²)
  - Material – Annealed A286
  - 1.2 on Yield
    - More Conservative than 1.2 Limit Load Followed by 1.5 on Ultimate
    - 51 ksi versus 68 ksi
- For Components Designed as CATIA Solid Models
  - 1.02 Factor Applied to Weight Because CATIA does not Use Splines
  - 1.05 Factor Applied to Weight for Fillets, welds, etc.

Structural

- Struts to Jet Pumps and Bottom of Turbopumps to Minimize Moments and Other Loads Carried Through Ducts
- Varying Minimum Duct and Cast Wall Thicknesses
  - Ducts
    - 0-2 in ID 0.030 in
    - 2-3 in ID 0.045 in
    - 3-6 in ID 0.060 in
    - > 6 in ID 0.072 in
  - Castings
    - Calculated Wall Thickness ≤ 0.125 in 0.125 in
    - Calculated Wall Thickness 0.125 in to 0.250 in 0.250 in
    - Use Calculated Wall Thicknesses Above 0.250 in

TA3-0861
Alternate Propulsion Subsystem Concepts
Weight Groundrules (Cont'd)

**Sizing**

- 0.5 in ID Minimum for Any Duct, Line, or Valve
- Liquid Lines Sized for 1.5% Velocity Head Based on Local Pressure
- Gas Lines Sized for 0.14 Mach
  - Except for Manifolds Which are Sized for 0.10 Mach
- Factor of 1.5 Applied to Wall Thickness on Hot Gas Manifolds for Dynamic Loading
- Factors on Ducts and Lines to Match SSME Experience
  - Factor on Calculated Wall Thickness
    - 1.33 for H₂
    - 1.66 for O₂ and RP
  - Factor on Calculated Weight – 1.4 for All Fluids

**Misc**

- Turbine Bypass Lines on All Turbines (Sized for 20% Preburner Flow)
- Ducts Insulated and Then Covered with Metal Sheath Up to Pumps
- Weight for Purge System (from SSME) for Ground Ops
- Include
  - FASCOS
  - POGO
  - Engine Mounted Controller
  - Line and Nozzle Insulation
  - Nozzle Attachment for Heat Shield
  - Drain Lines with Valves
Tripropellant Comparison Study
Weight Estimate Example
Alternate Propulsion Subsystem Concepts
Weight Estimating Procedure

• Overall Procedure
  • Various Individual Design Procedures Combined at CATIA Assembly Level for Packaging
    and in Spreadsheet for Weights

• Two Direct Design Procedures are Used
  • CATIA Solid Model (e.g., Hot Gas Manifold)
    • Designed as Individual Component
    • Wall Thickness Calculated
    • Minimums Applied in Model
      • 1.5 Factor for Dynamic Loads Applied to Wall Thickness if Appropriate
    • Solid Volume Returned to Spreadsheet for Weights
  • In Spreadsheet
    • Density used on Solid Volume for Weight
    • 1.02 Factor and 1.05 Factor Applied to Weight

  • CATIA Assembly Model (e.g., Duct)
    • Designed at Assembly Level for Dimensions, Clearances, and Packaging
    • Dimensions Returned to Spreadsheet for Weights
    • In Spreadsheet
      • Wall Thickness Calculated and Minimums Applied
      • Other Subcomponents Calculated (Flanges, Insulation, Insulation Shields, etc.)
      • Weights Calculated from Material Choices and Dimensions
      • Lines and Ducts Corrected to Match SSME Design Practice

• Other Procedures are Used For Some Components and the Procedures May be Combined
  • Scaled (e.g., Valves)
  • Outside Reference (e.g., STME-100 for Controller)
  • Outside Model or Correlation (e.g., SLIC™ Turbomachinery)
  • Directly from SSME (e.g., Static Seals)

TA3-0860
# Alternate Propulsion Subsystem Concepts

## Weight Calculations

<table>
<thead>
<tr>
<th>Component (on SSME) (% of SSME Weight) (Listed in Order of SSME Weight)</th>
<th>Procedure</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Turbomachinery (24.7%)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Fuel Turbopump | Outside Correlation from Adv Rotating Machinery (ARMD93-65) | (H₂) Pump — Al  
Turbine — RIM-D1 (Rotor)  
Thermo-Span (Housing)  
(RP) Pump — Inco 718  
Turbine — Inco 718 |
| Fuel Jet Pump | CATIA Solid Model | (H₂) Inco 903  
(RP) Ti-6Al-4V |
| Ox Turbopump | Outside Correlation from Adv Rotating Machinery (ARMD93-65) | Pump — Inco 718  
Turbine — Haynes 214 |
| Ox Jet Pump | CATIA Solid Model | Inco 718 |
| **Nozzle (18.7%)** | CATIA Solid Model for Manifolds, Mass flux and Spreadsheets for Tubes, Jacket, and Insulation | Tubes — A286  
Jacket — Ti Honeycomb  
Manifolds and Flanges — Thermo-Span  
Insulation — Nextel Ceramic  
Fiber Blanket (0.5 area) |
| **Hot Gas Manifolds/Inj/Thrust Cone (13.6%)** | | |
| Hot Gas Manifolds | CATIA Solid Model | (H₂) Thermo-Span  
(RP) Inco 718  
Transfer Tube, inlet, Ox Injector Dome — Haynes 214 NARloy |
| Fuel | CATIA Solid Model | Silicon Carbide Reinforced Al |
| Ox | CATIA Solid Model | |
| Injector | CATIA Solid Model | |
| Thrust Cone | Scaled from Previous CATIA Solid Model | |
### Alternate Propulsion Subsystem Concepts
Weight Calculations (Cont’d)

<table>
<thead>
<tr>
<th>Component (on SSME) (% of SSME Weight) (Listed in Order of SSME Weight)</th>
<th>Procedure</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant Ducts (11.8%)</td>
<td>CATIA Assembly Model</td>
<td>(H₂) Inco 903 (RP) Ti-6Al-4V Inco 718</td>
</tr>
<tr>
<td>Fuel (Ducts and Flanges)</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>Ox (Ducts and Flanges)</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>MCC (6.3%)</td>
<td>CATIA Solid Model (Liquid Interface Diffusion Bonding of Cast Manifolds to Liner)</td>
<td>Liner — NARloy Manifolds and Flanges — Thermo-Span Jacket — E.D. Ni/Co</td>
</tr>
<tr>
<td>Valves (5.9%)</td>
<td>Scaled from one Existing EMA Valve and Actuator</td>
<td></td>
</tr>
<tr>
<td>Avionics (5.4%)</td>
<td>From STME-100 (22 June 93)</td>
<td>Same as STME</td>
</tr>
<tr>
<td>Controller with FASCOS</td>
<td>From Sensor Suite of STME-100 (22 June 93) Minus ASI Sensor and Three Interpropellant Seal Leak Sensors</td>
<td>Same as STME</td>
</tr>
<tr>
<td>Sensors</td>
<td>Scaled from STME-100 (22 June 93). Scaled on Physical Size Approximated by ( (T_{vac})^{0.5} )</td>
<td>Same as STME</td>
</tr>
<tr>
<td>Misc (4.1%)</td>
<td>Scaled as Fraction of System Weight (3.6%). Baseline Percent Determined from SSME</td>
<td></td>
</tr>
</tbody>
</table>
### Alternate Propulsion Subsystem Concepts
### Weight Calculations (Cont’d)

<table>
<thead>
<tr>
<th>Component (on SSME) (% of SSME Weight)</th>
<th>Procedure</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preburners (2.8%)</td>
<td>CATIA Solid Model (Sizes from External Model)</td>
<td>(H₂) Thermo-Span, Inco 718, Inco 718 (RP), NARloy (Fuel — Thermo-Span (H₂), NARloy) (Ox — Inco 718)</td>
</tr>
<tr>
<td>Fuel Body</td>
<td>CATIA Solid Model (Sizes from External Model)</td>
<td>(RP)</td>
</tr>
<tr>
<td>Injector Inlets and Flanges</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>Ox Body</td>
<td>CATIA Solid Model (Sizes from External Model)</td>
<td>Haynes 214, NARloy (Fuel — Thermo-Span (H₂), Inco 718 (RP)) (Ox — Inco 718)</td>
</tr>
<tr>
<td>Injector Inlets and Flanges</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>Gimbal Bearing (1.5%)</td>
<td>Scaled from SSME on Material Density</td>
<td>Silicon Carbide Reinforced Al</td>
</tr>
<tr>
<td>Lines (Interface: Drain, Repress, and Bleed) (1.4%)</td>
<td>CATIA Assembly Model</td>
<td>(H₂) Inco 903, Ti-6AI-4V, Inco 718 (RP)</td>
</tr>
<tr>
<td>Fuel</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>Ox</td>
<td>CATIA Assembly Model</td>
<td></td>
</tr>
<tr>
<td>Pneumatics (1.1%)</td>
<td>Not Used</td>
<td>Same as SSME</td>
</tr>
<tr>
<td>POGO (1.1%)</td>
<td>Scaled from SSME (0.25 of Gas)</td>
<td></td>
</tr>
<tr>
<td>Hydraulics (0.4%)</td>
<td>Not Used</td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger (0.4%)</td>
<td>Autogenous Pressurization Using SSME Single Coil Design</td>
<td>Redundant Laser Igniters</td>
</tr>
<tr>
<td>Igniters (0.4%)</td>
<td>Estimate from Combustion Devices</td>
<td>Same as SSME</td>
</tr>
<tr>
<td>Purge (0.3%)</td>
<td>Direct from SSME</td>
<td>Same as SSME</td>
</tr>
<tr>
<td>Bleed Recirc Pumps (0.1%)</td>
<td>Twice the SSME Weight</td>
<td>Same as SSME</td>
</tr>
<tr>
<td>Static Seals (0.1%)</td>
<td>Direct from SSME</td>
<td>Same as SSME</td>
</tr>
</tbody>
</table>
Alternate Propulsion Subsystem Concepts
Weight Estimate Example and Comparison

- Bipropellant and Single Chamber Tripropellant
- FFSCC
- Design Point
  - Chamber Pressure – 4,000 psi
  - Sea Level Thrust – 421,000 lbf

- Characteristics
  - Fuel Rich Fuel Turbopump
  - LOX Rich LOX Turbopump
  - Jet Pump Low Pressure Pumps
  - Propellant Duct Gimbal Accommodation on Vehicle Side
  - SLIC™ Turbomachinery
  - Uncooled Powerhead
  - EMA Valves
  - Preburner Injectors Gas/Liq Impinging Jet
  - MCC Injectors Gas/Gas Co-Ax
  - Redundant Laser Igniters
  - Autogenous Pressurization on Both Sides
  - Pump Conditioning Fluid Recirculated to Tank on Both Sides
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bipropellant</th>
<th>Tripropellant (Single Chamber)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>FFSCC</td>
<td>FFSCC</td>
</tr>
<tr>
<td>Area Ratio</td>
<td>70</td>
<td>64</td>
</tr>
<tr>
<td>MR – Mode 1</td>
<td>6.9</td>
<td>4.4</td>
</tr>
<tr>
<td>MR – Mode 2</td>
<td>6.9</td>
<td>6.2</td>
</tr>
<tr>
<td>Chamber Pressure, psi</td>
<td>4,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Sea Level Thrust</td>
<td>421,000</td>
<td>421,000</td>
</tr>
<tr>
<td>Vacuum Thrust</td>
<td>484,585</td>
<td>477,630</td>
</tr>
<tr>
<td>Specific Impulse, sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 1 Vac</td>
<td>451.43</td>
<td>406.26</td>
</tr>
<tr>
<td>Mode 1 Sea Level</td>
<td>392.19</td>
<td>358.09</td>
</tr>
<tr>
<td>Mode 2 Vac</td>
<td>451.43</td>
<td>450.69</td>
</tr>
<tr>
<td>Mode 2 Sea Level</td>
<td>392.19</td>
<td>339.18</td>
</tr>
<tr>
<td>Mass Flow Fractions, percent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>81.3</td>
<td>81.5</td>
</tr>
<tr>
<td>H2</td>
<td>12.7</td>
<td>6.0</td>
</tr>
<tr>
<td>RP</td>
<td>-</td>
<td>12.5</td>
</tr>
<tr>
<td>Flowrate, lbm/sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>937.57</td>
<td>957.95</td>
</tr>
<tr>
<td>H2</td>
<td>135.88</td>
<td>70.53</td>
</tr>
<tr>
<td>RP</td>
<td>-</td>
<td>147.19</td>
</tr>
<tr>
<td>Total</td>
<td>1073.45</td>
<td>1175.67</td>
</tr>
<tr>
<td>Volume Flowrate, ft3/sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>12.7</td>
<td>13.0</td>
</tr>
<tr>
<td>H2</td>
<td>25.1</td>
<td>13.0</td>
</tr>
<tr>
<td>RP</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td>Throat Diameter, inches</td>
<td>8.88</td>
<td>8.78</td>
</tr>
<tr>
<td>Turbine Temperature, °R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>1,100</td>
<td>1,100</td>
</tr>
<tr>
<td>H2</td>
<td>1,150</td>
<td>1,150</td>
</tr>
<tr>
<td>RP</td>
<td>-</td>
<td>1,410</td>
</tr>
</tbody>
</table>
## Tripropellant Comparison Study

### Bipropellant/Tripropellant Engine Weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Bipropellant</th>
<th>Tripropellant (Single Chamber)</th>
<th>Difference (Biprop-Triprop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Chamber</td>
<td>496</td>
<td>485</td>
<td>-11</td>
</tr>
<tr>
<td>Nozzle</td>
<td>625</td>
<td>565</td>
<td>-60</td>
</tr>
<tr>
<td>Turbopumps</td>
<td>1,061</td>
<td>872</td>
<td>-189</td>
</tr>
<tr>
<td>O2</td>
<td>(562)</td>
<td>(563)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>(499)</td>
<td>(222)</td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>—</td>
<td>(87)</td>
<td></td>
</tr>
<tr>
<td>Preburners</td>
<td>374</td>
<td>364</td>
<td>-10</td>
</tr>
<tr>
<td>O2</td>
<td>(344)</td>
<td>(320)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>(40)</td>
<td>(24)</td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>—</td>
<td>(19)</td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td>361</td>
<td>349</td>
<td>-12</td>
</tr>
<tr>
<td>Ducts</td>
<td>623</td>
<td>665</td>
<td>+42</td>
</tr>
<tr>
<td>O2</td>
<td>(358)</td>
<td>(358)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>(265)</td>
<td>(240)</td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>—</td>
<td>(67)</td>
<td></td>
</tr>
<tr>
<td>Manifolds</td>
<td>460</td>
<td>597</td>
<td>+137</td>
</tr>
<tr>
<td>O2</td>
<td>(198)</td>
<td>(189)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>(262)</td>
<td>(228)</td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>—</td>
<td>(180)</td>
<td></td>
</tr>
<tr>
<td>Controller, Harness, Sensors, Ignition</td>
<td>150</td>
<td>168</td>
<td>+18</td>
</tr>
<tr>
<td>Structure</td>
<td>252</td>
<td>258</td>
<td>+6</td>
</tr>
<tr>
<td>Misc</td>
<td>165</td>
<td>168</td>
<td>+3</td>
</tr>
</tbody>
</table>

**Total**

<table>
<thead>
<tr>
<th>Bipropellant</th>
<th>4,567</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripropellant</td>
<td>4,492</td>
</tr>
<tr>
<td>Difference</td>
<td>-75</td>
</tr>
</tbody>
</table>
Tripropellant Comparison Study
Observations on Bipropellant/Tripropellant Engine Weights

- Single Chamber Tripropellant Engine is Not a LOX/RP Engine With a Little H₂
- It Is a High Mixture Ratio LOX/H₂ Engine with Some RP
  - Observe the Volumetric Flows

- Both Engines Have Essentially the Same Throat Area
  - Same Pressure
  - Slightly Higher Flowrate of Tripropellant Burned Gases Offset by Slightly Higher Molecular Weight
  - Effect is That the Chamber and the Nozzle (at the Same Area Ratio) Must Weigh About the Same

- Those Components Most Associated with Volumetric Flows Slightly Favor the Tripropellant
  - Chamber, Preburners, Valves (Main H₂ Valve), and Most Especially the Turbopumps
- Those Components Most Associated with Numbers of Different Flows Slightly Favor the Bipropellant
  - Ducts, Manifolds, Sensors

- Overall, It Should Not be Surprising That the Bipropellant and the Single Chamber Tripropellant Weigh About the Same for the Same Thrust and Chamber Pressure
Tripropellant Comparison Study
Effect of Engine Weight Changes

- Changes to Design Practices, Groundrules, or Technology Levels
  - Impact Absolute Value, Not Relative Value
    - Engine Weight
    - Vehicle Dry Weight
  - Because Engine Weights and Relative Component Group Weights are Similar

Consequently Such Changes Do Not Impact Tripropellant/Bipropellant Comparisons
### Advanced Booster Engine 4K PC O2/H2

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>4,567</td>
</tr>
<tr>
<td>Boil 4 Misc. Parts</td>
<td>165</td>
</tr>
<tr>
<td>Structure</td>
<td>252</td>
</tr>
<tr>
<td>Controller, Harness, Sensors, Ignition</td>
<td>150</td>
</tr>
<tr>
<td>Ox Hot Gas Manifold</td>
<td>198</td>
</tr>
<tr>
<td>Fuel Hot Gas Manifold</td>
<td>262</td>
</tr>
<tr>
<td>Includes: Repress, pump repress, drain, pogo systems, etc.</td>
<td></td>
</tr>
<tr>
<td>Oxidizer</td>
<td>623</td>
</tr>
<tr>
<td>Includes: Repress, pump repress, drain, cryo purge</td>
<td></td>
</tr>
<tr>
<td>Fuel Hold</td>
<td>358</td>
</tr>
<tr>
<td>Propellant Ducts</td>
<td>903</td>
</tr>
<tr>
<td>Valves</td>
<td>361</td>
</tr>
<tr>
<td>Thermospan</td>
<td>374</td>
</tr>
<tr>
<td>Pre-Burners</td>
<td>40</td>
</tr>
<tr>
<td>Turbopumps</td>
<td></td>
</tr>
<tr>
<td>Regenerative Cooled Nozzle</td>
<td></td>
</tr>
<tr>
<td>Main Combustion Chamber</td>
<td></td>
</tr>
<tr>
<td>Dual Mixed Pre-Burners</td>
<td></td>
</tr>
<tr>
<td>H2/O2 Core Pressure Ratio = 4000</td>
<td></td>
</tr>
<tr>
<td>Sea Level Thrust</td>
<td></td>
</tr>
<tr>
<td>Vacuum Thrust</td>
<td></td>
</tr>
<tr>
<td>Weight Breakdown</td>
<td></td>
</tr>
</tbody>
</table>
## Alternate Propulsion Subsystem Concepts
### Weight Estimate Example
### Weight Comparison to SSME

<table>
<thead>
<tr>
<th>Component Area</th>
<th>SSME Weights, lbm</th>
<th>Adv Low Cost Eng Weights, lbm</th>
<th>Difference lbm</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbomachinery</td>
<td>1,725.00</td>
<td>1,218.67</td>
<td>(506.33)</td>
<td>SLIC™, Jet Pumps, mixture ratio</td>
</tr>
<tr>
<td>Nozzle</td>
<td>1,310.54</td>
<td>625.30</td>
<td>(685.24)</td>
<td>Essentially same weight on equal surface area basis (1,371), Ti honeycomb jacket, lower hydrogen flowrate</td>
</tr>
<tr>
<td>Hot Gas Manifolds/Inj/Thrust Cone</td>
<td>953.00</td>
<td>689.76</td>
<td>(263.24)</td>
<td></td>
</tr>
<tr>
<td>Propellant Ducts</td>
<td>822.91</td>
<td>351.12</td>
<td>(471.79)</td>
<td>Gimbal flex accommodation on vehicle side, Jet Pump, shorter lines and routing, mixture ratio</td>
</tr>
<tr>
<td>MCC</td>
<td>438.54</td>
<td>399.71</td>
<td>(38.83)</td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td>410.62</td>
<td>361.35</td>
<td>(49.27)</td>
<td>Uses EMA Valves. Includes Valves and Actuators</td>
</tr>
<tr>
<td>Avionics</td>
<td>375.00</td>
<td>143.64</td>
<td>(231.36)</td>
<td>Controller with FASCOS</td>
</tr>
<tr>
<td>Misc</td>
<td>289.30</td>
<td>158.71</td>
<td>(130.59)</td>
<td>Proportional to weight (3.6%)</td>
</tr>
<tr>
<td>Preburners</td>
<td>195.75</td>
<td>373.99</td>
<td>178.24</td>
<td>Ox rich operation, both flows as gas</td>
</tr>
<tr>
<td>Gimbal Bearing</td>
<td>105.00</td>
<td>65.32</td>
<td>(39.68)</td>
<td>From Ti to Si carbide reinforced Al</td>
</tr>
<tr>
<td>Lines (Interface)</td>
<td>95.32</td>
<td>56.75</td>
<td>(38.57)</td>
<td>Simplified routing, combined recirc and repressurization, less drain</td>
</tr>
<tr>
<td>Pneumatics</td>
<td>76.90</td>
<td>0</td>
<td>(76.90)</td>
<td>EMA valves</td>
</tr>
<tr>
<td>POGO</td>
<td>75.13</td>
<td>40.65</td>
<td>(34.48)</td>
<td>Stiffer System, 25% SSME gas</td>
</tr>
<tr>
<td>Hydraulics</td>
<td>30.32</td>
<td>0</td>
<td>(30.32)</td>
<td>EMA Valves</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>26.00</td>
<td>26.00</td>
<td>0</td>
<td>Part of LOX rich preburner</td>
</tr>
<tr>
<td>Igniters</td>
<td>26.00</td>
<td>6.00</td>
<td>(20.00)</td>
<td>Laser Igniters</td>
</tr>
<tr>
<td>Purge</td>
<td>24.39</td>
<td>24.39</td>
<td>0</td>
<td>Left in for ground Ops</td>
</tr>
<tr>
<td>Bleed Recirc Pumps</td>
<td>10.00</td>
<td>20.00</td>
<td>10.00</td>
<td>Add to LOX side</td>
</tr>
<tr>
<td>Static Seals</td>
<td>6.00</td>
<td>6.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6,995.72</strong></td>
<td><strong>4,567.36</strong></td>
<td><strong>(2,428.36)</strong></td>
<td></td>
</tr>
</tbody>
</table>
Weight Comparison by Component Area

Component Weights, lbm

Components

TA3-0957
Tripropellant Comparison Study
Choice of Weight Baseline
Alternate Propulsion Subsystem Concepts
Choice of Weight Baseline
Approaches

• Approaches to Manufacturing and Operations Can Significantly Affect Engine Weight

• Current State-of-the-Practice
  • Coatings for Turbines
  • Welded Construction

• Approaches
  • Minimize Welds – Use Castings
    • Lower Strength Material Properties – Increased Weight
  • Use Materials Which Do Not Need Coatings
    • Poorer Material Properties
      • Lower \( AN^2 \) Limit – Lower T/P RPM, Increased Weight
      • Lower Strength – Increased Weight
  • RIM-D1 for H\(_2\) Rich Turbine Rotor
  • Thermo-Span for H\(_2\) Rich Turbine Housing, Hot Gas Manifold, Preburner Body
    • Welded
  • Haynes 214 or Inco X-750 for O\(_2\) Rich Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body
    • Cast or Welded
Tripropellant Comparison Study
Sample Case for Design Practice Study

- Bipropellant
- FFSCC
- MR = 6.0
- Nozzle Exit Pressure = 4.0
- Turbine Temperatures
- Fuel — 1100°R
- Oxidizer — 1100°R
## Weight Baseline – Design Choice Effects

<table>
<thead>
<tr>
<th>Coated*</th>
<th>Max Cast**</th>
<th>Current State-of-the-Art and Practice</th>
<th>Fuel Turbopump Not Cast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Coated***: Mixed Oxidizer (Haynes 214) Coated Turbine Rotor, Fuel Turbine Manifold, Coolant Manifolds, LOX Pump Housing
- **Max Cast****: No Coatings (Inconel 750) Max Cast Turbine Rotor, Fuel Preburner, Fuel Hot Gas Manifold

### Baseline Engine
- Full Flow Mixed Preburner Cycle
- Bi-propellant: O₂/H₂
- Nozzle Exit Pressure: 4 psi, MR = 6.0

<table>
<thead>
<tr>
<th>No Coatings (Haynes 214)</th>
<th>Coated*, Welded</th>
<th>Coated, Welded</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,184 lbm</td>
<td>4,781 lbm</td>
<td>4,662 lbm</td>
</tr>
<tr>
<td>5,065 lbm</td>
<td>4,781 lbm</td>
<td>4,662 lbm</td>
</tr>
<tr>
<td>5,054 lbm</td>
<td>4,552 lbm</td>
<td>4,461 lbm</td>
</tr>
<tr>
<td>5,054 lbm</td>
<td>4,552 lbm</td>
<td>4,461 lbm</td>
</tr>
<tr>
<td>4,552 lbm</td>
<td>4,391 lbm</td>
<td>4,391 lbm</td>
</tr>
</tbody>
</table>

**Note:**
- Coated Components
- Turbine Rotor
- Hot Gas Manifold
- Preburner

---

* TAG-0882b
# Alternate Propulsion Subsystem Concepts

## Engine Weight – Design Choice Effects

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Delta Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Practice (Welded, Coated)</td>
<td>4,391 lbm</td>
<td></td>
</tr>
<tr>
<td>No Fuel Coatings, Welded</td>
<td>4,461 lbm</td>
<td>+ 70 lbm</td>
</tr>
<tr>
<td>Cast, No Fuel Coatings</td>
<td>5,054 lbm</td>
<td>+ 663 lbm</td>
</tr>
<tr>
<td>No Fuel or Ox Coatings – Haynes 214</td>
<td>5,184 lbm</td>
<td>+ 793 lbm</td>
</tr>
<tr>
<td>No Fuel or Ox Coatings – Inco X-750</td>
<td>5,065 lbm</td>
<td>+ 674 lbm</td>
</tr>
<tr>
<td>Welded, No Fuel or Ox Coatings – Haynes 214</td>
<td>4,781 lbm</td>
<td>+ 390 lbm</td>
</tr>
<tr>
<td>No Fuel or Ox Coatings – Inco X-750</td>
<td>4,662 lbm</td>
<td>+ 271 lbm</td>
</tr>
</tbody>
</table>

## Weight Penalty

<table>
<thead>
<tr>
<th></th>
<th>Weight Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welded Fuel Uncoated</td>
<td>70 lbm</td>
</tr>
<tr>
<td>Ox Uncoated – Haynes 214</td>
<td>314 lbm</td>
</tr>
<tr>
<td>Ox Uncoated – Inco X-750</td>
<td>195 lbm</td>
</tr>
<tr>
<td>Fuel and Ox Uncoated – Haynes 214</td>
<td>390 lbm</td>
</tr>
<tr>
<td>Fuel and Ox Uncoated – Inco X-750</td>
<td>271 lbm</td>
</tr>
</tbody>
</table>

### Maximum Use of Castings

<table>
<thead>
<tr>
<th></th>
<th>Weight Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated</td>
<td>638 lbm</td>
</tr>
<tr>
<td>Fuel Uncoated</td>
<td>663 lbm</td>
</tr>
<tr>
<td>Ox Uncoated – Haynes 214</td>
<td>768 lbm</td>
</tr>
<tr>
<td>Ox Uncoated – Inco X-750</td>
<td>649 lbm</td>
</tr>
<tr>
<td>Fuel and Ox Uncoated – Haynes 214</td>
<td>793 lbm</td>
</tr>
<tr>
<td>Fuel and Ox Uncoated – Inco X-750</td>
<td>674 lbm</td>
</tr>
</tbody>
</table>

Bipropellant, FFSCC, 4000 psi Chamber Pressure, MR = 6, P_e = 4 psi

TA3-0897
Bipropellant $O_2/H_2$ Engines
Engine Weights – FFSCC

421,000 lbf Sea Level Thrust
MR = 6.0
Pe = 4.0 psi

Case 4 — Current State-of-the-Practice
Coated GOX Components, Welded

Case 2 — No Coatings, Some Welds:
Fuel T/P
Fuel Preburner
Fuel Hot Gas Manifold
Coolant Manifolds
LOX Pump Housing

Case 1 — No Coatings, Mostly Cast
(Fuel T/P not Cast)

Cycle (Fuel/Ox Turbine Temps)
- FFSCC (1100/1100R)-Case 4
- FFSCC (1100/1100R)-Case 2
- FFSCC (1100/1100R)-Case 1
Alternate Propulsion Subsystem Concepts
Choice of Weight Baseline
Conclusions

• Use Materials Which Do Not Need Coatings for H₂ Rich Gases
  • Major Operations Gain, Minimal Weight Penalty

• Use Materials Which Do Not Need Coatings for O₂ Rich Gases
  • Operations Improvement Too Important to Not Use
  • Significant Weight Penalty

• Use Welded Construction for Many Parts
  • Only Way to Recover Part of the No Coating Weight Penalty

• Si₃N₄ as Structural Material for Ducts and Housings
  • Not Used in Current Baseline
    • Too Far in Future

• Pursue Technology Programs to Increase the Strength of Oxygen Resistant Materials
  • Appears Very Feasible
Cycle Options and Turbopump Arrangements
Tripropellant Comparison Study
Currently Proposed Engines

- No Currently Proposed Tripropellant Engine Represents an Optimized Clean Sheet of Paper Tripropellant Engine Design
- All Attempt to Use Some Existing Hardware or Are Derived From, and Thus Constrained by, Existing Engines
  - RS-2000
  - RD-704
  - RD-0120TP
- A Clean Sheet Design Will Not Necessarily Resemble Any of Them
## Alternate Propulsion Subsystem Concepts
### Closed Cycle Thermodynamic Capabilities

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Added Energy (Combustion)</th>
<th>Flows Used</th>
<th>Expected Propulsion Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Side</td>
<td>Oxidizer Side</td>
<td>Fuel</td>
</tr>
<tr>
<td>Dual, Mixed Preburners</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Dual, Fuel (or Ox) Rich Preburners</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Single Preburner/Expander</td>
<td>√</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>Single Preburner Expander</td>
<td>—</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Expander</td>
<td>—</td>
<td>—</td>
<td>√</td>
</tr>
</tbody>
</table>
Bipropellant Engine Cycles
Tripropellant Comparison Study
Potential Engine Cycles

• Closed Cycles
  • FFSCC
    • Uses Both Fuel Rich and Ox Rich Preburners
  • SCC
    • Uses Either Fuel Rich Or Ox Rich Preburners, Not Both
  • Hybrid Cycle
    • Uses Fuel Rich Preburner for Fuel Side and Expander for Ox Side
  • Inverse Hybrid
    • Uses Ox Rich Preburner for Ox Side and Expander for Fuel Side
  • Expander
    • Uses Expander for Both Fuel and Ox Sides

• Open Cycles
  • GG
    • Uses a Gas Generator for Both Fuel and Ox Sides
For a Tripropellant Engine These Cycles can be Mixed
- Different Cycles Can be Used for the $O_2/RP$ System than for the $O_2/H_2$ System
- Additionally Various Turbopumps and Preburners/GGs Can be Shared Between the $O_2/RP$ and the $O_2/H_2$ Systems

Consequently the Number of Potential “Cycles” is Very Large

Since the Study Objective is to Compare the Best Potential Tripropellant Implementations to the Best Potential Bipropellant Implementations

- The Study Will be Limited to Only Those Cycles with the Best Expected Combination of Specific Impulse and Engine Weight
Tripropellant Comparison Study
Basic Cycle Choices

- From the Separately Reported Bipropellant Study Completed Earlier in the Contract
  - Without Engine Margin Considerations
    - Three Cycles Competitive
      - FFSCC
      - SCC
      - Hybrid
  - Two Cycles Maximum Chamber Pressure ~2,000 psi
    - Inverse Hybrid
    - Expander
- Common Thread
  - Cycles with the Highest Horsepower Pumps Driven by Expander
    Cycle Cannot Reach Competitive Chamber Pressures
    - Power Limited at Too Low a $P_c$

- With Engine Margin Considerations
  - FFSCC Very Robust
  - Fuel Rich SCC Turbine Temperatures Become High
  - Hybrid Cycle Turbine Temperatures Marginal Even Before Margins

- Conclusion
  - Examine Only FFSCC, SCC, and Hybrid
    - Hybrid Only With $H_2$ Driven RP Pump
Tripropellant Comparison Study
Cycle Considerations

- Primary Performance Parameters
  - Engine Sea Level Thrust/Weight
  - Mode 2 Vacuum Specific Impulse
  - Mode 1 Vacuum Specific Impulse

- All Cycle Selection Choices Should be Based on Their Impact on These Parameters

- One Simplifying Limitation
  - No RP in Mode 2
    - $I_{sp}$ Loss in Mode 2
  - No Sea Level Weight Improvement Except in Single Preburner Case
    - Then Probably Offset by Additional Ducting and Hot Gas Valves
Tripropellant Comparison Study
Numbers of Preburners

- All Staged Combustion Cycles Can Have Up to Four Preburners
- FFSCC Must Have at Least Two Preburners
- SCC Can Have as Few as One Preburner for the Whole Engine

<table>
<thead>
<tr>
<th>Preburner Configuration</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Per Turbine</td>
<td>Less Hot Gas Ducting</td>
<td>More Preburners</td>
</tr>
<tr>
<td></td>
<td>More Flexible Packaging</td>
<td>More, Smaller Feed Valves</td>
</tr>
<tr>
<td></td>
<td>Avoid Hot Gas Valves</td>
<td>More Complex Start</td>
</tr>
<tr>
<td></td>
<td>Better Control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Avoids Additional Complexity of Tripropellant Preburner</td>
<td></td>
</tr>
<tr>
<td></td>
<td>While Minimizing Turbine Temps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Possibly Least Weight</td>
<td></td>
</tr>
<tr>
<td>One per Engine</td>
<td>Less Preburners</td>
<td>More Hot Gas Ducting</td>
</tr>
<tr>
<td></td>
<td>Less Feed Valves</td>
<td>Less Flexible Packaging</td>
</tr>
<tr>
<td></td>
<td>Less Complex Start</td>
<td>Hot Gas Valves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More Difficult Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For Fuel Rich-Forces Either</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Higher Turbine Temps or More</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complex Tripropellant Preburner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possibly Most Weight</td>
</tr>
<tr>
<td>One for $O_2/H_2$</td>
<td></td>
<td>Mix of Both of the</td>
</tr>
<tr>
<td>One for $O_2/RP$</td>
<td></td>
<td>Above</td>
</tr>
</tbody>
</table>

- **Baseline**
  - Make No Specific Attempt to Minimize Number of Preburners
- **Argument Does Not Apply to GGs**
Tripropellant Comparison Study
Cooling Circuits

• Potential Options
  • H$_2$, RP, O$_2$ in Any Combination

• However
  • H$_2$ is the Most Efficient Coolant and Will Always be Used for Some of the Cooling
  • Each Fluid Used as a Coolant Must be Pumped to a Higher Pressure
  • Fuel and Oxidizer Coolants Used Together Pose Potential Operability Problems

• Consequently
  • Baseline H$_2$ as Only Coolant Used
    • Use Additional Coolants If, and Only If, Advantageous
Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Combined Mode 1/Mode 2 Oxygen Pump

• Single Chamber
  • Weight Impact
    • Single Versus Two Pumps +35 lbm
    • Extra Manifolding 0 lbm
    • Hot Gas Valve 0 lbm
  • Some Constraints on Pump Operating Map
    • Mode 2 Head -52%
    • Mode 2 Flow -56%

• Bell Annular
  • Weight Impact
    • Single Versus Two Pumps +35 lbm
    • Extra Manifolding +11 lbm
    • Hot Gas Valve +177 lbm
  • Major Constraints on Pump Operating Map
    • Mode 2 Head ~ Equal
    • Mode 2 Flow -72%

• Conclusions
  • Single Chamber
    • Use Combined Mode 1/Mode 2 Oxygen Pump Whenever Possible
  • Bell Annular
    • Do Not Use Combined Mode 1/Mode 2 Oxygen Pump at All
Tripropellant Comparison Study
Resulting Baseline Cycle Groundrules

- Closed Cycles Limited to FFSCC, SCC, and Hybrid Cycle Variants
  - Hybrid Cycle Limited to H₂ Driven RP Pump

- No RP in Mode 2

- H₂ Used as Primary Coolant

- Preburners
  - No Attempt to Minimize Number of Preburners
    - One Preburner per Turbine May be Ideal
  - Use H₂ for Ox Rich Preburners Where Available
  - For Fuel Rich Preburners
    - Use H₂, Then RP, Then Tripropellant
Tripropellant Comparison Study
Cycle Classes Included

- FFSCC  
  (cf. RS-2000)

- Fuel Rich SCC  
  (cf. RD-0120TP)

- Ox Rich SCC  
  (cf. RD-704)

- Hybrid Cycle
  - Limited - H2 Driven RP Pump

- GG
  - Bipropellant Only

- Within Each Cycle Class
  - Many Turbomachinery and Preburner Options
Tripropellant Comparison Study
Selected Engine Cycles
Tripropellant Comparison Study
Configuration Choices
Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Weight Baseline Used

- No Coatings
  - H₂ Rich
    - RIM-D1 Turbine Rotor
    - Thermo-Span Turbine Housing, Hot Gas Manifold, Preburner Body
  - RP Rich
    - Inco 718 Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body
  - O₂ Rich
    - Haynes 214 Turbine Rotor, Housing, Hot Gas Manifold, Preburner Body

- Welded
  - Fuel Turbopumps, Hot Gas Manifolds, Preburner Bodies
  - Coolant Manifolds
  - LOX Pump
  - Hydrogen and Oxygen Ducting

- Cast
  - Ox Rich Turbine, Hot Gas Manifold, Preburner Body
  - RP Ducts
<table>
<thead>
<tr>
<th>FFSCC Case</th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFSCC-1</td>
<td>H₂ Rich</td>
<td>RP Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>FFSCC-2</td>
<td>H₂ Rich</td>
<td>RP Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>FFSCC-3</td>
<td>H₂ Rich</td>
<td>—</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>FFSCC-4</td>
<td>H₂ Rich</td>
<td>—</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>FFSCC-5</td>
<td>H₂ Rich</td>
<td>H₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>FFSCC-6</td>
<td>H₂ Rich</td>
<td>H₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

| √     | Applicable | MCC Injection | H₂/RP/O₂ |
| —     | Not Applicable | G | Gas | X/X/X | Mode 1 |
| SC    | Single Chamber | L | Liquid | X/X/X | Mode 2 |
Tripropellant Configuration Study
FFSC-3(A) LOX/RP/H2 Engine Schematic

Annular Chamber
Tripropellant Configuration Study
FFSCC-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber

RP-1
LOX
H2-rich PB
O2-rich PB
LH2
Tripropellant Configuration Study
FFSCC-5(A) LOX/RP/H2 Engine Schematic

Annular Chamber
Tripropellant Configuration Study
FFSCC-6(SC) LOX/RP/H2 Engine Schematic

Single Chamber

LH2

LOX

RP-1

H2-rich PB

O2-rich PB

H2-rich PB

10-25-94

TA3-0809
## Tripropellant Comparison Study
### FFSCC Cases

<table>
<thead>
<tr>
<th>Cycle (Relative Weight) (SC/Annular)</th>
<th>H₂ (Tur Temp, °R)</th>
<th>RP (Tur Temp, °R)</th>
<th>Mode 1 (Tur Temp, °R)</th>
<th>Mode 2 (Tur Temp, °R)</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFSCC-1 (--- / 1.000)</td>
<td>H₂ Rich 1,100</td>
<td>RP Rich 1,394</td>
<td>O₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>FFSCC-2 (1.000 / ——)</td>
<td>H₂ Rich 1,100</td>
<td>RP Rich 1,400</td>
<td>O₂ Rich 1,100</td>
<td>Combined O₂ Pump 1,100</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>FFSCC-3 (1.040 / 1.050)</td>
<td>H₂ Rich 1,100/1,100</td>
<td>O₂ Rich 1,100/1,185</td>
<td>O₂ Rich 1,100/1,100</td>
<td>—</td>
<td>G/L/G</td>
<td>G/G</td>
</tr>
<tr>
<td>FFSCC-4 (1.061 / ——)</td>
<td>H₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>Combined O₂ Pump 1,100</td>
<td>—</td>
<td>G/L/G</td>
<td>G/G</td>
</tr>
<tr>
<td>FFSCC-5 (--- / 1.024)</td>
<td>H₂ Rich 1,555</td>
<td>H₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>FFSCC-6 (1.010 / ——)</td>
<td>H₂ Rich 1,172</td>
<td>H₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>Combined O₂ Pump 1,100</td>
<td>√</td>
<td>—</td>
</tr>
</tbody>
</table>

| √ | Applicable | MCC Injection | H₂/RP/O₂ | — | Not Applicable | G | Gas | X/X/X | Mode 1 |
|—  | Not Applicable | G | Gas | X/X/X | Mode 1 |
|SC | Single Chamber | L | Liquid | X/X/X | Mode 2 |

TA3-0746e
Alternate Propulsion Subsystem Concepts
FFSCC Cases

- Baseline Turbomachinery/Preburner Arrangement Selection

- Single Chamber
  - FFSCC-2
    - Lightest Weight
    - Only Single Chamber System With No Vehicle He Flow

- Bell Annular
  - FFSCC-1
    - Lightest Weight
    - Only Bell Annular System With No Vehicle He Flow
### Tripropellant Comparison Study
#### Ox Rich SCC Cases

<table>
<thead>
<tr>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/G</td>
<td>√</td>
</tr>
<tr>
<td>G/G</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ORSCC-1</th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ORSCC-2</th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>Combined O₂ Pump</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ORSCC-3</th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ORSCC-4</th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>Combined O₂ Pump</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Applicable</th>
<th>MCC Injection</th>
<th>H₂/RP/O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>√</td>
<td>G</td>
<td>X/X/X</td>
<td>Mode 1</td>
</tr>
<tr>
<td>—</td>
<td>L</td>
<td>X/X/X</td>
<td>Mode 2</td>
</tr>
<tr>
<td>SC</td>
<td>Single Chamber</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TA3-0749a
Tripropellant Configuration Study
ORSCC-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber

LH2

LOX

RP-1

O2-rich PB

O2-rich PB

O2-rich PB
# Tripropellant Comparison Study
## Ox Rich SCC Cases

<table>
<thead>
<tr>
<th>Cycle (Relative Weight) (SC/Annular)</th>
<th>H₂ (Tur Temp, °R)</th>
<th>RP (Tur Temp, °R)</th>
<th>Mode 1 (Tur Temp, °R)</th>
<th>O₂ (Tur Temp, °R)</th>
<th>Mode 2 (Tur Temp, °R)</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORSCC-1 (— / *)</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>ORSCC-2 (1.000 / —)</td>
<td>O₂ Rich 1,633</td>
<td>O₂ Rich 1,511</td>
<td>O₂ Rich Combined O₂ Pump 1,519</td>
<td>—</td>
<td>G/L/G</td>
<td>G/G</td>
<td></td>
</tr>
<tr>
<td>ORSCC-3 (— / *)</td>
<td>O₂ Rich</td>
<td>—</td>
<td>O₂ Rich Single Shaft</td>
<td>O₂ Rich</td>
<td>—</td>
<td>√</td>
<td>L/G</td>
</tr>
<tr>
<td>ORSCC-4 (1.054 / —)</td>
<td>O₂ Rich 1,616</td>
<td>—</td>
<td>Single Shaft Combined O₂ Pump 1,612</td>
<td>—</td>
<td>G/L/G</td>
<td>G/G</td>
<td></td>
</tr>
</tbody>
</table>

* Turbine Temperatures Excessive □ Applicable MCC Injection H₂/RP/O₂
  Pri Ox – 2,284°R — Not Applicable G Gas X/X/X Mode 1
  Pri Fuel – 2,287°R SC Single Chamber L Liquid X/X/X Mode 2

TA3-0749c
Alternate Propulsion Subsystem Concepts
ORS CC Cases

- Baseline Turbomachinery/Preburner Arrangement Selection

- H₂ Pump's Turbine is Coated
  - Haynes 214 AN² Capability Much Too Low at Temperature Needed

- Single Chamber
  - ORSCC-2
    - Lightest Weight
    - Other Option Also Has He Usage

- Bell Annular
  - No Viable Configuration for Ox-Rich Cycle
    - Primary Ox and Fuel Turbine Temperatures Too High
      - ~2,280°R
      - No Way to Use Secondary Ox for Primary Power Requirements
| FRSCC-1 | H₂ Rich | H₂ Rich | H₂ Rich | H₂ Rich | — | √ |
| FRSCC-2 | H₂ Rich | H₂ Rich | H₂ Rich | — | √ |
| FRSCC-3 | H₂ Rich | — | H₂ Rich | H₂ Rich | — | √ |
| FRSCC-4 | H₂ Rich | — | H₂ Rich | H₂ Rich | — | √ |
| FRSCC-6 | H₂ Rich | — | RP Rich | H₂ Rich | — | √ |
| FRSCC-7 | Tripropellant | Tripropellant | — | Tripropellant | — | √ |

<table>
<thead>
<tr>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/L</td>
<td>G/L</td>
</tr>
<tr>
<td>G/L/L</td>
<td>L/L</td>
</tr>
<tr>
<td>G/L</td>
<td>G/L</td>
</tr>
<tr>
<td>G/G/L</td>
<td>G/L</td>
</tr>
<tr>
<td>G/L</td>
<td>G/L</td>
</tr>
<tr>
<td>G/G/L</td>
<td>G/L</td>
</tr>
<tr>
<td>G/L</td>
<td>G/L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>√</th>
<th>Applicable</th>
<th>MCC Injection</th>
<th>H₂/RP/O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>Not Applicable</td>
<td>Gas</td>
<td>X/X/X</td>
</tr>
<tr>
<td>SC</td>
<td>Single Chamber</td>
<td>Liquid</td>
<td>X/X/X</td>
</tr>
</tbody>
</table>

TA3-0752a
Tripropellant Configuration Study
FRSPP-2(A) LOX/RP/H2 Engine Schematic

Annular Chamber

RP-1

LOX

H2-rich PH

LH2

H2-rich PH
Tripropellant Configuration Study
FRSCC-3(A) LOX/RP/H2 Engine Schematic

Annular Chamber
Tripropellant Configuration Study
FRSCC-4(A) LOX/RP/H2 Engine Schematic

Annular Chamber

LH2

LOX

RP-1

H2-rich PB

H2-rich PB

10-27-94
Tripropellant Configuration Study
FRSCE-7(SC) LOX/RP/H2 Engine Schematic

Single Chamber

LH2

LOX

RP-1

H2-rich
PB

H2-rich
PB

H2-rich
PB

TA3-0812a
<table>
<thead>
<tr>
<th>Cycle (Relative Weight) (SC/Annular)</th>
<th>H₂ (Tur Temp, °R)</th>
<th>RP (Tur Temp, °R)</th>
<th>Mode 1 (Tur Temp, °R)</th>
<th>Mode 2 (Tur Temp, °R)</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRSCC-1 (― / *)</td>
<td>H₂ Rich 1,825</td>
<td>H₂ Rich 1,550</td>
<td>H₂ Rich 1,750</td>
<td>H₂ Rich 1,760</td>
<td></td>
<td>G/L</td>
</tr>
<tr>
<td>FRSCC-2 (1.020 / *)</td>
<td>H₂ Rich 1,804/1,852</td>
<td>H₂ Rich 1,447/1,450</td>
<td>H₂ Rich 1,857/1,876</td>
<td>H₂ Rich 1,800/1,835</td>
<td>√</td>
<td>G/L/L</td>
</tr>
<tr>
<td>FRSCC-3 (1.040 / *)</td>
<td>H₂ Rich 1,800/1,848</td>
<td></td>
<td>H₂ Rich 1,850/1,860</td>
<td>1,800/1,835</td>
<td>√</td>
<td>G/L/L</td>
</tr>
<tr>
<td>FRSCC-4 (1.000 / *)</td>
<td>H₂ Rich 1,827/1,840</td>
<td></td>
<td>H₂ Rich 1,850/1,860</td>
<td></td>
<td>√</td>
<td>G/L/L</td>
</tr>
<tr>
<td>FRSCC-5 (1.101 / 1.007)</td>
<td>H₂ Rich 1,453/1,447</td>
<td>RP Rich 1,852/1,693</td>
<td>RP Rich 1,897/1,897</td>
<td>H₂ Rich 1,120/1,748</td>
<td>√</td>
<td>G/L</td>
</tr>
<tr>
<td>FRSCC-6 (1.103 / 1.000)</td>
<td>H₂ Rich 1,453/1,600</td>
<td></td>
<td>RP Rich 1,899/1,900</td>
<td></td>
<td>√</td>
<td>G/L</td>
</tr>
<tr>
<td>FRSCC-7 (1.029 / ―)</td>
<td>Tripropellant 1,700</td>
<td>Tripropellant 1,700</td>
<td></td>
<td></td>
<td>√</td>
<td>G/L</td>
</tr>
</tbody>
</table>

* Excessive turbine temperature due to thrust split

- Applicable
- Not Applicable
- MCC Injection
- H₂/RP/O₂
- Gas
- Liquid
- X/X/X Mode 1
- X/X/X Mode 2
Alternate Propulsion Subsystem Concepts
FRSCC Cases

• Baseline Turbomachinery/Preburner Arrangement Selection

• Single Chamber
  • FRSCC-7
    • Lowest Average Turbine Temperatures, Although Not Lowest Minimum Turbine Temperature
    • Tripropellant Preburner Allows Best Movement of Energy Among Turbines
    • Likely to Have Best Design Margins
    • Small Weight Penalty Over Lowest Weight Case

• Bell Annular
  • FFSCC-6
    • Lightest Weight
# Tripropellant Comparison Study

## Hybrid Cycle Cases

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>H₂</th>
<th>RP</th>
<th>O₂</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid-1</td>
<td>H₂ Rich</td>
<td>H₂ Exp</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>—</td>
</tr>
<tr>
<td>Hybrid-2</td>
<td>H₂ Rich</td>
<td>H₂ Exp</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>√</td>
</tr>
<tr>
<td>Hybrid-3</td>
<td>H₂ Rich</td>
<td>H₂ Exp</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>√</td>
</tr>
<tr>
<td>Hybrid-4</td>
<td>H₂ Rich</td>
<td>H₂ Exp</td>
<td>O₂ Rich</td>
<td>O₂ Rich</td>
<td>√</td>
</tr>
</tbody>
</table>

- **√**: Applicable
- **—**: Not Applicable
- **L/G**: Liquid Gas
- **G/G**: Gas Gas
- **G/L/G**: Gas Liquid Gas
- **L/L**: Liquid Liquid

**Symbols**:
- **HP**: High Pressure
- **LP**: Low Pressure
- **MCC**: Multi-Component Combustion
- **SC**: Single Chamber
- **Gas**: Gas
- **Liquid**: Liquid
- **X/X/X**: Mode 1
- **Mode 2**

---

TA3-0750a
Tripropellant Configuration Study
Hybrid-2(SC) LOX/RP/H2 Engine Schematic

Single Chamber

RP-1

LOX

K2

O2 inlet
PB

LH2

K2 inlet
PB
Tripropellant Configuration Study
Hybrid-4(SC) LOX/RP/H2 Engine Schematic

Single Chamber
<table>
<thead>
<tr>
<th>Cycle (Relative Weight) (SC/Annular)</th>
<th>H₂ (Tur Temp, °R)</th>
<th>RP (Tur Temp, °R)</th>
<th>Mode 1 (Tur Temp, °R)</th>
<th>Mode 2 (Tur Temp, °R)</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid-1  (— / 1.000)</td>
<td>H₂ Rich 1,700</td>
<td>H₂ Exp 1,000</td>
<td>O₂ Rich 1,100</td>
<td>O₂ Rich 1,100</td>
<td>—</td>
<td>√</td>
</tr>
<tr>
<td>Hybrid-2  (1.090 / —)</td>
<td>H₂ Rich 1,243</td>
<td>H₂ Exp 997</td>
<td>O₂ Rich Combined O₂ Pump 1,100</td>
<td>—</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Hybrid-3  (1.000 / **)</td>
<td>H₂ Rich 1,700</td>
<td>H₂ Exp</td>
<td>O₂ Rich 1,100</td>
<td>√</td>
<td>G/L/G</td>
<td>G/G</td>
</tr>
<tr>
<td>Hybrid-4  (*/ *)</td>
<td>H₂ Rich</td>
<td>H₂ Exp</td>
<td>O₂ Rich 1,100</td>
<td>√</td>
<td>G/L/G</td>
<td>L/L</td>
</tr>
</tbody>
</table>

* Balance only to ≤ 3,000 psi.
** Excessive H₂ turbine temperature due to expander H₂ drawdown for horsepower of O₂ pump.
Alternate Propulsion Subsystem Concepts
Hybrid Cycle Cases

- Baseline Turbomachinery/Preburner Arrangement Selection

- Single Chamber
  - Hybrid-3
    - Lightest Weight
    - Hybrid-2 has considerably lower temperatures but the weight penalty is too high

- Bell Annular
  - Hybrid-1
    - Lightest Weight
    - Only viable Bell Annular System
### Tripropellant Comparison Study

**Bipropellant Cycle Cases**

<table>
<thead>
<tr>
<th></th>
<th>H₂</th>
<th>RP</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>O₂</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFSCC</td>
<td>H₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>O₂ Rich</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>SCC (FR)</td>
<td>H₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H₂ Rich</td>
<td>—</td>
<td>G/G</td>
</tr>
<tr>
<td>Hybrid</td>
<td>H₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H₂ Exp</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>GG</td>
<td>H₂ Rich</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H₂ Rich</td>
<td>√</td>
<td>G/L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>√</th>
<th>Applicable</th>
<th>MCC Injection</th>
<th>H₂/RP/O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>Not Applicable</td>
<td>Gas</td>
<td>X/X/X Mode 1</td>
</tr>
<tr>
<td>SC</td>
<td>Single Chamber</td>
<td>Liquid</td>
<td>X/X/X Mode 2</td>
</tr>
</tbody>
</table>
FFSCC Mixed Preburner Engine
Regen Cooled MCC and Nozzle
Alternate Propulsion Subsystem Concepts
Bipropellant Cycles

SCC Dual Fuel-Rich Preburner Engine
Regen Cooled MCC and Nozzle
Alternate Propulsion Subsystem Concepts
Bipropellant Cycles

Hybrid Cycle Engine
(Fuel Side Preburner, Ox Side Expander)
Regen Cooled MCC and Nozzle

Diagram of a hybrid cycle engine with fuel and oxidizer pumps, turbines, and burners.
# Tripropellant Comparison Study

## Bipropellant Cycle Cases

<table>
<thead>
<tr>
<th></th>
<th>H$_2$</th>
<th>RP</th>
<th>O$_2$</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>SC</th>
<th>Annular</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFSCC</td>
<td>H$_2$ Rich 1,150</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>O$_2$ Rich 1,100</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>SCC (FR)</td>
<td>H$_2$ Rich 1,400</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H$_2$ Rich 1,100</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>Hybrid</td>
<td>H$_2$ Rich 1,700</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H$_2$ Exp 614</td>
<td>√</td>
<td>—</td>
</tr>
<tr>
<td>GG</td>
<td>H$_2$ Rich 1,900</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>H$_2$ Rich 1,357</td>
<td>√</td>
<td>—</td>
</tr>
</tbody>
</table>

√: Applicable  
—: Not Applicable  
SC: Single Chamber  
L: Liquid  
G: Gas  
MCC Injection  
H$_2$/RP/O$_2$: X/X/X  
Mode 1  
X/X/X  
Mode 2

TA3-1118a
Tripropellant Comparison Study
Operating Parameter Determination
Alternate Propulsion Subsystem Concepts
Tripropellant Configuration Study
Operating Parameter Choices

- Nozzle Exit Pressure
  - Bipropellant
  - Bell Annular
  - Single Chamber

- Bipropellant Mixture Ratio

- Bell Annular Thrust Split

- Bell Annular Mode 2 Mixture Ratio

- Bell Annular Mode 1 Mixture Ratio

- Single Chamber Percent Hydrogen

- Single Chamber Mode 1 Mixture Ratio

- Single Chamber Mode 2 Mixture Ratio
Nozzle Exit Pressure
Engine Performance – Bipropellant FFSCC
Nozzle Exit Pressure Variation

Specific Impulse, sec

Exit Pressure, psi

- ■ Vacuum Isp (MR=6.0)
- □ Vacuum Isp (MR=6.9)
- ▲ Sea Level Isp (MR=6.0)
- △ Sea Level Isp (MR=6.0)

TA3–0965a
Engine Weights – FFSCC
Nozzle Exit Pressure Variation

Exit Pressure, psi

Engine Weight, lbm

Bell Annular - MR (O2/H2) = 6
Single Chamber - MR (Mode 2) = 6
Bipropellant - MR=6
Engine Performance – FFSCC
Tripropellant

Specific Impulse, sec

Nozzle Exit Pressure, psi

Single Chamber
(MR Mode 2 = 6.0)

Bell Annular
(MR O2/H2 = 6.0)

△ Vac - Mode 2
◆ Vac - Mode 1
● SL - Mode 1
△ Vac - Mode 2
○ Vac - Mode 1
○ SL - Mode 1

TA3-0968
SSTO Performance – Tripropellant – FFSCC
Nozzle Exit Pressure Variation

Relative Vehicle Dry Weight

Exit Pressure, psi

Bell Annular - MR
(O2/H2) = 6.0

TA3-0959
Bipropellant Mixture Ratio
Engine Weights – FFSCC
Bipropellant

Exit Pressure = 5 psi
Engine Performance – FFSCC
Bipropellant

Exit Pressure = 5 psi

Specific Impulse, sec

Mixture Ratio, O2/H2

- Vacuum Isp
- Sea Level Isp
SSTO Performance – Bipropellant FFSCC
Engine Mixture Ratio Variation

Exit Pressure = 5 psi

Relative Vehicle Dry Weight

Engine Mixture Ratio, O/F
Engine Weights – FFSCC
Bipropellant - Dual Mixture Ratio

Exit Pressure = 4.5 psi

Mode 1 Mixture Ratio, O2/H2
Engine Performance – FFSCC
Bipropellant - Dual Mixture Ratio Operation

Exit Pressure = 4.5 psi

- Mode 1 Mixture Ratio = 7
- Mode 1 Mixture Ratio = 10
- Mode 1 Mixture Ratio = 12

Vacuum - Mode 2
Vacuum - Mode 1
Sea Level - Mode 1

Specific Impulse, sec

Mode 2 Mixture Ratio, O2/H2
SSTO Performance – Bipropellant FFSCC
Dual Mixture Ratio Operation

![Graph showing relative vehicle dry weight vs. mode 1 mixture ratio (O/F) with different modes: Mode 2 MR = 7 (circles), Mode 2 MR = 6 (triangles), Mode 2 MR = 5 (diamonds).]
Engine Weights – GG Cycle
Bipropellant

Exit Pressure = 4.5 psi
- - - Pc = 4,000 psi
- - - Pc = 2,000 psi

Engine Mixture Ratio, O2/H2

Engine Weight, lbm
SSTO Performance – Bipropellant GG Cycle
Engine Mixture Ratio Variation

Relative Vehicle Dry Weight

Engine Mixture Ratio, O/F

Exit Pressure = 4.5 psi
Pc = 4,000 psi
Pc = 2,000 psi

TA3–0993
SSTO Performance – Bipropellant GG Cycle
Optimum Engine Mixture Ratio

Exit Pressure = 4.5 psi
Specific Impulse – FFSCC
Bell Annular Configuration

Exit Pressure = 5.0 psi
MR (O₂/RP) = 2.6

- Thrust Split = 60/40
- Thrust Split = 70/30
- Thrust Split = 75/25

- Vac – Mode 2
- Δ Vac – Mode 1
- ◦ SL – Mode 1
- • Vac – Mode 2
- Δ Vac – Mode 1
- ◦ SL – Mode 1

O₂/H₂ Mixture Ratio

TA3-0987
Coolant Temperature – Tripropellant – FFSCC
Bell Annular Configuration

Exit Pressure = 5 psi

Mode 1 RP Thrust Percentage, (O2/RP Thrust)/Total Thrust
SSTO Performance – Tripropellant – FFSCC
Bell Annular Configuration

Exit Pressure = 5 psi

Bulk Temp = 800 °R

Bulk Temp = 1,000 °R

Mode 1 RP Thrust Percentage, (O2/RP Thrust)/Total Thrust

Relative Vehicle Dry Weight

TA3–0962
Thrust Split Vs Chamber Pressure
Bell Annular Configuration

Exit Pressure = 5.5 psi
MR (O₂/H₂) = 6.8
MR (O₂/RP) = 2.8
Avg Coolant Temp = 1,000°R
Bell Annular Mode 1 Mixture Ratio
Engine Weights – FFSCC
Bell Annular Configuration

Exit Pressure = 5.5 psi
MR (O₂/H₂) = 6.8
Thrust Split = 71.5/28.5

Engine Weight, Ibm
O₂/RP Mixture Ratio

TA3-0984
Specific Impulse – FFSCC
Bell Annular Configuration

Exit Pressure = 5.5 psi
MR (O₂/H₂) = 6.8
Thrust Split = 71.5/28.5

O₂/RP Mixture Ratio

Specific Impulse, sec
SSTO Performance – FFSCC
Bell Annular Configuration

Relative Vehicle Dry Weight

O2/RP Mixture Ratio

- Exit Pressure = 5.5 psi
- MR (O₂/H₂) = 6.8
- Thrust Split = 71.5/28.5
Single Chamber Percent Hydrogen
O2/H2/RP ODK Performance

PC=4000, EPS=88, Hf=0.55, Rt=4.47

2-9-95
Energy Release Efficiency

- Chart From MSFC

**Eta C* Range for Rocketdyne Study**  
**Dual Mode Tripropellant Injectors**

[Chart of Eta C* range for Rocketdyne study on dual mode tripropellant injectors. The chart shows three lines labeled MIN, MAX, and Used as baseline, indicating the range of Eta C* values for different percentages of H2.]
Engine Weights – FFSCC
Tripropellant – Single Chamber

Exit Pressure = 4 psi
MR (Mode 2) = 6.0

\[ \Delta \text{H}_2, \text{Percent} \]
Exit Pressure = 4 psi
MR (Mode 2) = 6.0
Single Chamber Mode 1 Mixture Ratio
SSTO Performance
Tripropellant Single Chamber – FFSCC

Exit Pressure = 4 psi
MR (Mode 2) = 6.0

Overall MR (MR O2/H2 = 6.0)
Single Chamber Mode 2 Mixture Ratio
Engine Weights – FFSCC
Tripropellant Single Chamber

Exit Pressure = 5 psi
Overall Mode 1 MR = 4.4

Mode 2 Mixture Ratio, O2/H2

Model 2 MR
Engine Performance – FFSCC
Tripropellant Single Chamber

Exit Pressure = 5 psi
Overall Mode 1 MR = 4.4

Mode 2 Mixture Ratio, O2/H2

Specific Impulse, sec
Exit Pressure = 5 psi
Overall Mode 1 MR = 4.4

Mode 2 Mixture Ratio, O2/H2

Relative Vehicle Dry Weight

Mode 2 MR
## Alternate Propulsion Subsystem Concepts

### Baseline Parameter Selections

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Chamber Tripropellant</th>
<th>Annular Tripropellant</th>
<th>Bipropellant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Exit Pressure, psi</td>
<td>6.0</td>
<td>5.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Mode 1 Mixture Ratio</td>
<td>4.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mode 2 Mixture Ratio</td>
<td>6.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(O_2/R_P) Mixture Ratio</td>
<td>—</td>
<td>2.8</td>
<td>—</td>
</tr>
<tr>
<td>(O_2/H_2) Mixture Ratio</td>
<td>—</td>
<td>6.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Percent Hydrogen, %</td>
<td>6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mode 1 (O_2/R_P) to (O_2/H_2) Thrust Split</td>
<td>—</td>
<td>(H_2) Cooling Limit</td>
<td>—</td>
</tr>
</tbody>
</table>
## Resulting Nominal Engines

<table>
<thead>
<tr>
<th></th>
<th>Single Chamber Tripropellant</th>
<th>Bell Annular Tripropellant</th>
<th>Bipropellant Closed Cycles</th>
<th>Gas Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thrust, Sea Level, lbf</strong></td>
<td>421,000</td>
<td>421,000</td>
<td>421,000</td>
<td>421,000</td>
</tr>
<tr>
<td><strong>Thrust, Vacuum, lbf</strong></td>
<td>477,630</td>
<td>478,701</td>
<td>484,585</td>
<td>486,706</td>
</tr>
<tr>
<td><strong>Specific Impulse, sec</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 2 Vacuum</td>
<td>450.69</td>
<td>461.13</td>
<td>451.43</td>
<td>445.28</td>
</tr>
<tr>
<td>Mode 2 Sea Level</td>
<td>339.18</td>
<td>267.33</td>
<td>392.19</td>
<td>385.16</td>
</tr>
<tr>
<td>Mode 1 Vacuum</td>
<td>406.26</td>
<td>369.33</td>
<td>451.43</td>
<td>445.28</td>
</tr>
<tr>
<td>Mode 1 Sea Level</td>
<td>358.09</td>
<td>324.81</td>
<td>392.19</td>
<td>385.16</td>
</tr>
<tr>
<td><strong>Chamber Pressure, psi</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 1</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Mode 2</td>
<td>1,966</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
</tr>
<tr>
<td><strong>Area Ratio</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 1</td>
<td>63.56</td>
<td>59.60/64.54*</td>
<td>69.77</td>
<td>69.84</td>
</tr>
<tr>
<td>Mode 2</td>
<td>63.56</td>
<td>226.73</td>
<td>69.77</td>
<td>69.84</td>
</tr>
<tr>
<td><strong>Engine Weight, lbm (Uncoated/Coated)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFSCC</td>
<td>4,492 / 4,176</td>
<td>4,473 / 4,201</td>
<td>4,567 / 4,242</td>
<td>—</td>
</tr>
<tr>
<td>ORSCC</td>
<td>4,610 / 4,295</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>FRSCC</td>
<td>4,040 / —</td>
<td>4,189 / —</td>
<td>4,049 / —</td>
<td>—</td>
</tr>
<tr>
<td>Hybrid Cycle</td>
<td>4,161 / 4,026</td>
<td>4,528 / 4,227</td>
<td>4,058 / —</td>
<td>—</td>
</tr>
<tr>
<td>Gas Generator Cycle</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>/ 3,629</td>
</tr>
</tbody>
</table>

* (O₂/H₂)/(O₂/RP)*
Tripropellant Comparison Study
Engine Weights and Vehicle Performance
Tripropellant Comparison Study
Mission Groundrules

- Consistent With Option 1 Evaluation

- RLV Application
  - SSTO
  - 25K Payload
  - 220 NMi, 51.6°

- Option 3 Winged Vehicle

- CONSIZE and POST
  - Choose a Version of CONSIZE with LaRC
    - Bipropellant
    - Tripropellant
  - Freeze the Choice for Remainder of Task
  - April/May 1994 Version Used
    - Consistent Tripropellant and Bipropellant Models
Tripropellant Comparison Study

Helium Usage

- Engine Requirements

- SSME
  - Start and Shutdown Purges
    - Majority of Usage
  - Turbomachinery Interpropellant Seal Purges During Operations
    - Only for Turbopumps with Dissimilar Working Fluids
      - e.g., Fuel Rich Preburner Powering Oxygen Pump
    - Solid Seal

- Future Engines
  - Turbomachinery Interpropellant Seal Purges During Operations
    - Segmented Seals
      - Much Lower He Requirements
Tripropellant Comparison Study
Helium Usage

- All Future Engines are Expected to Need Very Little He Compared to SSME

- Use
  \[ \text{Flowrate (lbm/sec)} = 0.0000264 \times D \times P \]
  \[ D = \text{shaft diameter (inches)} \]
  \[ P = \text{purge pressure (psi)} \]
  100 psi is reasonable pressure
- Once for Each Turbopump with Dissimilar Working Fluids

- CONSIZ He Constant of \( \sim 4.5 \times 10^{-5} \), of Which \( 3.83 \times 10^{-5} \) is Vehicle Usage, is Typical of Cycles Needing Interpropellant Seals

- Effect on Vehicle Dry Weight is Small with Future Engines
  - \( \sim 500 \) lbm

- Not a Cycle Discriminator with Future Engines
Effect of Turbine Temperature on SSTO Performance

Bipropellant FFSCC

Vehicle Empty Weight, lbm

Chamber Pressure, psi

Uncoated (1150/1100)
Uncoated (1700/1500)
Coated Ox Side (1150/1100)
Coated Ox Side (1700/1500)

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

TA3-0995e
Effect of Turbine Temperature on SSTO Performance

Bipropellant FFSCC

Relative Vehicle Dry Weight

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

Chamber Pressure, psi

- Uncoated (1150/1100)
- Uncoated (1700/1500)
- Coated Ox Side (1150/1100)
- Coated Ox Side (1700/1500)
Tripropellant Comparison Study
Effects of Turbine Temperature

• Turbine Temperatures Can Extend Chamber Pressure Capabilities
  • Effect on Vehicle Dry Weight Decreasing Significantly Above
    ~ 4,000 psi
  • 4,000 psi About Limit of Consideration for Next Generation Engines

• Turbine Temperatures Have No Appreciable Effect on Engine Weight
  • Except Just Before the Power Limit for That Temperature

• Lower Turbine Temperatures Will Reduce the Thermal Environment and Improve Engine Margins, Life and Operations

• Net Effect
  • All Design Points Will Use Those Turbine Temperatures That Will Produce a Power Limit of Around 4,500 psi Chamber Pressure
  • Lowest That Will Not Effect Engine Weight Below ~ 4,000 psi Chamber Pressure
Engine Weights

Tripropellant Single Chamber

- **FFSCC - Uncoated**
  - $T_{HT} = 1150^\circ R$, $T_{OT} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$

- **ORS CC - Uncoated**
  - $T_{HT} = 1700^\circ R$, $T_{OT} = 1700^\circ R$
  - $T_{RPT} = 1700^\circ R$

- **FRSCC - Uncoated**
  - $T_{HT} = 1700^\circ R$, $T_{OT} = 1700^\circ R$
  - $T_{RPT} = 1700^\circ R$

- **Hybrid Cycle - Uncoated**
  - $T_{HT} = 1700^\circ R$, $T_{OT} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$

- **FFSCC - Coated Ox Components**
  - $T_{HT} = 1150^\circ R$, $T_{OT} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$

- **ORS CC - Coated Ox Components**
  - $T_{HT} = 1700^\circ R$, $T_{OT} = 1700^\circ R$
  - $T_{RPT} = 1700^\circ R$

- **Hybrid - Coated Ox Components**
  - $T_{HT} = 1700^\circ R$, $T_{OT} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$
Engine Weights

Tripropellant Bell Annular

- FFSCC - Uncoated
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$
- FRSCC - Uncoated
  - $T_{HT} = 1600^\circ R$, $T_{O1T} = 1400^\circ R$
  - $T_{RPT} = 1900^\circ R$
- Hybrid Cycle - Uncoated
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$
- FFSCC - Coated Ox Components
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$
- Hybrid - Coated Ox Components
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$
SSTO Performance

Tripropellant Bell Annular

- Tripropellant Bell Annular
  - $P_e = 5.5$ psi
  - MR, $O_2/H_2 = 6.8$
  - MR, $O_2/RP = 2.8$
  - Thrust Split = Cooling Limit
- FFSCC - Uncoated
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$
- FRSCC - Uncoated
  - $T_{HT} = 1600^\circ R$, $T_{O1T} = 1400^\circ R$
  - $T_{RPT} = 1900^\circ R$
- Hybrid Cycle - Uncoated
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$
- FFSCC - Coated Ox Components
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$
- Hybrid - Coated Ox Components
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$

25K Payload
220 NMI, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994
SSTO Performance

**Tripropellant Bell Annular**

- $P_e = 5.5$ psi
- $MR, O_2/H_2 = 6.8$
- $MR, O_2/RP = 2.8$
- Thrust Split = Cooling Limit

- **FFSCC - Uncoated**
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$

- **FRSCC - Uncoated**
  - $T_{HT} = 1600^\circ R$, $T_{O1T} = 1400^\circ R$
  - $T_{RPT} = 1900^\circ R$

- **Hybrid Cycle - Uncoated**
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$

- **FFSCC - Coated Ox Components**
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$

- **Hybrid - Coated Ox Components**
  - $T_{HT} = 1700^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1000^\circ R$, $T_{O2T} = 1100^\circ R$

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

**Relative Vehicle Dry Weight**

**Chamber Pressure, psi**
SSTO Performance

**Bipropellant**

- Bipropellant
  - $P_e = 4.5 \text{ psi}, \text{MR} = 6.9$

- FFSCC - Uncoated
  - $T_{HT} = 1150^\circ R, T_{OT} = 1100^\circ R$

- FRSCC - Uncoated
  - $T_{HT} = 1400^\circ R, T_{OT} = 1100^\circ R$

- Hybrid Cycle - Uncoated
  - $T_{HT} = 1700^\circ R, T_{OT} = 800^\circ R$

- FFSCC - Coated Ox Side
  - $T_{HT} = 1150^\circ R, T_{OT} = 1100^\circ R$

- GG Cycle - Coated (Rotor Only)
  - $T_{HT} = 1900^\circ R, T_{OT} = 1360^\circ R$

---

**25K Payload**

220 NMi, 51.6°

15% Weight Margin in Vehicle Code

CONSIZ Version April/May 1994

---

**Chamber Pressure, psi**
SSTO Performance

Bipropellant

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

Bipropellant

\( P_e = 4.5 \text{ psi}, \ MR = 6.9 \)

- FFSCC - Uncoated
  \( T_{HT} = 1150^\circ R, \ T_{OT} = 1100^\circ R \)

- FRSCC - Uncoated
  \( T_{HT} = 1400^\circ R, \ T_{OT} = 1100^\circ R \)

- Hybrid Cycle - Uncoated
  \( T_{HT} = 1700^\circ R, \ T_{OT} = -600^\circ R \)

- FFSCC - Coated Ox Side
  \( T_{HT} = 1150^\circ R, \ T_{OT} = 1100^\circ R \)

- GG Cycle - Coated (Rotor Only)
  \( T_{HT} = 1900^\circ R, \ T_{OT} = 1360^\circ R \)

Relative Vehicle Dry Weight

Chamber Pressure, psi

TA3-0995b
Tripropellant Comparison Study
Cycle Observations

- GG Cycle Not Competitive for This Application

- FRSCC Always the Lightest Engine Weight
  - Temperatures at Cooled/Uncooled Powerhead Interface
  - Limited Temperature Margins

- All Cycles With Hot Ox Rich Gases
  - Greatly Benefit From Improved Strength Oxygen Resistant Materials
    - Technology Programs to Achieve Such Strength Materials is Feasible
  - Their Weights and Vehicle Dry Weight Performance Results Would Then Equal Their Coated Counterparts

- Use of Higher Strength Oxygen Resistant Materials or Use of Coatings Makes All Closed Cycles Approximately the Same
  - Allows Cycle Choice on Basis of Margins, Life, Operations
**Engine Weights**

![Graph of Engine Weights](image)

- **Bipropellant**
  - $P_e = 4.5$ psi, $MR = 6.9$
  - $T_{HT} = 1150^\circ R$, $T_{OT} = 1100^\circ R$

- **Tripropellant Single Chamber**
  - $P_e = 6.0$ psi, $\%H_2 = 6$
  - $MR, O_2/(H_2+RP) = 4.4$
  - $MR, Mode 2 = 6.2$
  - $T_{HT} = 1150^\circ R$, $T_{OT} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$

- **Tripropellant Bell Annular**
  - $P_e = 5.5$ psi
  - $MR, O_2/H_2 = 6.8$
  - $MR, O_2/RP = 2.8$
  - Thrust Split = Cooling Limit
  - $T_{HT} = 1150^\circ R$, $T_{O1T} = 1100^\circ R$
  - $T_{RPT} = 1410^\circ R$, $T_{O2T} = 1100^\circ R$

**TA3-0979b**
SSTO Performance

FFSCC

- Uncoated Turbomachinery
- Coated Ox Side

- Bipropellant
  \( P_e = 4.5 \text{ psi}, \ MR = 6.9 \)
  \( T_{HT} = 1150^\circ R, T_{OT} = 1100^\circ R \)

- Tripropellant Single Chamber
  \( P_e = 6.0 \text{ psi}, \%H_2 = 6 \)
  \( MR, O_2/(H_2+RP) = 4.4 \)
  \( MR, \text{ Mode 2} = 6.2 \)
  \( T_{HT} = 1150^\circ R, T_{OT} = 1100^\circ R \)
  \( T_{RPT} = 1410^\circ R \)

- Tripropellant Bell Annular
  \( P_e = 5.5 \text{ psi} \)
  \( MR, O_2/H_2 = 6.8 \)
  \( MR, O_2/RP = 2.8 \)
  Thrust Split = Cooling Limit
  \( T_{HT} = 1150^\circ R, T_{OT} = 1100^\circ R \)
  \( T_{RPT} = 1410^\circ R, T_{OT} = 1100^\circ R \)

25K Payload
220 NMI, 51.6°
15% Weight Margin in Vehicle Code
CONSIG Version April/May 1994

Vehicle Empty Weight, lbm

Chamber Pressure, psi

TA3-0975c
SSTO Performance

FFSCC

- Uncoated Turbomachinery
- Coated Ox Side

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSz Version April/May 1994

Bipropellant
\[ P_e = 4.5 \text{ psi, } MR = 6.9 \]
\[ T_{HT} = 1150\text{°R}, T_{OT} = 1100\text{°R} \]

Tripropellant Single Chamber
\[ P_e = 6.0 \text{ psi, } \%H_2 = 6 \]
\[ MR, O_2/(H_2+RP) = 4.4 \]
\[ MR, Mode 2 = 6.2 \]
\[ T_{HT} = 1150\text{°R}, T_{OT} = 1100\text{°R} \]
\[ T_{RPT} = 1410\text{°R} \]

Tripropellant Bell Annular
\[ P_e = 5.5 \text{ psi} \]
\[ MR, O_2/H_2 = 6.8 \]
\[ MR, O_2/RP = 2.8 \]
Thrust Split = Cooling Limit
\[ T_{HT} = 1150\text{°R}, T_{OT} = 1100\text{°R} \]
\[ T_{RPT} = 1410\text{°R}, T_{OT} = 1100\text{°R} \]
Engine Weights

Staged Combustion Cycles (SCC)

- Bipropellant - Uncoated
  \( P_e = 4.5 \text{ psi}, \text{MR} = 6.9 \)
  \( T_{HT} = 1400^\circ \text{R}, T_{OT} = 1100^\circ \text{R} \)

- Tripropellant Single Chamber
  \( P_e = 6.0 \text{ psi}, \% \text{H}_2 = 6 \)
  \( \text{MR, } O_2/(\text{H}_2+\text{RP}) = 4.4 \)
  \( \text{MR, Mode 2} = 6.2 \)
  \( T_{HT} = 1700^\circ \text{R}, T_{OT} = 1700^\circ \text{R} \)
  \( T_{RPT} = 1700^\circ \text{R} \)

- Ox Rich - Uncoated
  (Except \( \text{H}_2 \) Turbine Rotor)

- Ox Rich - Coated

- Fuel Rich - Uncoated

- Tripropellant Bell Annular - Uncoated
  \( P_e = 5.5 \text{ psi} \)
  \( \text{MR, } O_2/\text{H}_2 = 6.8 \)
  \( \text{MR, } O_2/\text{RP} = 2.8 \)
  \( \text{Thrust Split = Cooling Limit} \)
  \( T_{HT} = 1600^\circ \text{R}, T_{OT} = 1400^\circ \text{R} \)
  \( T_{RPT} = 1900^\circ \text{R}, T_{O2T} = 1185^\circ \text{R} \)

---

TA3-0994
SSTO Performance

Staged Combustion Cycles (SCC)

- Bipropellant - Uncoated
  \( P_e = 4.5 \text{ psi}, \text{MR} = 6.9 \)
  \( T_{HT} = 1400^\circ R, T_{OT} = 1100^\circ R \)

- Tripropellant Single Chamber
  \( P_e = 6.0 \text{ psi}, \%H_2 = 6 \)
  \( \text{MR}, O_2/(H_2+RP) = 4.4 \)
  \( \text{MR}, \text{Mode 2} = 6.2 \)
  \( T_{HT} = 1700^\circ R, T_{OT} = 1700^\circ R \)
  \( T_{RPT} = 1700^\circ R \)

- Ox Rich - Uncoated
  (Except H_2 Turbine Rotor)

- Ox Rich - Coated

- Fuel Rich - Uncoated

- Tripropellant Bell Annular - Uncoated
  \( P_e = 5.5 \text{ psi} \)
  \( \text{MR}, O_2/H_2 = 6.8 \)
  \( \text{MR}, O_2/RP = 2.8 \)
  Thrust Split = Cooling Limit
  \( T_{HT} = 1600^\circ R, T_{O1T} = 1400^\circ R \)
  \( T_{RPT} = 1900^\circ R, T_{O2T} = 1185^\circ R \)

25K Payload
220 NMI, 51.6°
15% Weight Margin in Vehicle Code
CONSID Version April/May 1994

Vehicle Empty Weight, lbm

Chamber Pressure, psi

TA3-0994a
Staged Combustion Cycles (SCC)

25K Payload
220 NMi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

Bipropellant - Uncoated
$P_e = 4.5$ psi, MR = 6.9
$T_{HT} = 1400°R$, $T_{OT} = 1100°R$

Tripropellant Single Chamber
$P_e = 6.0$ psi, %H2 = 6
MR, $O_2/(H_2+RP) = 4.4$
MR, Mode 2 = 6.2
$T_{HT} = 1700°R$, $T_{OT} = 1700°R$
$T_{RPT} = 1700°R$

Ox Rich - Uncoated
(Except H2 Turbine Rotor)

Fuel Rich - Uncoated

Tripropellant Bell Annular - Uncoated
$P_e = 5.5$ psi
MR, $O_2/H_2 = 6.8$
MR, $O_2/RP = 2.8$
Thrust Split = Cooling Limit
$T_{HT} = 1600°R$, $T_{O1T} = 1400°R$
$T_{RPT} = 1900°R$, $T_{O2T} = 1185°R$

TA3-0994b
Engine Weights

Hybrid Cycle

Bipropellant - Uncoated
$P_e = 4.5 \text{ psi, MR} = 6.9$
$T_{HT} = 1700^\circ R, T_{OT} = 600^\circ R$

Tripropellant Single Chamber
$P_e = 6.0 \text{ psi, } \%H_2 = 6$
$MR, O_2/(H_2+RP) = 4.4$
$MR, \text{ Mode} 2 = 6.2$
$T_{HT} = 1700^\circ R, T_{OT} = 1100^\circ R$
$T_{RPT} = 1000^\circ R$

Uncoated
Coated

Tripropellant Bell Annular
$P_e = 5.5 \text{ psi}$
$MR, O_2/H_2 = 6.8$
$MR, O_2/RP = 2.8$
Thrust Split = Cooling Limit
$T_{HT} = 1700^\circ R, T_{01T} = 1100^\circ R$
$T_{RPT} = 1000^\circ R, T_{02T} = 1100^\circ R$

Uncoated
Coated
SSTO Performance

Hybrid Cycle

25K Payload
220 Nmi, 51.6°
15% Weight Margin in Vehicle Code
CONSIZ Version April/May 1994

Bipropellant - Uncoated
\( P_e = 4.5 \text{ psi, MR} = 6.9 \)
\( T_{HT} = 1700^\circ R, T_{OT} = -600^\circ R \)

Tripropellant Single Chamber
\( P_e = 6.0 \text{ psi, } %H_2 = 6 \)
MR, \( O_2/(H_2+RP) = 4.4 \)
MR, Mode 2 = 6.2
\( T_{HT} = 1700^\circ R, T_{OT} = 1100^\circ R \)
\( T_{RPT} = 1000^\circ R \)

Uncoated
Coated

Tripropellant Bell Annular
\( P_e = 5.5 \text{ psi} \)
MR, \( O_2/H_2 = 6.8 \)
MR, \( O_2/RP = 2.8 \)
Thrust Split = Cooling Limit
\( T_{HT} = 1700^\circ R, T_{O1T} = 1100^\circ R \)
\( T_{RPT} = 1000^\circ R, T_{O2T} = 1100^\circ R \)

Uncoated
Coated

TA3–0994e
Tripropellant Comparison Study
Propellant Choice Observations

• Bipropellant and Tripropellant Vehicle Dry Weight Results Within 3% at All Chamber Pressures and All Cycles
  • Single Chamber Very Slightly Better Than Bell Annular (<3%)
  • Bipropellant Slightly Better Than Either Tripropellant

• Tripropellant Has No Vehicle Performance Advantage Over Bipropellant
Reconciliation Between This Study and the Access-to-Space Results
From the Access-to-Space Report

WEIGHT GROWTH MARGIN GAINS (by technologies)

Chart shows how much the dry vehicle weight produced by the use of each technology could grow before reaching the Baseline value of 233k.

\[
\begin{align*}
W_T \text{ Baseline (SSME)} &= 233K = W_{TB} \\
W_T \text{ Tripropellant} &= W_{Tp} \\
W_{Tp} \cdot (1 + 0.2) &= W_{TB} \\
W_{Tp} &= W_{TB} / 1.31 \\
&= 178K
\end{align*}
\]

- Payload = 45,000 lb into 100 nmi 28° orbit
- Vehicle dry weight constant at 233k lb

Limit of 1993 Technology Plan

\[+40\%\]

\[+31\%\]

\[+21\%\]

\[+15\%\]

\[+2.5\%\]

Not achievable with these technologies

<table>
<thead>
<tr>
<th>Use STS Technology Only</th>
<th>Advanced Subsystems</th>
<th>Advanced TPS</th>
<th>Aluminum-Lithium Tanks</th>
<th>Composite Structures</th>
<th>Composite Hydrogen Tank</th>
<th>Tripropellant Propulsion</th>
<th>Lightweight Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cumulative Incorporation of Advanced Technologies

Figure 32.—Weight growth margin available.
Access to Space Study
Baseline Engines

• Bipropellant Engine
  • Modified SSME
    • Large Throat
    • Chopped Nozzle
      • Area Ratio = 50
  • MR = 6
  • Chamber Pressure = 2,800 psi
• Conditions Far Off-Optimum for SSTO Mission
• Essentially Existing Engine With Weights Known
• 25 Year Old Design
• Produced Dry Vehicle Weight of 233,000 lbm

• Tripropellant Single Chamber Engine
  • Chamber Pressure = 4,200 psi
  • Mode 1 MR = 4.4
  • Mode 2 MR = 6
  • Propellant Percentages = 81.5 O₂/ 6 H₂/ 12.5 RP
• All At or Near Optimum for SSTO Mission
• New Paper Engine - Weights Malleable
• New Design
• Produced Dry Vehicle Weight of 178,000 lbm
  • 23.6 % Lighter than Baseline Bipropellant Engine

TA3-1152
**Access to Space Study**
**Bipropellant/Tripropellant Engine Reconciliation**

- Effect of Bringing Both Engines to Comparable Conditions
  - Same Chamber Pressure, Optimum MR's and Area Ratios, Same Design
  - Groundrules and Practices and Technology Use

<table>
<thead>
<tr>
<th></th>
<th>Change in Dry Vehicle Weight From Baseline of 233,000 Ibm, Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tripropellant</td>
</tr>
<tr>
<td>Access to Space Study</td>
<td>—</td>
</tr>
<tr>
<td>Mode 2 MR (Tri — 6.2; Bl — 6.9)</td>
<td>-0.1</td>
</tr>
<tr>
<td>Chamber Pressure (4,000 psi)</td>
<td>+0.5</td>
</tr>
<tr>
<td>Both as New Engines Common Design Practices, Same Technologies</td>
<td>-6.9</td>
</tr>
<tr>
<td>He Usage</td>
<td>-0.0</td>
</tr>
</tbody>
</table>

- Essentially the Same — Excellent Agreement with Current Study
Tripropellant Comparison Study
Engine Cycle Margins
Alternate Propulsion Subsystem Concepts
Tripropellant Comparison Study
Margin Study

• Margins Studied
  • +5% Thrust
    • Chamber Pressure Increased
    • Nozzle Area Ratio Increased for Optimum Exit Pressure
  • 5:1 Throttling
    • LOX Cooled Nozzle
    • Kick Pump and RP Pump Fluids
      • 50% Preburner Injector Pressure Drop at Full Thrust
  • -5% All Turbopump Efficiencies
  • +10% Pump Discharge Pressures
  • All Margins Together
## Alternate Propulsion Subsystem Concepts
### Tripropellant Comparison Study
#### Margin Study – Bipropellant Engines

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>+5% Thrust</th>
<th>5:1 Throttling</th>
<th>-5% TP Eff</th>
<th>+10% Pd’s</th>
<th>All Margins</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FFSCC-Bipropellant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Weight, Ibm</td>
<td>4,567</td>
<td>4,809</td>
<td>4,688</td>
<td>4,738</td>
<td>4,796</td>
<td>5,308</td>
</tr>
<tr>
<td>Vehicle Dry Weight, Ibm</td>
<td>181,105</td>
<td>180,264</td>
<td>183,492</td>
<td>184,494</td>
<td>185,670</td>
<td>189,843</td>
</tr>
<tr>
<td>Chamber Pressure, psi</td>
<td>4,000</td>
<td>4,187</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
<td>4,187</td>
</tr>
<tr>
<td>Pump Discharge Pressure, psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>10,839</td>
<td>11,255</td>
<td>10,839</td>
<td>10,839</td>
<td>11,923</td>
<td>12,339</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>9,889</td>
<td>10,304</td>
<td>10,356</td>
<td>9,889</td>
<td>10,878</td>
<td>11,760</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>1,150</td>
<td>1,176</td>
<td>1,150</td>
<td>1,310</td>
<td>1,273</td>
<td>1,460</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,110</td>
<td>1,104</td>
<td>1,385</td>
</tr>
<tr>
<td><strong>SCC-Bipropellant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Weight, Ibm</td>
<td>4,049</td>
<td>4,235</td>
<td>4,157</td>
<td>4,194</td>
<td>4,204</td>
<td>4,645</td>
</tr>
<tr>
<td>Vehicle Dry Weight, Ibm</td>
<td>171,739</td>
<td>170,474</td>
<td>173,689</td>
<td>174,367</td>
<td>174,547</td>
<td>177,598</td>
</tr>
<tr>
<td>Chamber Pressure, psi</td>
<td>4,000</td>
<td>4,187</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
<td>4,187</td>
</tr>
<tr>
<td>Pump Discharge Pressure, psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>11,673</td>
<td>12,128</td>
<td>11,673</td>
<td>11,673</td>
<td>12,840</td>
<td>13,295</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>11,276</td>
<td>11,761</td>
<td>15,564</td>
<td>11,276</td>
<td>12,403</td>
<td>17,375</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>1,400</td>
<td>1,400</td>
<td>1,400</td>
<td>1,540</td>
<td>1,498</td>
<td>1,800</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,335</td>
</tr>
</tbody>
</table>
### Alternate Propulsion Subsystem Concepts

**Tripropellant Comparison Study**

**Margin Study – Tripropellant Single Chamber Engines**

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>+5% Thrust</th>
<th>5:1 Throttling</th>
<th>-5% TP Eff</th>
<th>+10% Pd's</th>
<th>All Margins</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FFSCC-Tripropellant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Weight, Ibm</td>
<td>4,492</td>
<td>4,735</td>
<td>4,660</td>
<td>4,614</td>
<td>4,667</td>
<td>5,253</td>
</tr>
<tr>
<td>Vehicle Dry Weight, Ibm</td>
<td>184,144</td>
<td>183,188</td>
<td>187,853</td>
<td>186,824</td>
<td>188,011</td>
<td>194,352</td>
</tr>
<tr>
<td>Chamber Pressure, psi</td>
<td>4,000</td>
<td>4,187</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
<td>4,187</td>
</tr>
<tr>
<td>Pump Discharge Pressure, psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>10,468</td>
<td>10,876</td>
<td>10,468</td>
<td>10,468</td>
<td>11,515</td>
<td>11,923</td>
</tr>
<tr>
<td>RP</td>
<td>9,023</td>
<td>9,417</td>
<td>12,529</td>
<td>9,023</td>
<td>9,925</td>
<td>13,988</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>9,830</td>
<td>10,262</td>
<td>10,247</td>
<td>9,830</td>
<td>10,814</td>
<td>11,662</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1,150</td>
<td>1,150</td>
<td>1,150</td>
<td>1,254</td>
<td>1,217</td>
<td>1,447</td>
</tr>
<tr>
<td>RP</td>
<td>1,410</td>
<td>1,423</td>
<td>1,567</td>
<td>1,450</td>
<td>1,447</td>
<td>1,694</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,100</td>
<td>1,303</td>
</tr>
<tr>
<td><strong>FRSCC-Tripropellant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Weight, Ibm</td>
<td>4,040</td>
<td>4,247</td>
<td>4,173</td>
<td>4,207</td>
<td>4,247</td>
<td>4,759</td>
</tr>
<tr>
<td>Vehicle Dry Weight, Ibm</td>
<td>175,067</td>
<td>173,990</td>
<td>177,759</td>
<td>178,459</td>
<td>179,288</td>
<td>184,085</td>
</tr>
<tr>
<td>Chamber Pressure, psi</td>
<td>4,000</td>
<td>4,187</td>
<td>4,000</td>
<td>4,000</td>
<td>4,000</td>
<td>3,451</td>
</tr>
<tr>
<td>Pump Discharge Pressure, psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>10,822</td>
<td>11,247</td>
<td>10,822</td>
<td>10,822</td>
<td>11,904</td>
<td>10,657</td>
</tr>
<tr>
<td>RP</td>
<td>10,186</td>
<td>10,637</td>
<td>14,176</td>
<td>10,189</td>
<td>11,208</td>
<td>13,337</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>10,200</td>
<td>10,648</td>
<td>14,187</td>
<td>10,200</td>
<td>11,221</td>
<td>13,350</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1,700</td>
<td>1,800</td>
<td>1,900</td>
<td>2,008</td>
<td>1,950</td>
<td>2,200</td>
</tr>
<tr>
<td>RP</td>
<td>1,700</td>
<td>1,800</td>
<td>1,900</td>
<td>2,008</td>
<td>1,950</td>
<td>2,200</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>1,700</td>
<td>1,800</td>
<td>1,900</td>
<td>2,008</td>
<td>1,950</td>
<td>2,200</td>
</tr>
</tbody>
</table>

TA3-1142
Vehicle Dry Weight Sensitivity to Margin Requirements
Pc = 4,000 psi
Bipropellant Engines

Relative Vehicle Dry Weight

Baseline
+5% SL Thrust
≈ 5:1 Throttling
≈5% on All TP Efficiencies
+10% Pump Delta P
All Margins Together
Vehicle Dry Weight Sensitivity to Margin Requirements
Pc = 4,000 psi
Single Chamber Tripropellant Engines

Relative Vehicle Dry Weight

Baseline
+5% SL Thrust
≥ 5:1 Throttling
−5% on All TP Efficiencies
+10% Pump Delta P
All Margins Together

FFSCC
FRSCC

TA3-0907g
Turbine Operating Temperature as a Measure of Cycle Design Margin

- Margin can be Expressed in Terms of Turbine Inlet Temperature
  - Can be Increased to Increase Margin Where Desired or to Change Component Design Point Relationships
    - Thrust (Chamber Pressure)
    - Turbopump Parameters (Tip Speeds, Pitch-Line Velocities, Discharge Pressures, etc.)
    - Combustion Device Parameters (Throttling, Pressure Drops)
    - System Routing Pressure Drops
    - Weights (Line Pressure Drops, Nozzle Coolant Pressure Drops)
  - Full Flow Staged Combustion Cycle Turbine Inlet Temperature is More Robust than any Other Cycle
    - Max Power Possible
      - All Flow is Available for Power
      - Both Sides Add Chemical Energy
Hydrogen Turbine Temperature Sensitivity to Margin Requirements

\( P_c = 4,000 \text{ psi} \)

Single Chamber Tripropellant Engines

* Ox Turbine Temperature (Nominally 1100°F) Also Raised to 1303°F, and RP Turbine (Nominally 1410°F) to 1694°F

** Chamber Pressure Also Limited to 3451 psi as Opposed to 4187 psi
Alternate Propulsion Subsystem Concepts
Tripropellant Comparison Study
Margin Study Observations

- Without Margin Considerations
  - FFSCC, SCC, and Hybrid Cycles are Comparable
    - At 4,000 psi and Below
    - All Cycles Except FFSCC At Least Marginal on
      Turbine Temperature to Avoid Cooled
      Powerhead

- With Margin Considerations
  - FFSCC is the Most Robust Cycle
    - Little Impact Except With All Margins
    - Still Uncooled Powerhead Even With All Margins
Tripropellant Comparison Study

Conclusions
Cycle Choice Affects Life and Weight

- Reduced turbine temperatures provide capability to accommodate engine/vehicle design uncertainties

- Fuel rich engine cycles operate near strength limits of available materials
Engine Cycle Choice Can Provide Increased Design Margins and Opportunity for Future Growth

Potential Margin Uses
- Design Maturation
- Increased Mixture Ratio
- Increased Chamber Pressure
- Deep Throttling

Preburner Temperatures, °R

Uncooled Hardware
Cooled Hardware

Power Level, percent

32% Power Margin
8% Power Margin
26% Power Margin

FFSCE > 400°F Temperature Margin Potential
FRSCE > 150°F Temperature Margin Potential
SSME Operating Point

Fuel Rich
Full Flow

TA3-0946
<table>
<thead>
<tr>
<th>Technology Areas</th>
<th>Bipropellant</th>
<th>Tripropellant</th>
<th>Impact</th>
<th>Increase in Vehicle Dry Weight if Not Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased $P_c$</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions Up to $\sim 4,000$ psi</td>
<td></td>
</tr>
<tr>
<td>Improved Strength Oxygen Resistant Materials</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions in Cycles with Best Operating Margins</td>
<td>$+3.0%$</td>
</tr>
<tr>
<td>High Confidence, Long Life Coatings on the Ox Side</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions in Cycles with Best Operating Margins</td>
<td>$+3.0%$</td>
</tr>
<tr>
<td>Lower Turbine Operating Temperatures</td>
<td>X</td>
<td>X</td>
<td>Margin, Ops Costs</td>
<td></td>
</tr>
<tr>
<td>LOX Rich LOX Turbopumps</td>
<td>X</td>
<td>X</td>
<td>Margin, Ops Costs Thru Lower Turbine Temperatures by Allowing Cycles Which are Less Sensitive in Turbine Operating Temperature versus $\Delta P$, Throttling, and $P_c$</td>
<td></td>
</tr>
<tr>
<td>LOX Rich Preburners</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions, Better Ops</td>
<td>$+7.5%$</td>
</tr>
<tr>
<td>SLIC™ Turbomachinery</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions, Better Ops</td>
<td>$+5.8%$</td>
</tr>
<tr>
<td>Jet Pumps</td>
<td>X</td>
<td>X</td>
<td>Significant Weight Reductions on Engine</td>
<td>$+1.9%$</td>
</tr>
<tr>
<td>Vehicle Side Gimbal Flex Accommodation</td>
<td>X</td>
<td>X</td>
<td>Lower Turbomachinery Weights</td>
<td>$+1.2%$</td>
</tr>
<tr>
<td>AI Fuel Pump</td>
<td>X</td>
<td>X</td>
<td>Easier Development, Better Ops</td>
<td></td>
</tr>
<tr>
<td>Laser Ignition</td>
<td>X</td>
<td>X</td>
<td>Margin for Deep Throttling (e.g., 5:1)</td>
<td></td>
</tr>
<tr>
<td>Gasify LOX</td>
<td>X</td>
<td>X</td>
<td>Reliability, Ops Costs</td>
<td></td>
</tr>
<tr>
<td>Health Monitoring/Life Prediction</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tripropellant Comparison Study
Conclusions

- For Newly Designed Engines, Using the Same Groundrules and Technology

- No Significant Differences in Vehicle Dry Weight Performance Between Tripropellant and Bipropellant Engines
  - < 3% Across Chamber Pressure Range 2,000-5,000 psi
    - Bipropellant Engine Slightly Better
    - Single Chamber and Bell Annular Tripropellant Configurations Similar in Vehicle Performance (< 1%)

- Much Larger Vehicle Performances Differences Within Any One Engine Configuration Due to Operating Point and Design Choices
  - Mixture Ratio
  - Chamber Pressure
  - Nozzle Exit Pressure
  - Power Cycle
  - Coated versus Uncoated Materials
  - Welded versus Cast

- FFSCC Has Significantly Higher Available Margins Than Staged Combustion Cycle (SCC)
  - For Both Bipropellant and Tripropellant Engines
    - Differences More Pronounced for Tripropellant Engines
  - Inherent Engine Weight Difference ~ 2-5%
    - Favors SCC
      - Applies if Coated Oxide Or Improved Ox Resistant Materials
  - Strongly Supports the Value of Ox Resistant Material Technology Programs
Propulsion: Pocket Engine, SSTO, Propellant, Propellent

Paper for this application proposes a mixture ratio, internal alpha, etc. Inter propelent applications were separated with in terms of operating pressures, etc.

A study was conducted under MSE contract NAS8-3910 to compare internal and external conditions.