Propulsion

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Propulsion Mission Requirements

- Provide Thrust for Spacecraft Orbit Raising, Attitude Control, and Stationkeeping
- Provide Single Fault Tolerant Design
  - Thruster Failure
  - Valve Leakage
- 5 Year Mission Life
  - Design For Delivery By August 15, 2003
    - Derived From Integrated Master Schedule
  - Design, Qualify, and Test for FAME Mission and Launch Environments
    - NCST-TP-FM001, FAME Test Plan
    - New or Re-Designed Systems Will Have Protoflight Testing
- Meet Launch Base Safety Requirements and Verification Process
  - EWR-127-1 TBD Version, Tailored for FAME
- Support Science Mission Requirements
  - Minimize CG Migration, Plume Contamination, and Minimum Impulse Bit
- Minimize Cost and Schedule Risk
  - Provide Most Flexible Design With Given Schedule and Budget

Key Propulsion Derived Requirements (1 of 3)

- Provide GEO Insertion From Delta II 2425 Launch Vehicle
  - Baseline Thiokol STAR 30BP Solid Rocket Motor
    - 1100 Kg Launch Vehicle Throw Weight
    - 1478 m/s GEO Insertion Maneuver
- Provide Vehicle 3 Axis Attitude Control
  - Spin Control (About Vehicle Z Axis-Roll)
    - Requires Pure Torque Couples
    - Spin Stabilize for Solid AKM Firing 40-60 RPM
    - Rotation Control for Science Mission
      - 1 Revolution Per 40 Minutes
  - Active Nutation Control (ANC)
    - Solid Rocket Motor Firing
    - Science Collection (TBD System)
  - Spin Axis Precession (SAP) Control
    - Solid Rocket Motor Firing
    - Science Collection (TBD Backup for Solar Precession)
  - Correct for Delta V Thrust Misalignment With CG

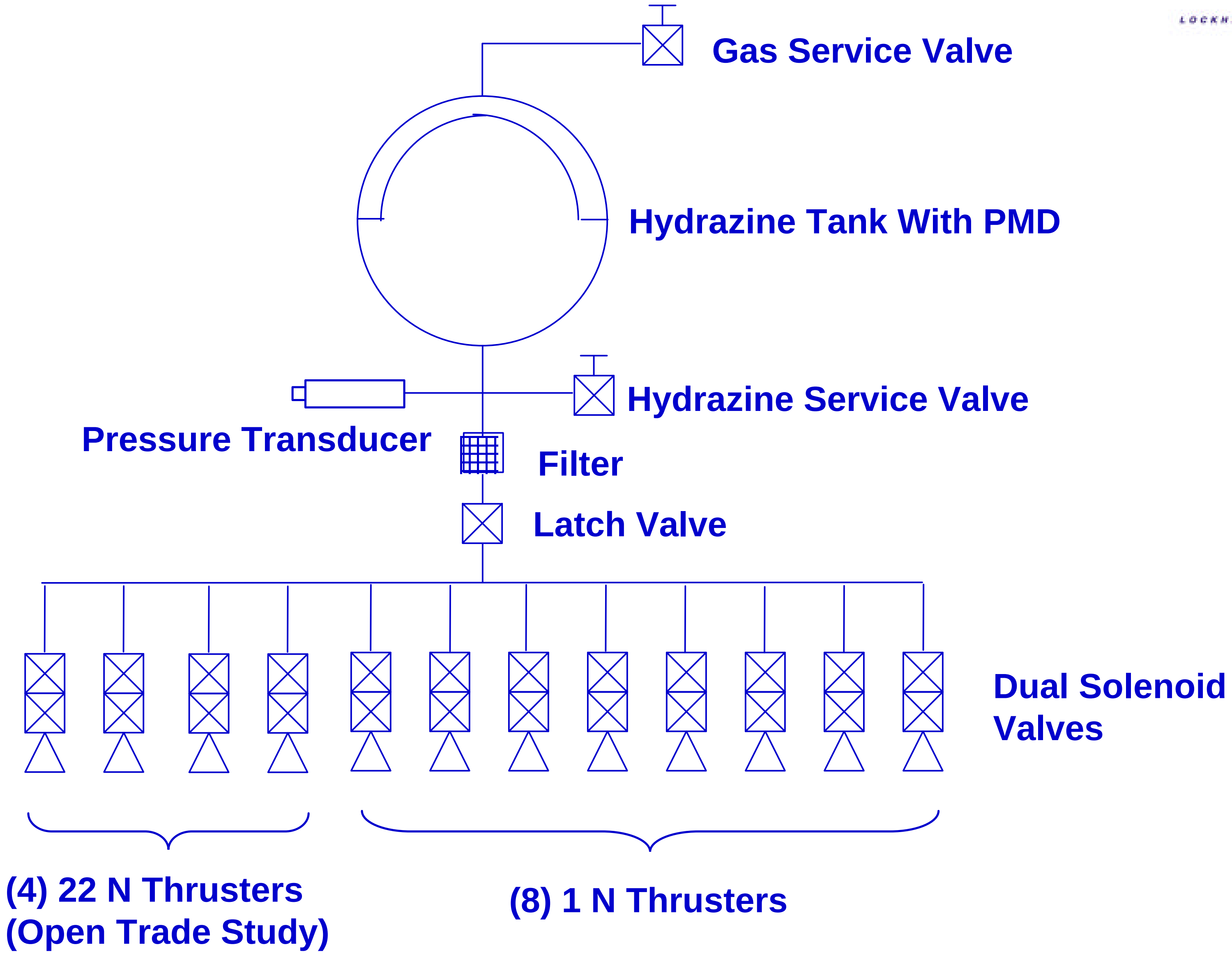
Key Propulsion Derived Requirements (2 of 3)

- Provide Delta V Thrust Through + Z Axis (Velocity Vector) for Orbital Maneuvers
  - Correct Delta II 2425 Launch Vehicle Insertion Error
    - 1st/2nd Stage Pointing Error
    - 3rd Stage (STAR 48) Pointing and Impulse Errors
  - Correct Transfer Stage SRM (STAR 30BP) Pointing and Impulse Errors
  - Errors Requires Additional Impulse Capability From the On-Board Propulsion System
    - Stage Pointing Errors Produce Inclination Changes
      - Evaluated and Found Acceptable to 30° With No Correction
  - De-Orbit Transfer Stage Before Science Mission
  - Provide Stationkeeping (Drag Make Up) Delta Velocity
    - No North-South Stationkeeping Requirement (Allows Inclination Drift)
    - East-West Stationkeeping Required for 1 Degree GEO Orbit Position
      - GEO Orbit Optimized For One TBD Maneuver Each 15 Months
  - De-Orbit From GEO Position for Orbital Debris Mitigation

Key Propulsion Derived Requirements (3 of 3)

- Mono-Propellant Hydrazine Propellant System
  - Moderate Mission Total Impulse Requirements
  - Blowdown Pressurization
- Positive Expulsion Tank Required for Precision CG Alignment During Expulsion
  - Science Mission Requirement
  - Eliminates Passive PMD Designs (i.e., Vanes, Sumps)
- Drop Off SRM Stage Due to Uncertainty in Post Burn Mass Properties
  - Science Mission Requirements for CG Knowledge and Alignment
- De-Orbit in Accordance With NASA Policy Directive (NPD) 8710.XX
  - GEO Is an Active Orbit Requiring Removal of Orbital Debris
  - 300 Km Above GEO Disposal Orbit
  - Applies to Solid Apogee Transfer Stage
  - Final Disposal of FAME Vehicle

FAME Propulsion Schematic



Current Baseline/Approach

- One Centrally Located Pressurized Monopropellant Hydrazine Tank
  - Contains a Propellant Management Device (PMD)
  - Blowdown Pressurization Ratio Dependent on Tank Selection and Propellant Load (Nominal 4:1)
- Eight 1 N Thrusters (Beginning-of-Life 1.13 N vs End-of-Life 0.19 N)
  - Thrusters for Spin and Attitude Control
  - Series Thruster Valves (Leakage Protection)
  - Each Thruster Has a Catalyst Bed Heater
- Four 22 N to Thrusters Under Investigation (Open Trade) For GTO Active Nutation Control (ANC) In Preparation for SRM Firing
  - Vehicle Delta V and ANC
- Latch Valve Provides Leakage Tolerance and Personnel Protection
- One Pressure Transducer Provides Telemetry Data
  - Determines Propellant Usage and Allows Predict Thruster Performance
- Two Fill Valves for Propellant Loading and System Check-Out
- Thiokol STAR 30BP Solid Rocket Motor

Solid Rocket Motor (SRM) for GEO Insertion

- Thiokol STAR 30 BP Solid Rocket Motor
  - Hughes HS-376 AKM
  - > 60 STAR 30 Series Flights
  - TI 6AL-4V Case
  - Carbon-Carbon Throat With Carbon-Phenolic Nozzle
- Performance
  - Total Impulse 328,200 lb-sec
  - Average Thrust 6070 lb
  - Burn Time 55 sec
  - Effective Specific Impulse 292 sec
  - Spin Capability 40 to 100 rpm
  - Capable of 20% Propellant Offload
- Weights
  - Total Loaded 1196.7 lb
  - Propellant 113.6 lb
  - Empty Weight 72 lb
- Current Mass Estimates Indicate 15% Propellant Offload

Propulsion Requirements Matrix (1 of 2)

Item	Requirement	Description
3 Axis Attitude Control	Yes	Top Level ADCS Requirement
Spacecraft Delta Velocity	22 m/s	Top Level Propulsion Requirement Mission Orbit Insertion and De-orbit
Single Fault Tolerant Design	Yes	Mission Success - Proposal
Mission Life	5 Years	Mission Success - Proposal
Component Qualification	Protoflight	Margin over Worst Case Mission and Launch Environments
Component and System Verification	NCST-TP-FM001	FAME Test Plan
System Delivery Date	8/15/03	Supports Integrated Mechanical Schedule
Cost and Program Risk	Minimize	Lowest Cost and Risk Within Budget Allocations
Maximum Propellant Weight	50 kg (TBR)	Establishes Tank Size
EWR 127-1	Compliant/Waivered	TBD Dated Version
Component Safety Factors	2.5:1	Derived from Mil-Std-1522 and EWR 127-1
Mechanical Faults To Activation	2	Single Fault Tolerant, EWR 127-1
Electrical Faults to Activation	3	Dual Fault Tolerant, EWR 127-1
Adiabatic Detonation	None	Mission Success Requirement
Maximum Water Hammer Surge Pressure	700 psi	Mission Success Requirement, Exceeds System MEOP, Defines System Proof
Spacecraft Pitch Rate	TBD °/sec	ADCS Requirement used for Thruster Sizing and Propellant Slosh Analysis
Spacecraft Yaw Rate	TBD °/sec	ADCS Requirement used for Thruster Sizing and Propellant Slosh Analysis
Spacecraft Roll Rate	TBD °/sec	ADCS Requirement used for Thruster Sizing and Propellant Slosh Analysis
Thruster Control Authority Margin	25%	ADCS Requirement used for Thruster Sizing and Location
Simultaneous Thruster Firings	5	Used for Hydraulics Analysis
Maximum Dry Weight	50 kg (TBR)	Spacecraft Spec Requirements
Vibration	TBD	Environmental Requirement
Shock	TBD	Enviromental Requirement
Static Acceleration	TBD	Enviromental Requirement
Minimum Temperature	5 C	No Hydrazine Freezing
Maximum Temperature	40 C	Establishes Tank MEOP
Component Cleanliness	Mil-Std-1246 100A	Spacecraft Spec Requirements
Maximum Power	TBD W	Spacecraft Spec Requirements
Bus Voltage (Vbus)	24 < Vbus < 36	Spacecraft Spec Requirements
Maximum Thruster Pulses	< 200000	Thruster Spec Requirement
Minimum Impulse Bit	.013 N sec	Thruster Spec Requirement, MR-103G Capability
Minimum Thrust Level	.19 N	Thruster Spec Requirement, MR-103G Capability
Maximum Thrust Level	22 N or 5 N (TBR)	Thruster Spec Requirement, Open ANC Thruster Trade
Minimum Burn Duration	10 ms	Thruster Spec Requirement
Maximum Delta V Maneuver Time	40 minutes	10° GEO Burn Arc. Used for Delta V Thruster Sizing
Maximum Burn Duration	40 min	Thruster Spec Requirement
Thruster Cold Starts	0	Thruster Spec Requirement, EPS and Software Design
Total Impulse Per Thruster	< 80,000 N-sec	Thruster Spec Requirement

Propulsion Requirements Matrix (2 of 2)

Item	Requirement	Description
Thruster Mechanical Alignment	1°	For ADCS Analysis
Thruster Alignment Knowledge	0.1°	For ADCS Analysis
Plume Contamination	TBD % EOL Data Loss	Instrument Spec Value
Component External Leakage	< 1E10-5 scc/sec He	Determines Propellant/ Pressurant Requirements and Spacecraft Error Torques
Valve Leakage Per Seat	< 1E10-5 scc/sec He	Determines Propellant/ Pressurant Requirements and Spacecraft Error Torques
Tank Design	Mil-Std-1522	Derived from Mil-Std-1522 and EWR 127-1
Propellant Center of Gravity	.1 mm	For ADCS Analysis
Propellant Slosh Amplitude	.1 mm	For ADCS Analysis
Propellant Slosh Frequency	TBD > f < TBD	For ADCS Analysis
Launch Tower Fill/Drain Access	Yes	Contingency Propellant Offlaoding Requirement
Propulsion Ground Support Equipment	Yes	Pressurant Control Console, Vacuum Cart
Fill Valve Protective Covers	Yes	Remove Before Flight Ground Support Equipment
Thruster Protective Covers	Yes	Remove Before Flight Ground Support Equipment
Tank Protective Cover	Yes	Remove Before Flight Ground Support Equipment
SRM Delta V	1478 m/s	Top Level Propulsion Requirement
SRM Maximum Total Weight	542.7 kg	Thiokol STAR 30BP Maximum, Spacecraft Spec Requirements
SRM Case Leakage	< 1E10-4 scc/sec He	SRM Spec Requirement
SRM Maximum Acceleration	7 g's	Spacecraft Spec Requirements
SRM Maximum Offload	20%	SRM Spec Requirement
SRM Maximum Spin Rate	60 RPM	SRM Spec Requirement
SRM Temperature	5 to 32°C	SRM Spec Requirement
SRM Maximum Differential Temperature	20° C	SRM Spec Requirement
SRM Maximum Burn Time	300 sec	SRM Spec Requirement
SRM Static Balance	TBD oz in	Spacecraft Spec Requirements
SRM Dynamic Balance	TBD oz in2	Spacecraft Spec Requirements
STAR Motor Alignment	1°	For ADCS and Mission Analysis
STAR Motor Alignment Knowledge	0.1°	For ADCS and Mission Analysis
STAR Motor Case Temperature	370 C	For Thermal Analysis and Design
STAR Motor Thermal Model	Yes	Required for Thermal Analysis
SRM Mass Simulator	Yes	System Verification and test
SRM Thermal Simulator	Yes	Thermal Integration Support
SRM Shipping Container	Yes	Lease From Thiokol
SRM Ground Support Equipment	Yes	Lease From Thiokol Turn Over Stand, Proof and Leak Test Fixture
Thruster Alignment Verification Plan	Yes	Integration Support
SRM Alignment Verification Plan	Yes	Integration Support
SRM Interface Verification Plan	Yes	Integration Support
Propellant Servicing Equipment	Yes	Support Propulsion Fueling Effort
Propellant Servicing Procedures	Yes	Range Safety Verification
Range Safety Verification Support	Yes	Range Safety Verification

Propulsion Trade Completed - Hydrazine

- Monopropellant Hydrazine Propulsion System Selected for FAME Mission Orbit Insertion
  - Other Propellant Systems Considered Include:
  - Cold and Warm Gas Systems
    - Volumetrically Large and Massive for FAME Total Impulse
  - Bi-Propellant System
    - Higher Specific Impulse Results in Less Propellant Weight
    - High System Complexity and Cost
      - Two Propellant Feed Systems
    - Higher Force and Impulse Bit Thrusters Not Suitable for Precise Attitude Control
  - Electric Propulsion
    - Low Thrust Good for Precision Impulse Bit
    - High System Complexity
      - Separate Propellant Feed System
      - Separate Power System
    - Low Total Impulse Required Does Not Justify High Dry Mass

Propulsion Trades - Tanks

- Tank Selection Issues
  - Tank Volume Determination Requires Additional Analysis
    - Requires Quantification of Propellant and Pressurization
    - Single Blowdown Tank vs Augmented Pressurization Tank
  - Tank Geometry
    - Oblate Spheroid Desired But Has Limited Availability
      - Reduces Spacecraft Overall Height Allowing Preferred Sun Angle Between the Sun Shield and Payload
    - Mounting Options Include Boss and Girth (Tabs or Skirt)
  - PMD Selection Limits Availability
    - Passive PMD Is Not Possible (Accelerations, Spin, and CG Control)
    - Trade Elastomeric Tank Bladder vs. Metal Diaphragm
  - Cost and Delivery Schedule
    - Heritage Design Is Desirable
    - New Design and Qualification Possible (Lengthy Delivery and Costly)
    - New Tank Design and Qualification Requires 24 Months ARO
      - Multiple Designs and Vendors Available

Propulsion Trades - Hydrazine Thrusters (1 of 2)

- Thruster Quantity and Force Selection
  - 8 1N or 4N (from CSR) Thrusters
    - Spin Control and 3-Axis ACS
  - Zero, Two, or Four 22 N Thrusters
    - SAP, ANC, and Vehicle Delta V Thrusters
  - Minimum Impulse Bit and Maximum Thrust Are Design Drivers
    - Conflicting Requirements for a Single Thruster Size
- Multiple Designs and Vendors Including
- Hamilton Standard 22N (5 lbf)
  - In Stock at NRL From Previous Programs
  - Single Seat Valve Originally Included Was Replaced With Dual Seat Valve For Clementine
- MR-111C 4N (1.0 lbf)
  - Flown on Clementine
- MR-111E 2N (0.5 lbf)
  - Possible Compromise Between the Conflicting Small Impulse and High Thrust Requirements

Propulsion Trades - Hydrazine Thrusters (2 of 2)

- MR-103C 1N (0.2 lbf)
  - Small Impulse Bit, But Being Discontinued by Manufacturer
  - Ibitmin= .0044 N-sec @15ms and 100 psia
- MR-103D 1N (0.2lbf) Long Life Thruster Variant
  - More Costly Than Warranted by FAME Mission Requirements
- MR-103G 1N (0.2 lbf) IRIDIUM Design
  - Ibitmin= .0133 N-sec @15ms and 100 psia
- MR-103H 1N (0.2 lbf) Smallest Impulse Bit
  - Single Fast Acting Solenoid Valve Rather Than Dual Valves
  - High Cost ~$80K
  - Ibitmin= .0022 N-sec @15ms and 100 psia
- ValveTech Consortium 0.2 lbf Low Cost Thruster
  - Recently Flight Demonstrated
  - Qualification and Delivery Status TBD

Propulsion Trades – Small Impulse Bit Control (1 of 2)

- **Propulsion Options for Stellar Mapping Backup Solar Precession, Nutation Damping Augmentation and Spin Rate Variation Control**
  - **Current Hydrazine System Cannot Perform These Functions With Current Minimum Impulse Bit Capabilities**
- **Augment Current Hydrazine System**
  - **Incorporate Fast Acting 1 N Thruster and Investigate Re-Orificing for Smaller Impulse Bit**
    - **TBD Cost and Schedule**
  - **Incorporate Separate Tank for Blowdown Pressure Control**
    - **Lower Operating Pressure for Thrusters During Stellar Mapping**
    - **Requires Additional Gas Storage Tank**
    - **Pressure Regulation Options**
      - **Bang - Bang With Feed Back Control Similar to *Clementine***
      - **Mechanical Regulator**
      - **Shuttle Solenoid Valves**
  - **Optimize Blowdown Ratio for High Beginning of Life Thrust and Small Science Collection (End of Life) Impulse Bit**

Propulsion Trades – Small Impulse Bit Control (2 of 2)

- Implement a Cold Gas Nitrogen Thruster System
  - Blowdown or Regulated System Options
    - 60 Second Specific Impulse
  - Relatively Inexpensive
  - Good For Low Total Impulse Missions
- Implement a Warm Gas Thruster System
  - Ammonia Propellant System
    - 90 Second Specific Impulse
  - Applicable for Higher Total Impulse Than Cold Gas
  - Somewhat More Complicated Than Cold Gas
    - Component Availability is TBD
- Implement a Pulsed Plasma Thruster System
  - Solid Teflon Propellant
  - Dawgstar Design (AIAA-00-3256) Has Two Nozzles Firing Simultaneously
    - 13.1 Watts and 500 Seconds Specific Impulse
    - 55μN-Sec Impulse Bit
- Implement Torque Rod System (Investigated In the ADCS SRR Package)

Propulsion Analysis Updated for SRR

- Delta 2425-10 Launch Vehicle
  – Determined Throw Weight and Margin to FAME Injection Orbit
  – Preliminary Analysis Based on August 2000 Masses
  – Evaluated Injection Errors
- STAR 30BP AKM
  – Determine Margins and Offload Requirements
  – Evaluate Total Impulse and Pointing Errors
- On-Board Hydrazine System
  – Propellant Selection and System Sizing
    - Re-Evaluation of 1N Versus 4 N Thrusters and Incorporation of 22 N ANC Thrusters as Open Trade
  – Propellant Analysis Including Margins Analysis
    - Incomplete Due to Missing Analysis and Mission Design
      - TBD Thruster Back-Up for Solar Precession
      - TBD Orbit Insertion Error Contingency Plan
    - Presenting CSR Propellant Budget Instead
      - Close Approximation to Current Propellant Allocations

CSR Propellant Budget

Manuever	Prop Used (kg)
Initial Acquisition and Pointing	0.9
Spin-Up FAME With SRM	5.1
Active Nutation Control	2.0
Despin FAME With SRM	5.1
AKM Total Impulse Error (0.5%)	3.4
Jetison SRM and Adaptor	0.1
1 Deg AKM Pointing (i=.63 Deg) Error Correction	NA
Decrease Perigee by 300 km to Final GEO Orbit	1.3
Decrease Apogee by 300 km to Final GEO Orbit	1.3
North-South Station keeping	NA
E-W Station Keeping (for ± 1 Deg Longitude)	2.4
Spin-Up for Mission	0.2
5 Yr Mission ACS (All Thruster Precession)	7.3
Raise Apogee by 300 km to Deorbit	1.3
Raise Perigee by 300 km Miles to Deorbit	1.3
20 Mission Safe Hold Manuevers	3.4
2% Unusable Residual	2.2
25% Fuel Margin	12.6
Total	49.8

Issues (1 of 3)

- Schedule
  - Long Lead Time Procurements Are Required
    - Tank Delivery Is 24 Months for New Design and Qualification
      - Procurement Initiation By 2/15/01
    - Thrusters Delivery Is 20 Months
      - Procurement Initiation By 6/15/01
  - Major Procurements Are Required Before CDR (Sept 01)
    - Requires Early and Accurate Mission Design and Analysis
    - Requires Program Management Support
  - Expedited Procurement Process Will Be Required If Procurement Initiation Is Delayed
    - 180 Day Contracting Period Has Been Assumed
- Tank Selection and Procurement
  - Requires Additional Mission, Propulsion and ADCS Analysis To Be Completed Immediately (Preliminary by January 15, 2001)
    - Required to Complete Component Specification

Issues (2 of 3)

- Thruster Selection and Procurement
  - Requires Additional Mission, Propulsion and ADCS Analysis to Be Completed By April 1, 2001
    - Required to Complete Component Specification/s
    - Minimize Different Thruster Designs for Cost Efficiency (Specifications, Procurements, Integration, and Test Simplification)
- Possible Thruster Solar Precession Back-Up Requirement
  - Small Impulse Bit Control System Would Be Required
  - Additional Costs and Effort Above Previously Quoted for CSR
  - Requirement Evaluation and Definition Are Necessary by Feb 2001
    - Long Lead Items Are Required for Propulsive Implementation
      - 18 Months for the Tank
      - TBD Months for Pulsed Plasma Thruster
- Outstanding Analysis Are Critical for Tank and Thruster Procurements
  - Detailed Mission Analysis
    - Evaluate Staging Errors and Formulate Contingency Operations Plan
    - Develop Detailed Maneuver Plan

Issues (3 of 3)

- Investigate or Re-evaluate Orbit Insertion Options to Improve Margins
  - Delta II 2425-10 Additional Throw Capabilities
  - SRM Stage De- Orbit Options
  - Above GEO is CSR Baseline vs Below GEO With Staging Efficiency That Reduces Overall System Mass
- Optimize SRM Propellant Offload
  - Overfill and Offset Point for Desired Altitude
    - Additional Impulse Applied to Inclination Reduction
    - Reducing Tracking Antennae Travel Requirements
    - Approach Somewhat Limits Available SC Mass
- Perform ADCS Analysis Using Updated FAME Mass Properties
  - Propellant Budget Inputs Required for ADCS Maneuvers
    - Acquisition and Pointing, Spin-up, ANC, Spin Down
    - Attitude Control Required for SC Delta V Maneuvers
- Perform Detailed Thruster Sizing Analysis (All Mission Phases)
  - Vehicle Control Authority, Thruster Forces, and Impulse Bits