Design For Reusable Crewed Low Earth Orbit Transportation Vehicle

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Agenda

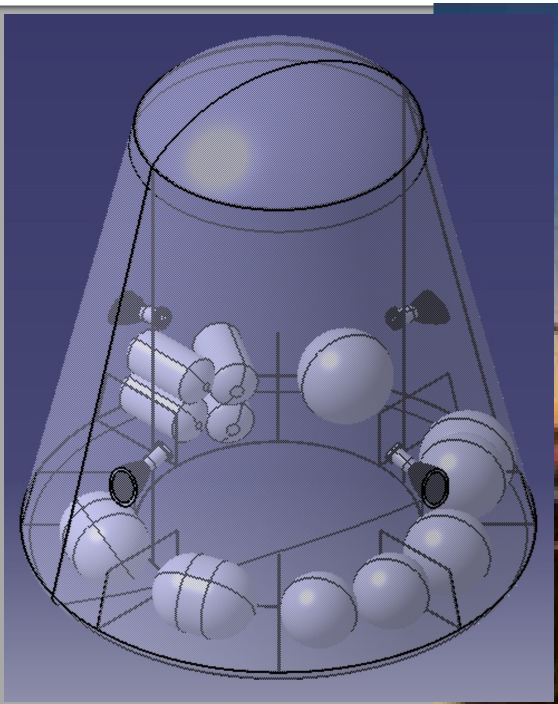
- Problem Description
- Vehicle Configuration
- Decision Making Methodology
- Concept of Operations
- Critical Technologies
- RLV Life Cycle Cost and Schedule

Problem Description

- Reusable Launch Vehicle (RLV)
- 10,000 to 20,000 Lbs to Low Earth Orbit
- 400 km circular orbit, 52 deg inclination
- Fleet lifetime of 20 years
- Reusable
  - Level of reusability not defined – trade studies
- Meet all FAA requirements

Vehicle Configuration

- 2 stage, LOX/RP-1, rocket vehicle
- 5 astronaut crew capsule (20 klbs)
- Launched from CCAFS
- Capsule landing in water
- Reusable 1st stage
- 2nd stage deorbit burn capability
- Capability to launch commercial satellites



Decision Making Methodology

- **Trade Studies performed for all critical system-level decisions**
- Studies Performed:
  - Land/Sea/Air Launch
  - Launch Location
  - Runway/Splashdown
  - Pad Configuration
  - Propellants
  - Number of Stages
  - Heat Shield Material
  - Abort System Configuration
  - Capsule Power System
  - Tank Insulation
  - Attitude Control System

- **Criteria used in trade studies:**
- Risk
- Feasibility
- Reusability
- Performance
- Cost
- Schedule
- Technology Readiness Level

- **Example on next slide**

Trade Study Example

- Landing Trade Study

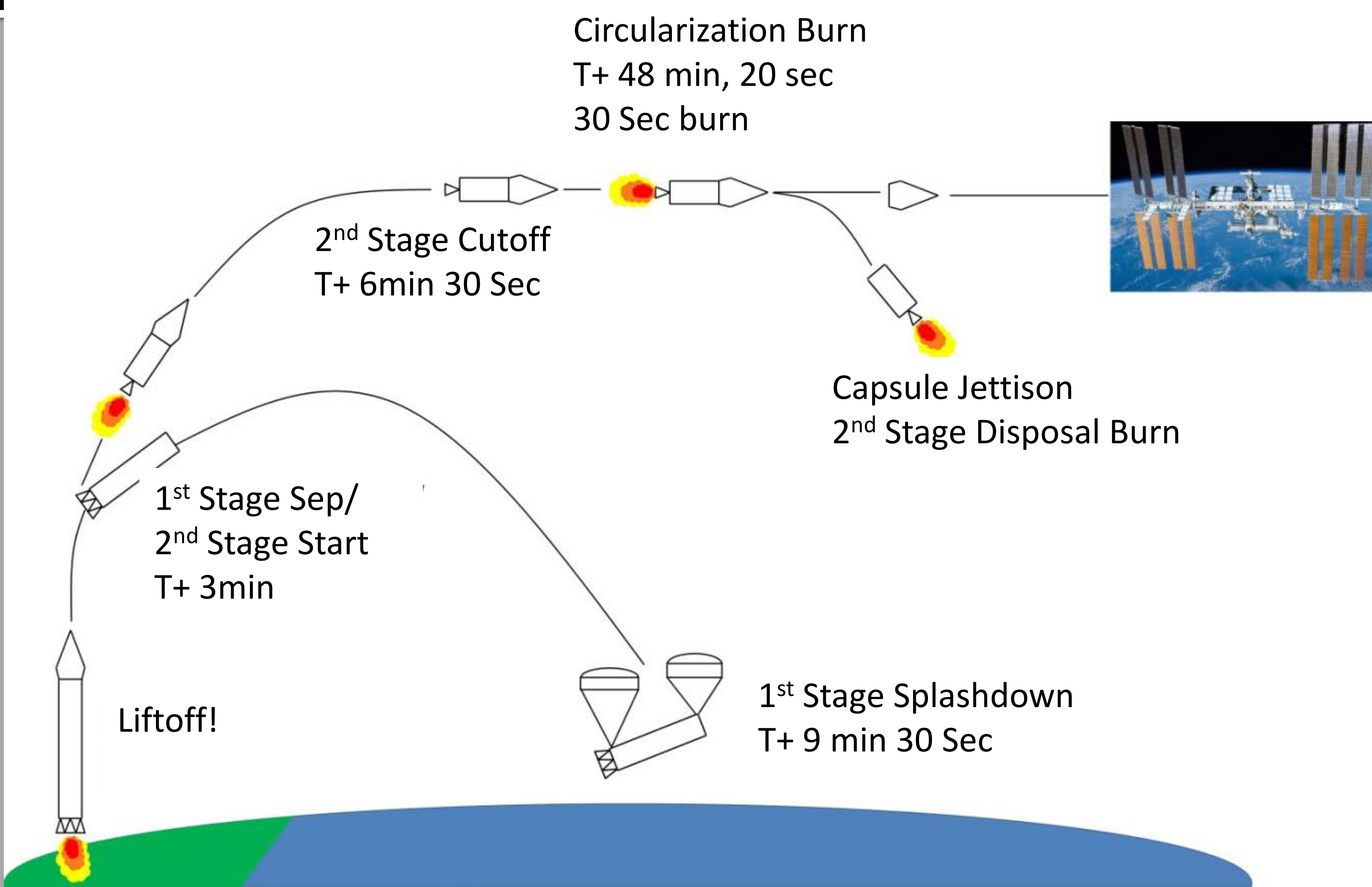
	Water Landing	Ground Landing	Powered, Runway	Unpowered, Runway
Landing Risk	5	1	2	1
Launch Risk	5	5	3	3
Feasibility	5	4	3	3
Reusability	3	4	3	4
Cost	3	5	3	4
Schedule	3	4	5	5
Tech Readiness Level	5	5	4	5
Total:	**29**	**28**	**23**	**25**

- Cost Breakdown

	Water Landing	Ground Landing	Powered, Runway	Unpowered, Runway
Vehicle Design/ Manufacture	4	4	2	3
Recovery/ Transportation Vehicle Purchase	1	4	2	2
Maintenance / Refurbishment	1	3	2	3
Transportation	3	4	2	2
Total:	**9**	**15**	**8**	**10**

- **Water Landing Chosen**

Launch Profile



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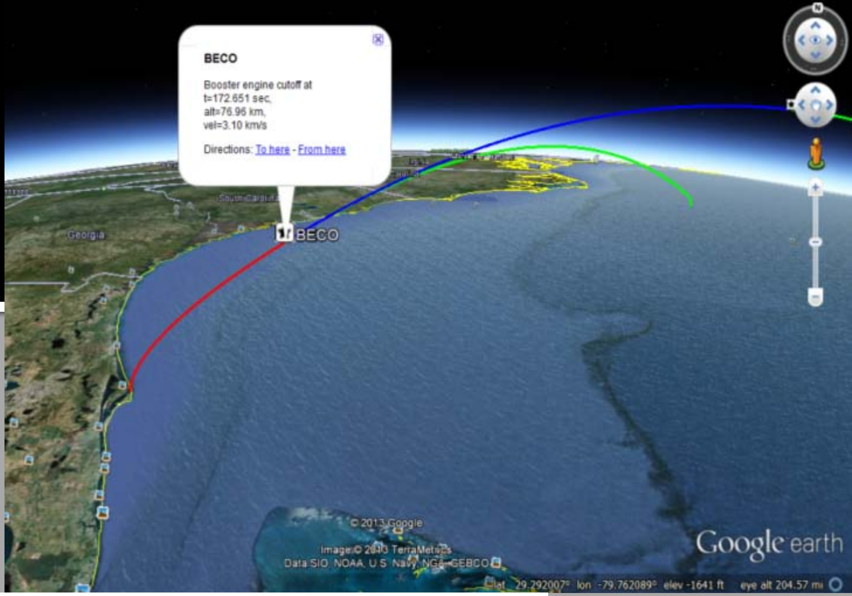
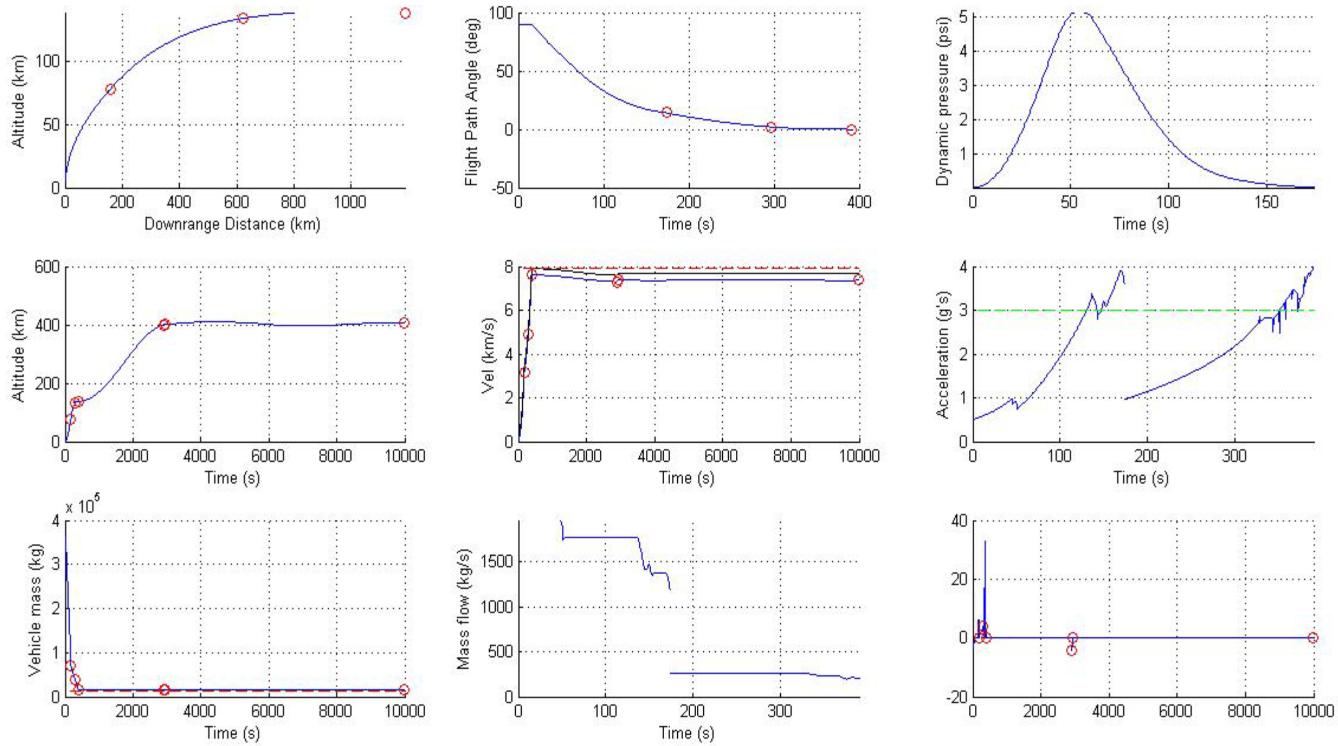
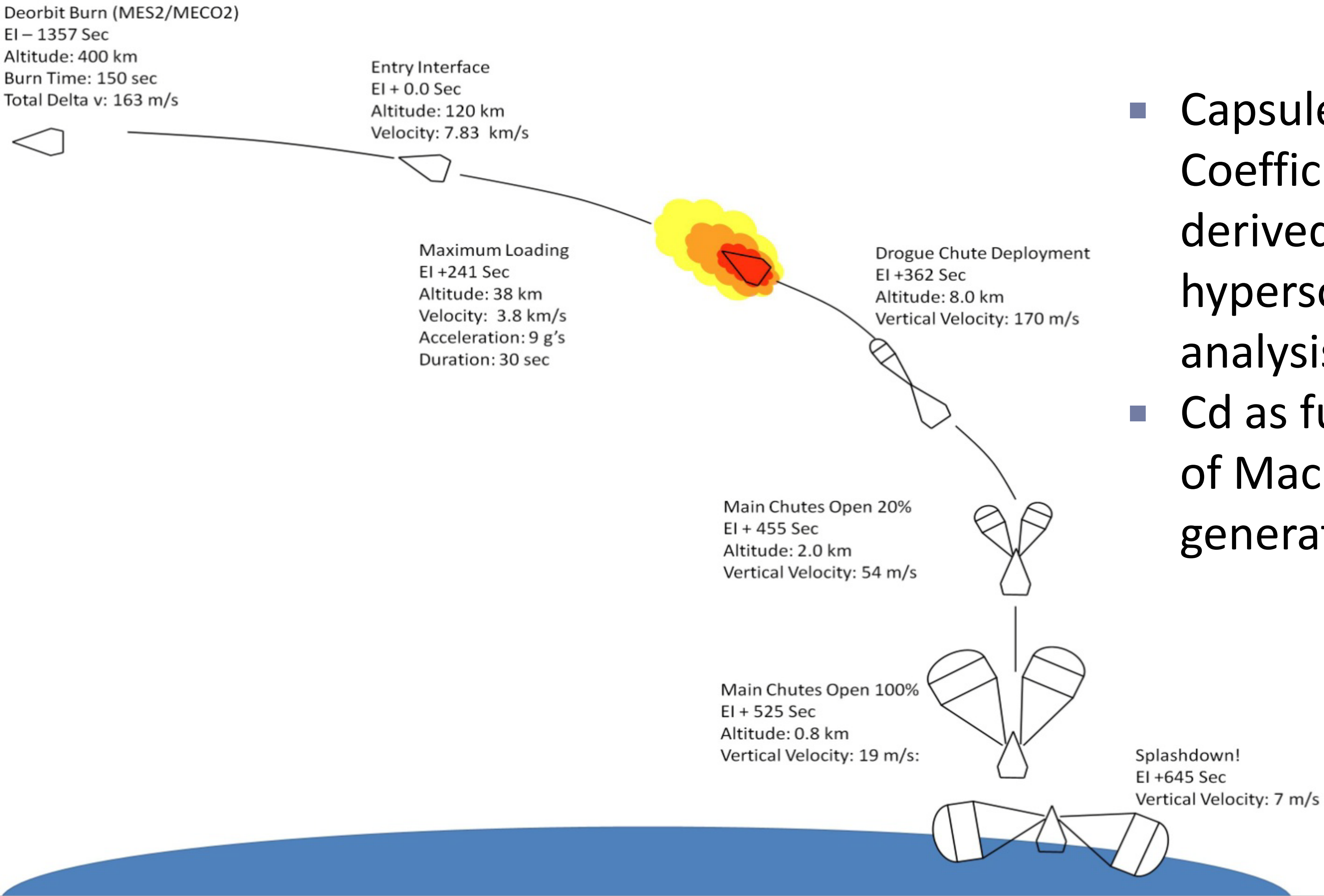
Trajectory Simulation

- 3 Degree of Freedom Simulation Using MATLAB
- Plotted over Google Earth





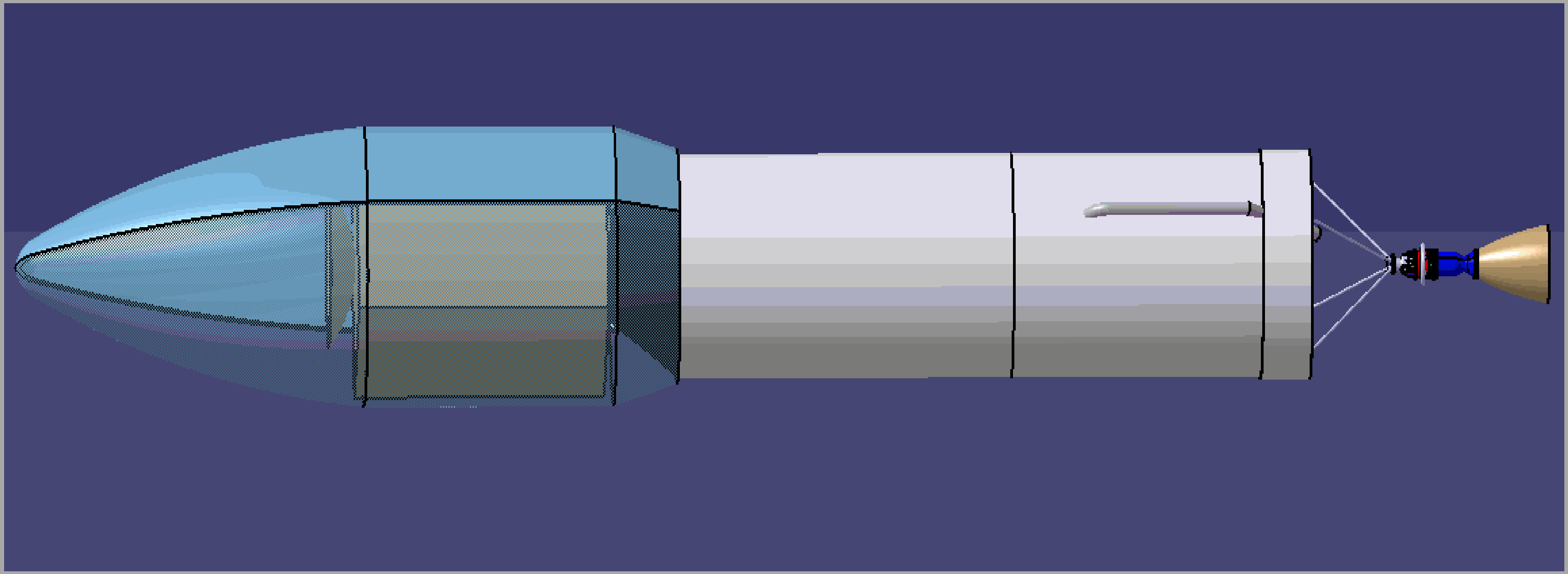
Reentry Profile



- Capsule Drag Coefficients derived from hypersonic CFD analysis
- Cd as function of Mach # generated

Commercial Payload Capability

- Composite Ogive fairing
- Composite Spacecraft adapter
- Increased marketability

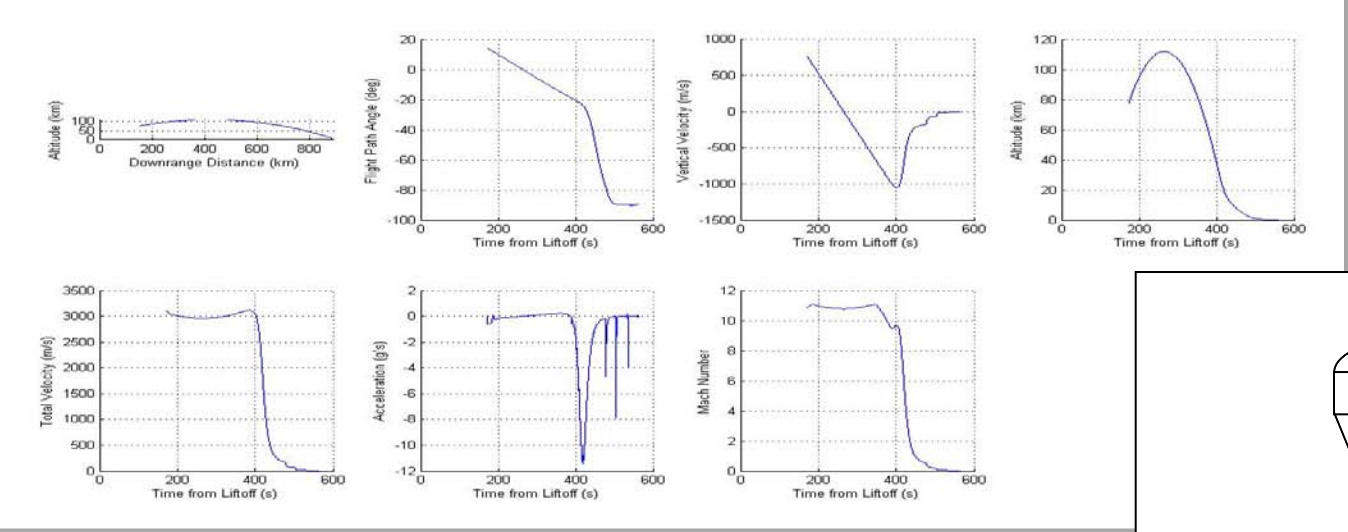


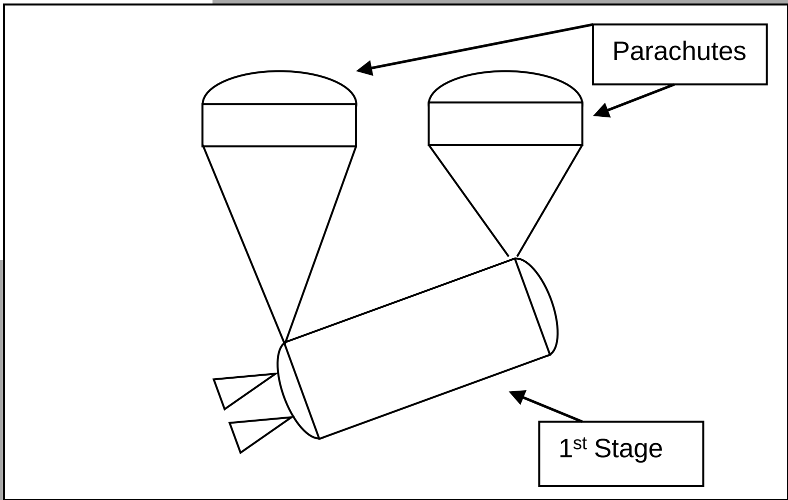
Critical Technologies

- 1^{st} Stage Recovery
- 2 Part polyurethane foam – 1^{st} stage engines
  - Protects copper combustion chamber from corrosion
- Large Phenolic Impregnated Carbon Ablator (PICA) Heat Shield
  - Current max size is 1.07 x 0.61 x 0.25 meters. We need 4.5 meter diameter.
- Orbital Maneuvering System (OMS) Engine Conical Injector
  - New Design
- Main Engine Pintle Injector
  - New Design

1st Stage Recovery

- Parachutes- 6x 40 m diameter Annular
- Simulation in MATLAB
- **Foam – 2 Part polyurethane foam – Critical Tech**





1st Stage Engine Protection

•26.75 cubic feet of expanded foam required

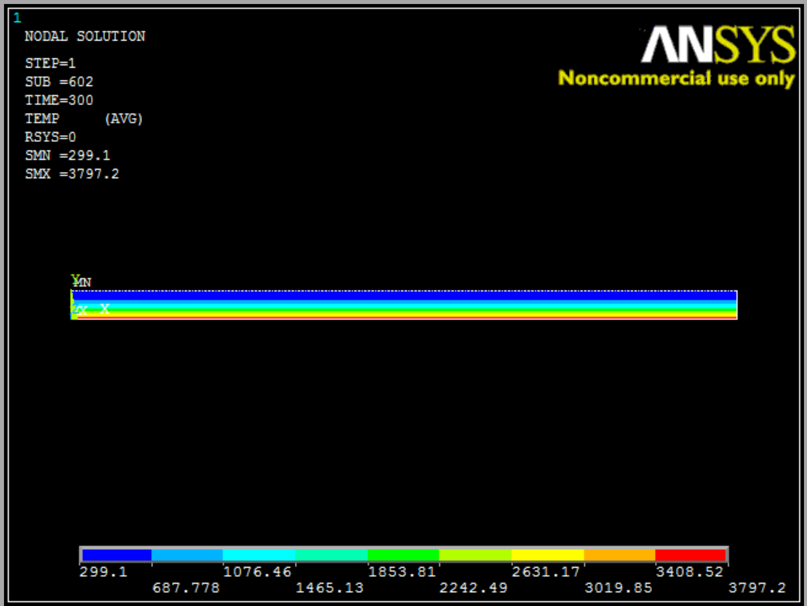
•Two tanks required then tubing to each engine

•Injection ports also used for chamber pressure ports

Total foam weight of
11.5 lbs
System weight of
50 lbs

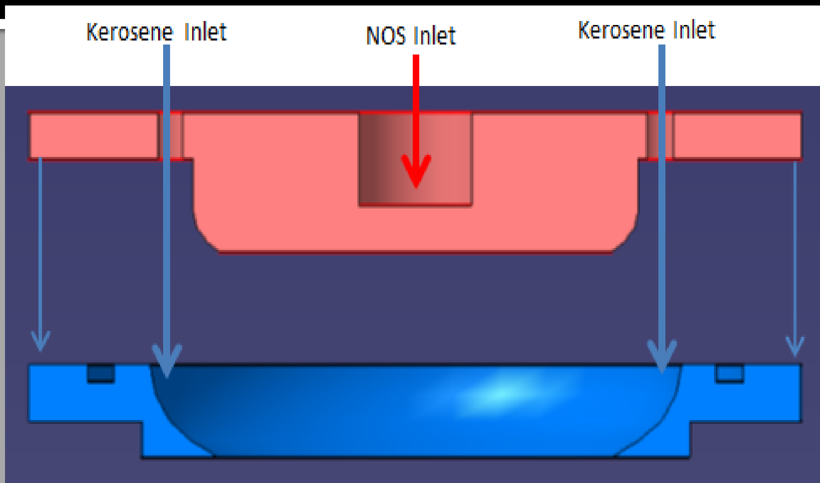
Capsule Thermal Protection System

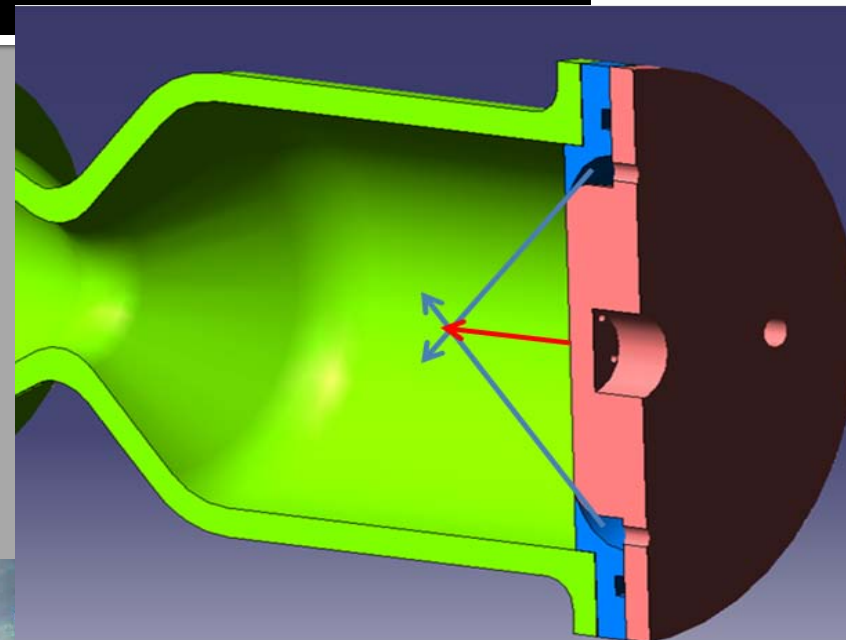
- Capsule Aft Body (Blunt Side):
  - **PICA – Critical Tech**
  - 2D Transient Thermal Analysis performed using ANSYS
- Capsule Fore Body (Tapered Side):
  - Toughened Unipiece Fibrous Insulation (TUFI)



	PICA	TUFI
Surface Area (m^2)	13.11	64.11
Thickness (m)	0.0624	-
Mass (kg)	220.7	134.0
	Total TPS Mass (kg)	354.7

OMS Injector

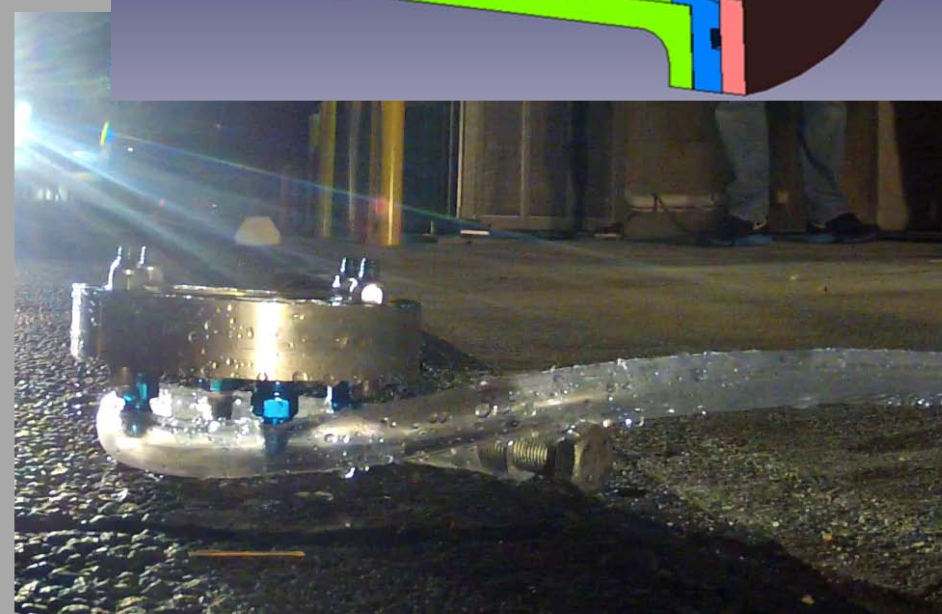




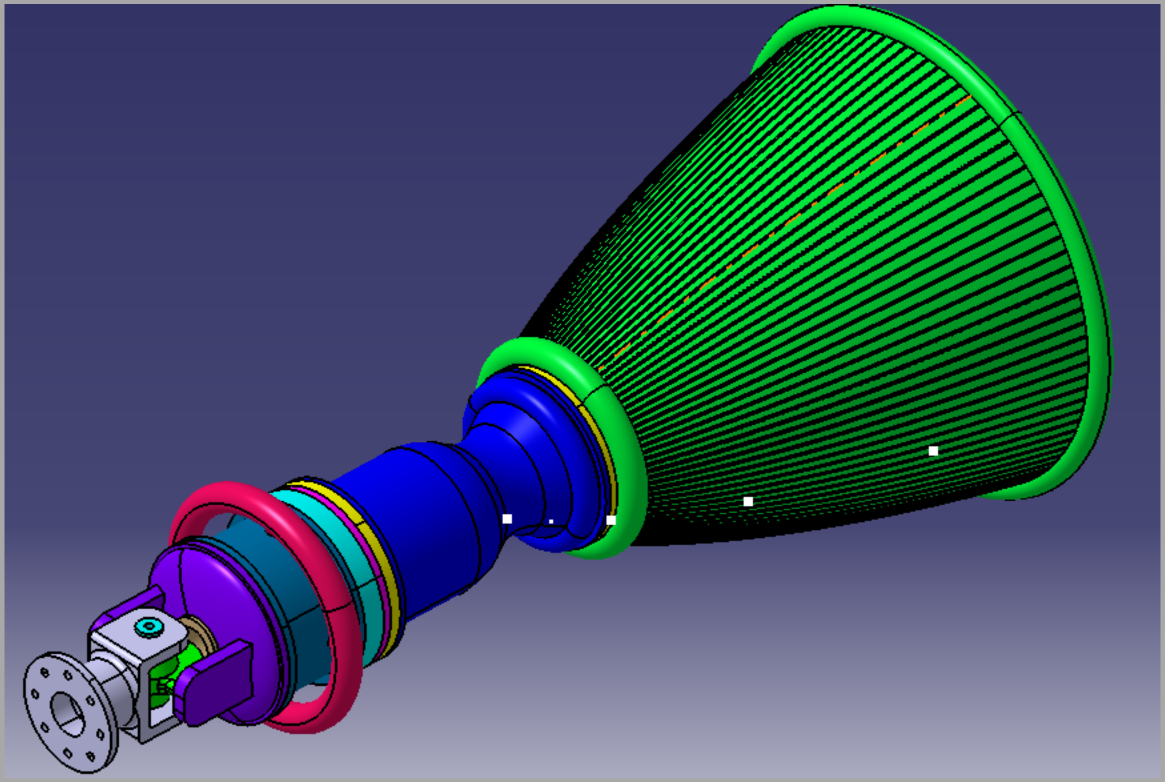
Kerosene/NO2 engine, 532 lbf Thrust

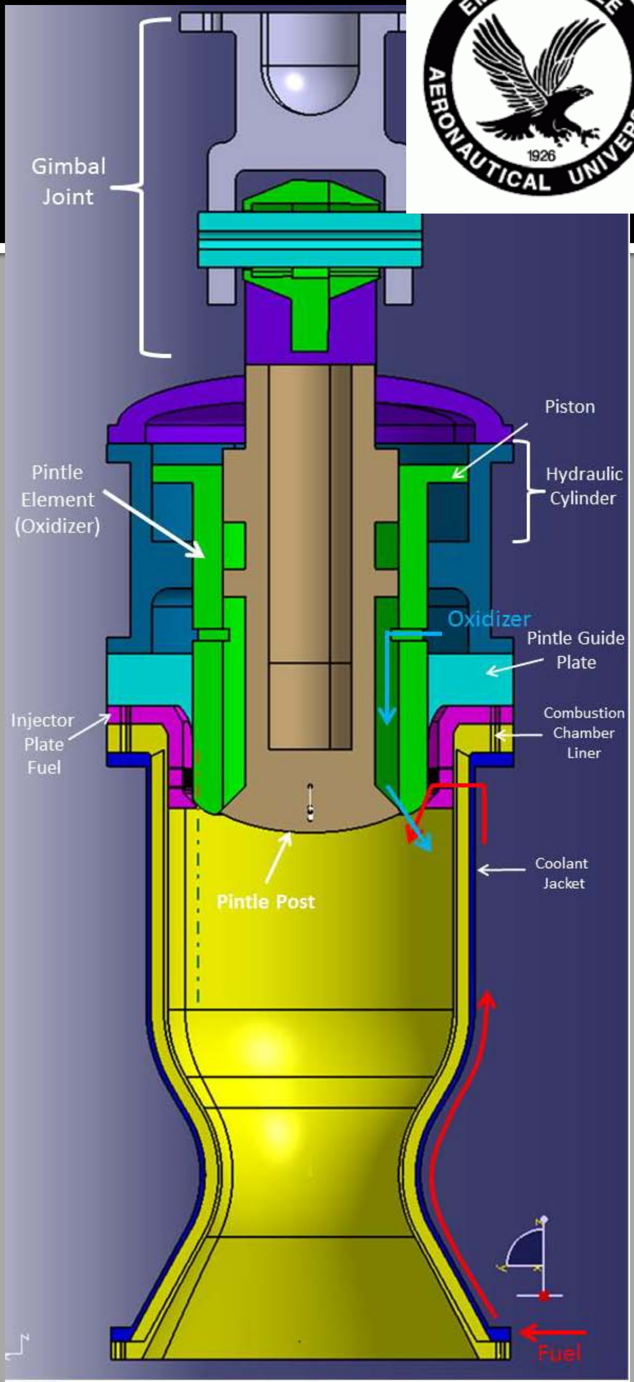
Brand New Injector Design:

- Conical Fuel Shape
- Relatively Simple to Manufacture
- Moves O/F mixing to center of chamber
- Test hardware built, cold flow testing finished



Main Engine





Gimbal Joint
Piston
Hydraulic Cylinder
Pintle Element (Oxidizer)
Oxidizer
Pintle Guide Plate
Injector Plate Fuel
Combustion Chamber Liner
Coolant Jacket
Pintle Post
Fuel

RLV Life Cycle Cost and Total Schedule

	Prototype	New Vehicle	Refurbished Vehicle
Cost	$16.5 million	$7.75 million	$4.05 million
Critical Path Method	1091 days (4.4 years)	263 days (1.06 years)	257 days (1.03 years)
Man-hours Method	910 days (3.7 years)	244 days (0.99 years)	156 days (0.63 years)

- Critical Path: Total time is time of longest subsystem * 1.5
- Man-hours: Total man-hours of all subsystems. Assume 80 workers, 8 hours per day, 248 work days per year

- Refurbished Vehicle turn-around time: 8 months
- Launch Rate: 14 launches per year (to be domestically competitive)
- Fleet size: 14-18 vehicles

Ground Facilities Cost and Schedule

- Includes GSE, launch control and mission control buildings

	Construction	**Operation (per launch)**
Cost	$15.7 million	$2.8 million
Critical Path Method	5.4 years	n/a
Man-hours Method	1.5 years	n/a

FAA Reusable Launch Vehicle (RLV) Permit

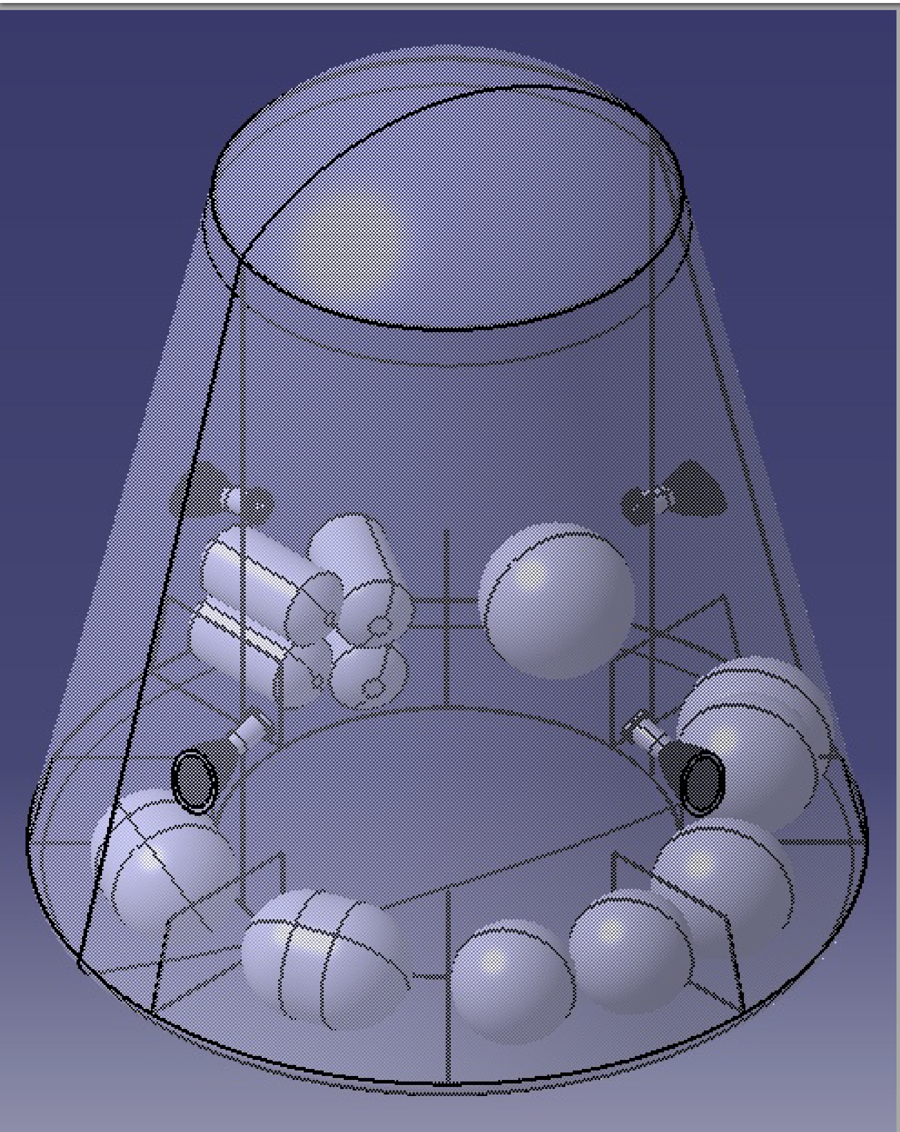
- Application Requirements
  - Policy Review
  - Safety Review
  - Payload Review
  - Financial Responsibility
  - Environmental Review
  - Compliance Monitoring
- FAA will make a determination within 180 days after submission

Hazards Assessments

Preliminary Hazards List Pre-Launch					
ID	Hazard	Causal Factors	Recommendations	Risk ID	Standards
1	RP1 Contamination	Leak during fuel transfer or storage	Proper handling and Storage Techiniques	3B	MSDS
2	Temperature Extreme	Unwanted contact with LOX	Proper handling and Storage Techniques, LOX fill as late in countdown as possibl	3E	
3	Injured Personnel	Dropped Hardware	Safe personnel placement and handling procedures	2E	
4	Damaged Flight Hardware	ground handling mishap	Proper handling procedures and GSE	2D	
5	Corrosion	Sea-Side locale	Hardware coating/corrosion control, frequent inspections	2B	
6	Fire	RP-1 Leak near ignition source	Avoid ignition sources near RP-1, leak detection system	1E	MSDS
7	Fire	LOX Leak near ignition source	Avoid ignition sources near LOX, leak detection system	1E	MSDS
8	Explosion	Lox check valve malfunction	Redundant check valves	2E	
9	Explosion	COPV Failure	Proper pressurant monitoring and anomaly warning	2E	MSDS
10	Hypergol Contamination (Personnel)	Spacecraft Handling Mishap	Proper Personal Protective Equipment(PPE)/Handling	2E	
11	Loss of Habitable Atmosphere	Crew module life support fails	Redundant systems/Accessible escape path	1E	
12	Injured Personnel	Personnel exposed to nitrogen purged area	Proper signage and PPE	3D	
13	Injured Personnel	Falling from assembly building access pads	Proper railings and PPE	1E	
14	Injured Personnel	Crushed appendages during stage and payload mate	Safe personnel placement and handling procedures	3C	
15	Corrosion	LOX contact with groud support and flight hardware	Proper handling and Storage Techniques/hardware coatings	3D	
16	Explosion	Hypergol tanking mishap	Proper handling and Storage Techniques/hardware coatings	1E	MSDS

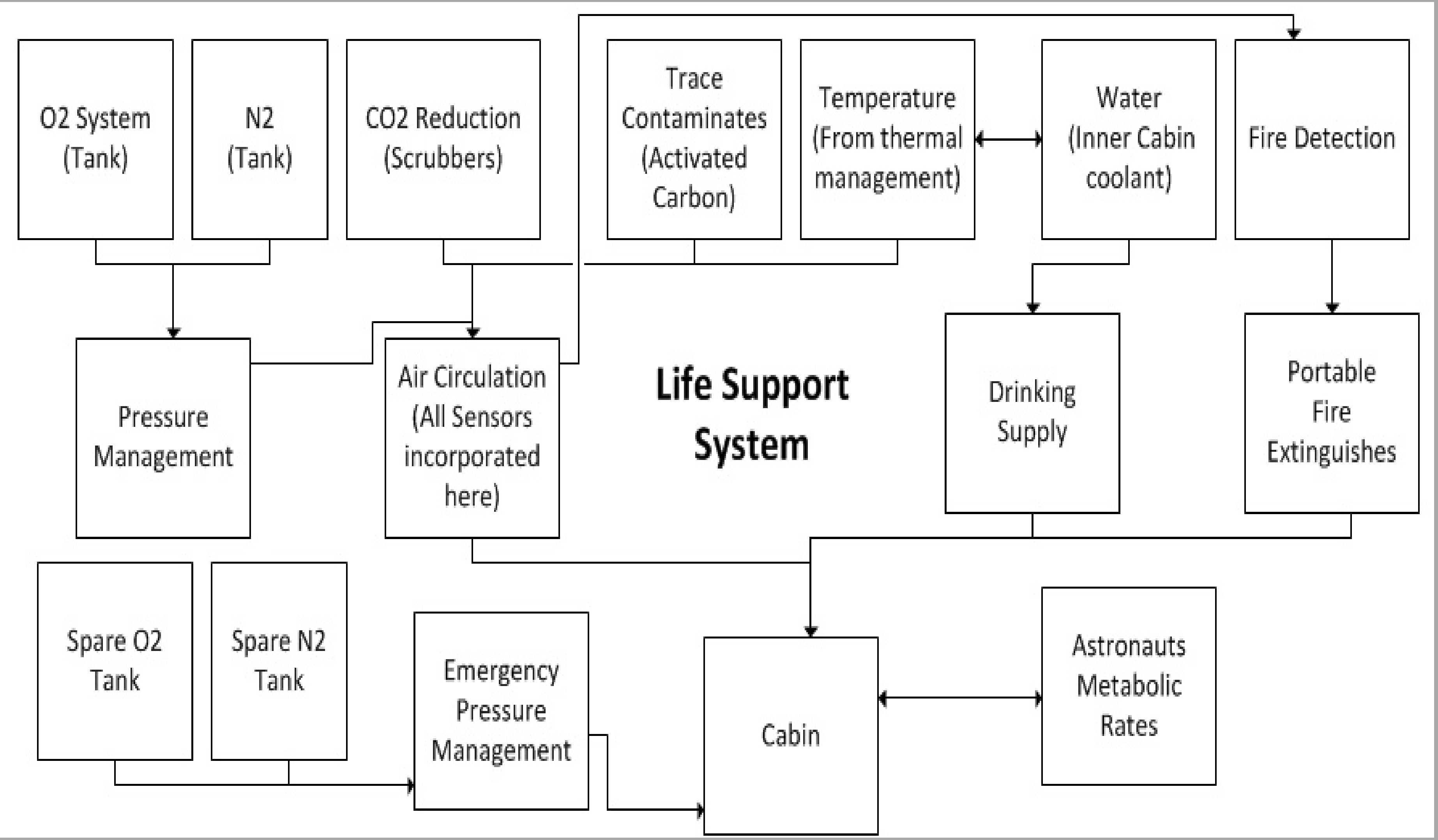
Preliminary Hazards List Launch					
ID	Hazard	Causal Factors	Recommendations	Risk ID	Standards
17	Fire	Liftoff plume damages pad hardware	Water supression system and plume mititgation (flame trench)	3C	
18	Loss of Vehicle	Main engine failure	Redundant engine components (engine out capability)	1E	
19	Loss of Vehicle	Second Stage engine failure	Redundant engine components	1E	
20	Fuel Tank Structural Failure	Greater-than anticipated flight angle of attack	Robust Control algorithms	1E	
21	Oxidizer tank failure	Poor material properties	Quality control	1E	
22	Oxidizer tank failure	LOX vent malfunction	Redundant check valves	1E	
23	Explosion	vehicle diverts from preplanned trajectory(remote destruct)	Robust Control algorithms, well designed trajectory, launch over ocean	1E	
24	Personnel Injury	Anomaly shortly after liftoff	Safe personnel placement, PPE	1E	
25	Damaged Hardware	Anomaly shortly after liftoff	Proper hardware storage and protection	1E	
26	Fire	"Pad drift" burns area surrounding pad	Water supression, obey wind placards	3C	
27	Loss of Crew	Main engine failure	Launch abort system, Redundant engine components	1E	
28	Loss of Crew	Upper Stage engine failure	Launch abort system, Redundant engine components	1E	
29	Mission Failure	Failed Booster Staging	Redundant staging mechanisms	1E	
30	Mission Failure	Failed upper stage ignition	Redundant engine components	1E	
31	Mission Failure	Failed payload separation	Redundant seperation mechanisms	1E	
32	Mission Failure	Off-Nominal payload insertion orbit	Robust Control algorithms/ calculated fuel margins	1E	
33	Loss of Spent Booster	Recovery System Failure	Robust Control algorithms/ redundant recovery components	2E	

Capsule



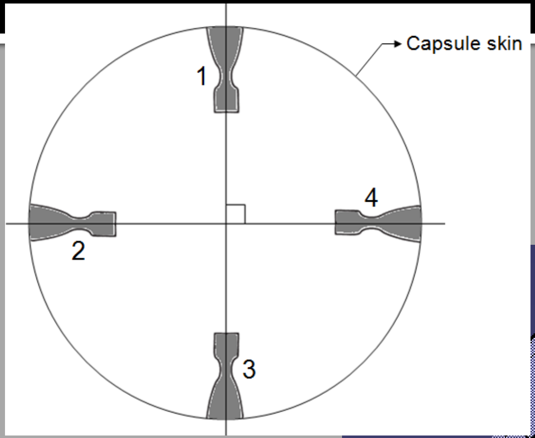
Material	7075 aluminum
Internal Pressure	101 kPa
Reentry Loading	723 kPa
Parachute Loading	1337 kN
Landing Loading	909 kN
Helium Req	45 kg

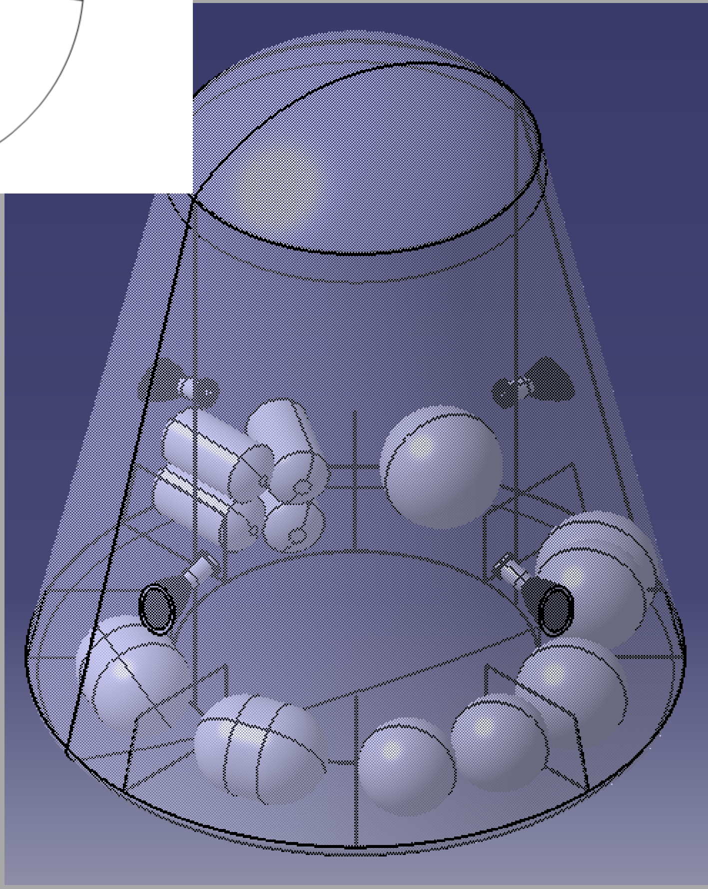
Life Support System



OMS Engines

- Ablative Cooling
- 4 Flush Mounted engines
- FUEL - T-1 grade Kerosene
- OX - Nitrous Oxide (N_2O)
- O/F: 2.56
- **New conical Injector Design – Critical Tech**



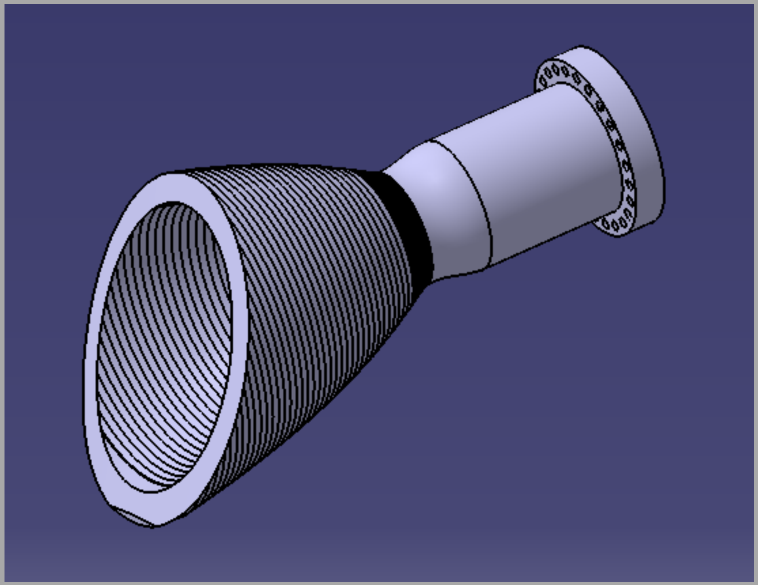


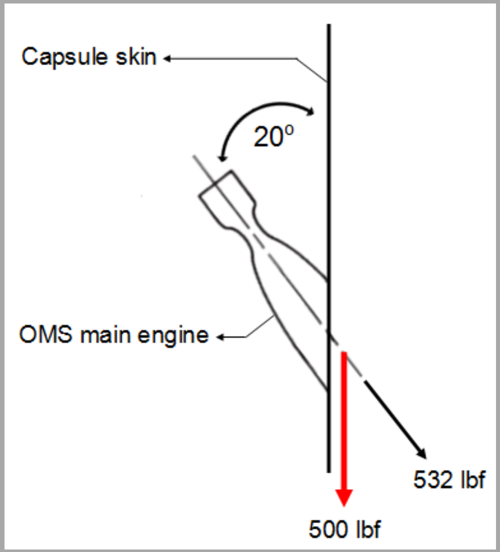
Parameter	Value (English)	Value (Metric)
Thrust at vacuum	532 lbf	2366 N
Maximum burn time	57 s	57 s
Isp at vacuum	282 s	282 s
Oxidizer Mass Flow	1.36 lbm/s	0.618 kg/s
Fuel Mass Flow	0.534 lbm/s	0.242 kg/s
Area Expansion Ratio	25	25
Chamber Pressure	700 psi	4.83 MPa

OMS Nozzle Scarf

Flush Mounted Nozzle:

- Highly underexpanded in vacuum
- Nonsymmetrical pressure distribution
- 20^o scarf angle
- 0.283 psi from nozzle lower lip





OMS Engine Cooling

Ablative carbon-phenolic composite:

- T800H carbon fiber (60%)
- Borofen DX30 phenol-phormaldehide resin (40%)
- 14.6% weight loss during 30s 773K exposure
- 3670K for 90s, safety factor of 1.5
- Supported by silica cloth phenolic

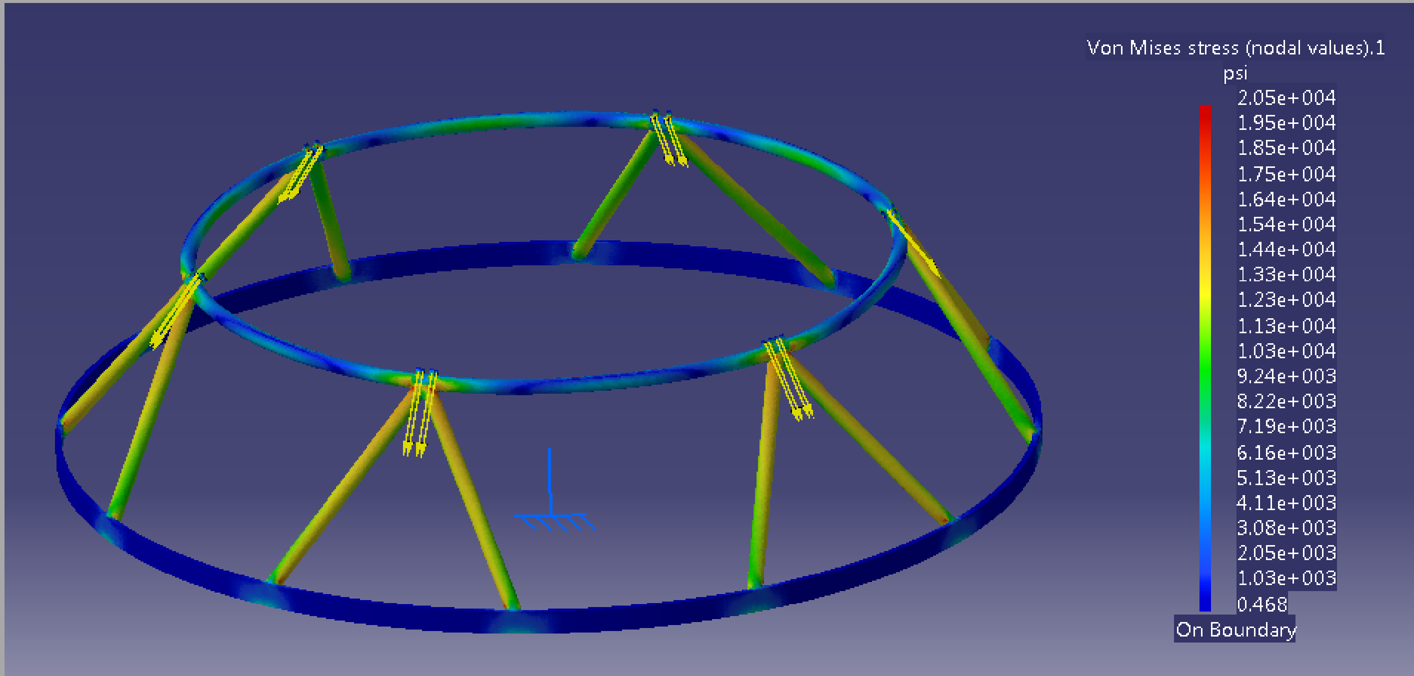
Parameter	Value
Thickness	9 mm
Fiber strand width	25 mm
Flexural Strength	247 MPa
Young's Modulus	27.5 GPa

Abort Truss Structure

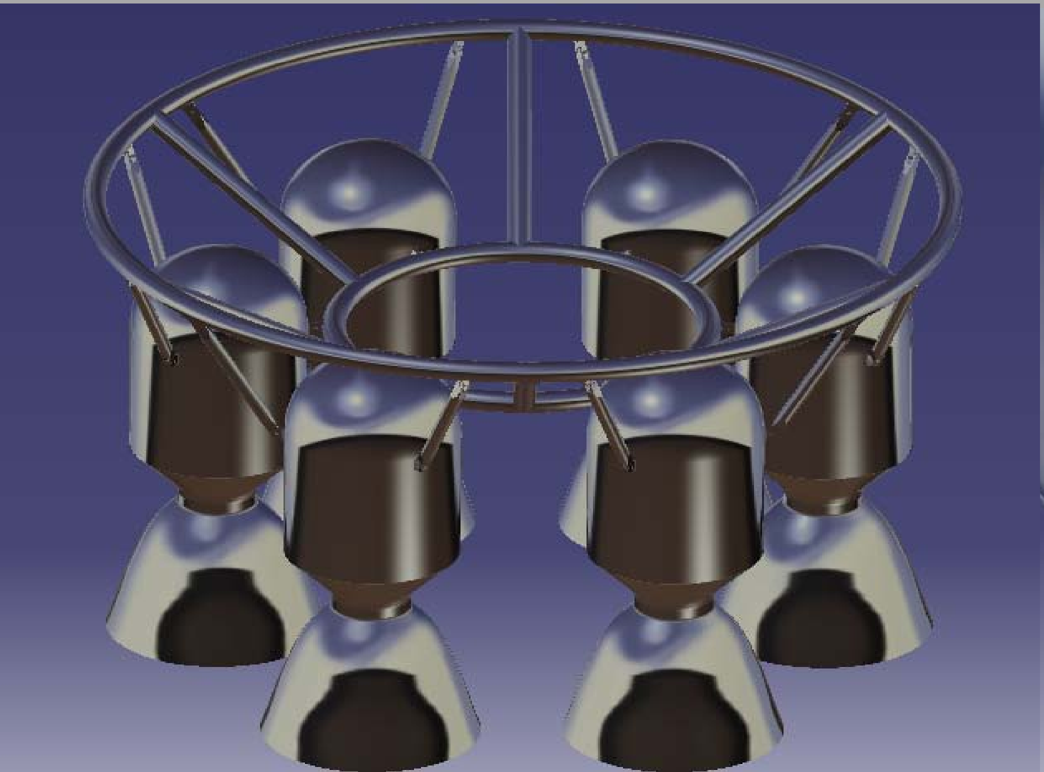
- Requirements
  - Support the load of the six abort motors in the event of abort.
  - Separate from spacecraft at MECO 2
- Design
  - Tapering truss structure similar to the SPA
  - Cradles the spacecraft at the same six points as the SCA
  - Constructed from 7075 aluminum
  - Members are 2.5 inches in diameter and .125 inch wall thickness
  - The motors will be joined to the truss by two struts and the inner truss ring

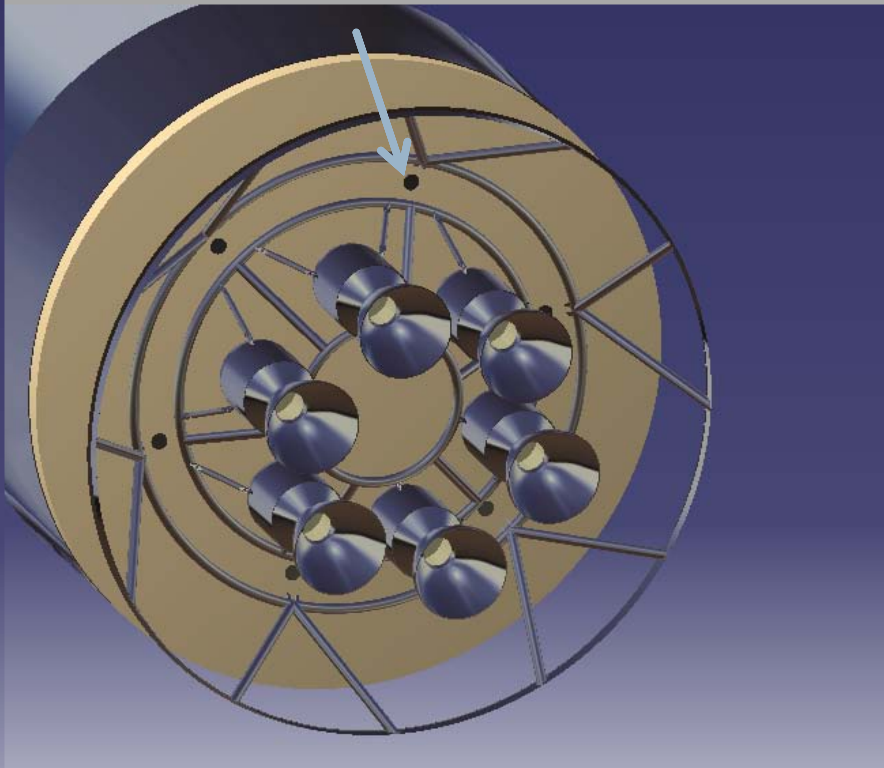
Spacecraft Adapter

- Constructed from 7075 aluminum
- 6 Point attachment to spacecraft
- Explosive Bolt Separation
- Designed using CATIA FEA



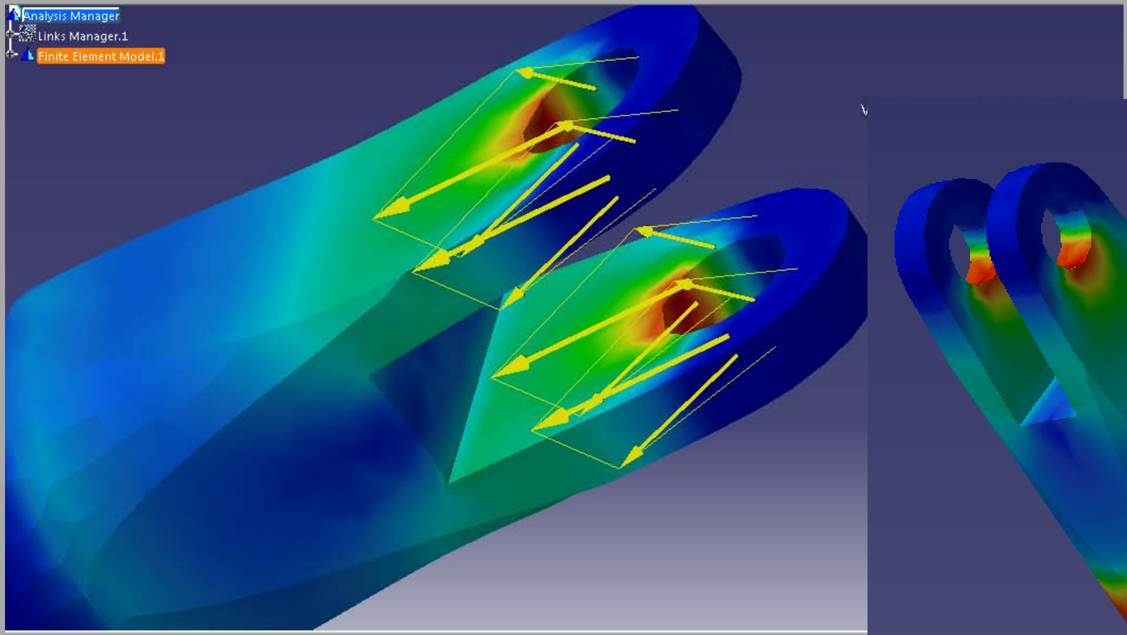
Spacecraft Adapter

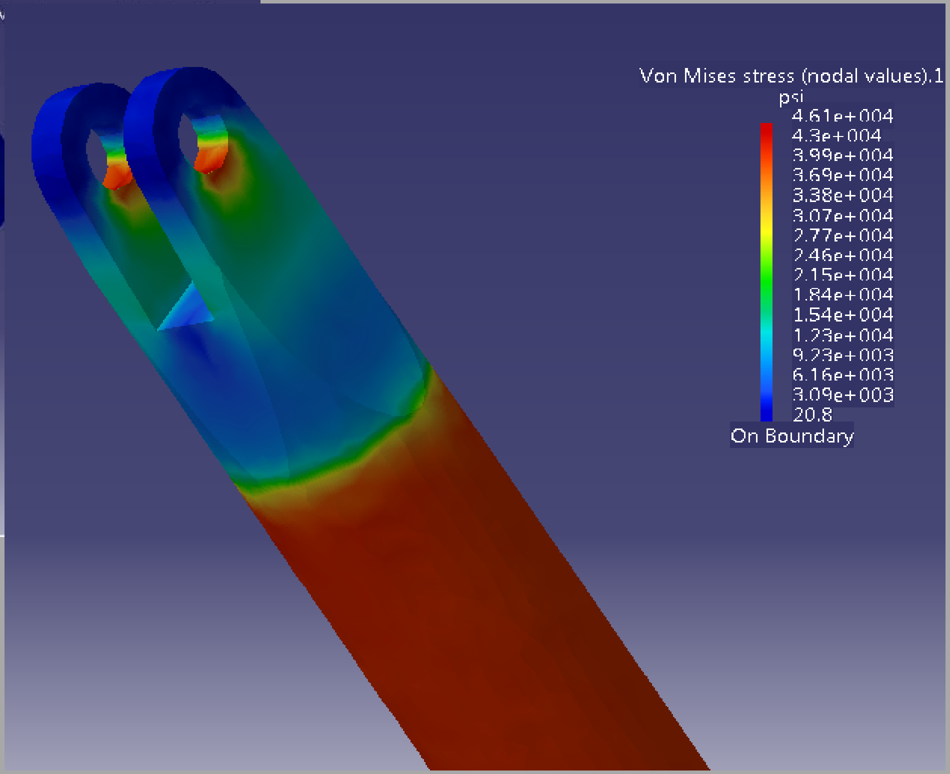




FEA

Maximum Von Mises Stress 46.1 ksi





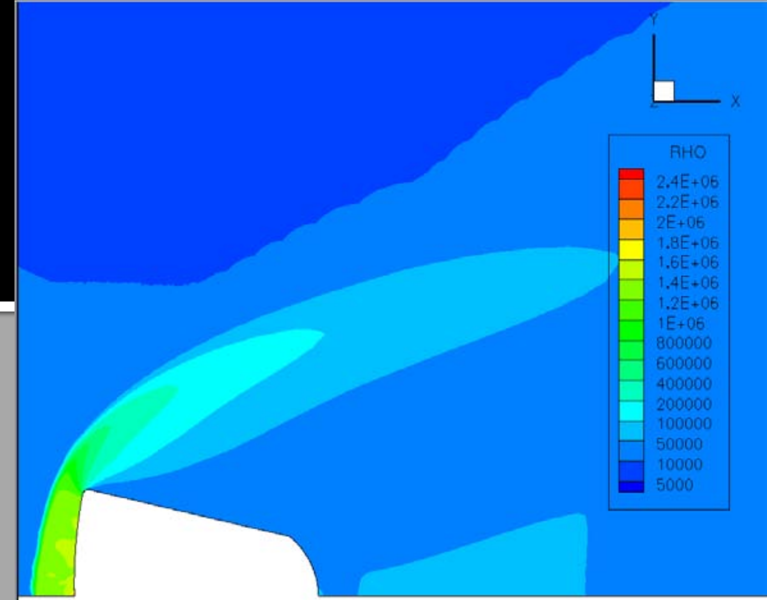
Parachute Sizing Tool

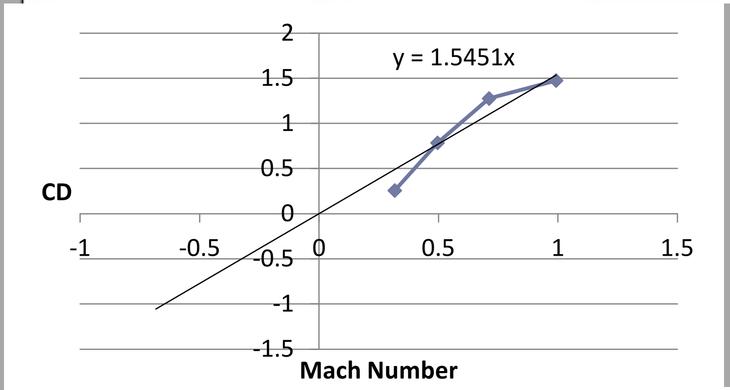
- Annular Parachute (CD=1.0)
- 8 m/s terminal velocity if 1 parachute fails
- 45 g/m^2

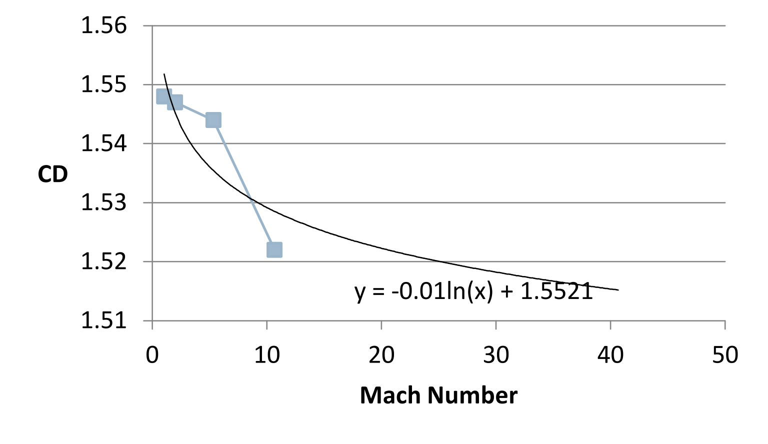
$$d = \sqrt{\frac{8m \cdot g_0}{\pi n \rho_{air} C_D v_{term}^2}}$$

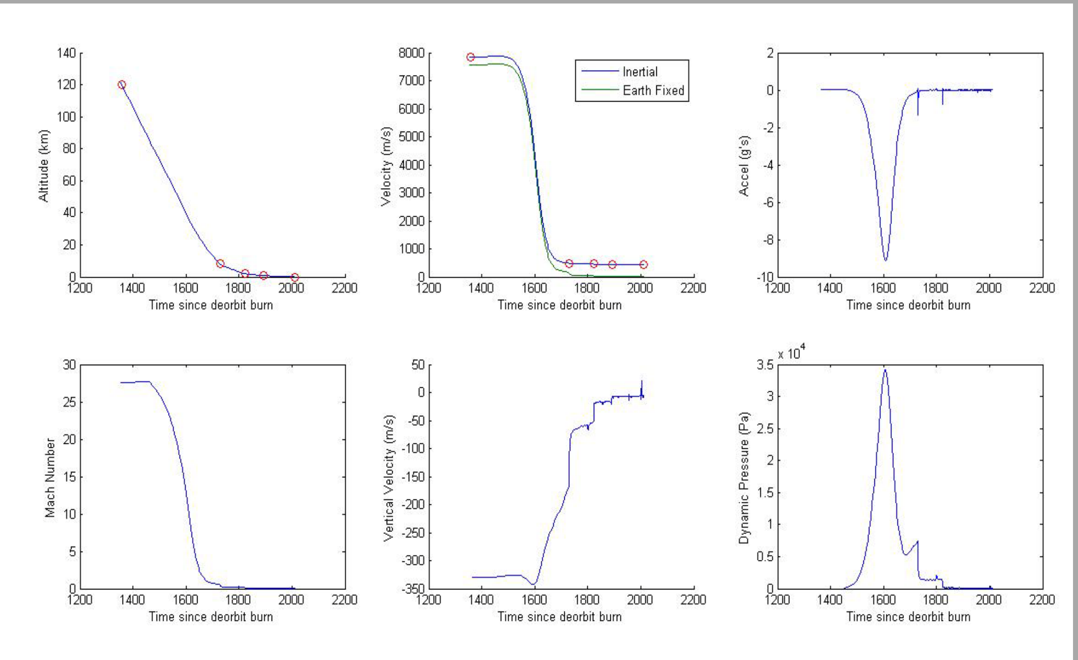
Reentry Simulation

- Hypersonic CFD code used to generate Cd curve fits
- Simulation run in MATLAB









Battery Cell Selection

- Off the shelf selection
  - SAFT Batteries VES 180
  - Li-ion Battery Cell

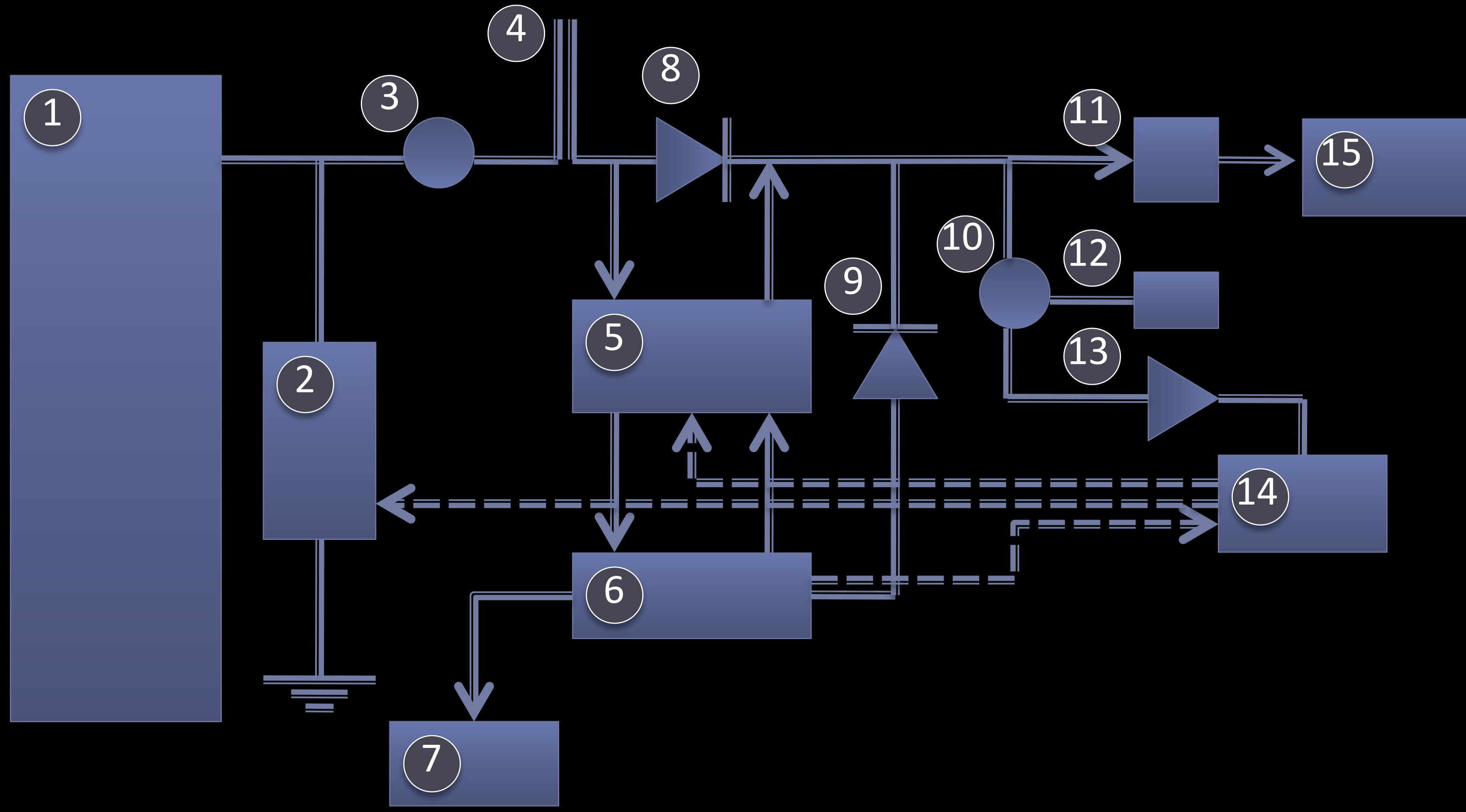
http://www.saftbatteries.com/images/Produits/Photos/VES.jpg

Battery Sizing and Thermal Output

- Required energy of 3000 Watt-hours
- Battery mass estimate
  - 84 VES 180 cells
  - 86 kg mass
- Battery Thermal Output
  - Per cell output of 0.6 Watts
  - 50 Watts thermal output of system

Solar Array Sizing

- Designed at EOL conditions
- 37 m^2 solar array area
- 18.5 m^2 area for each array
- Dimensions estimate
  - 2.5 x 7.4 meters
  - 8.22 x 24.34 ft
- Upon reentry solar arrays jettison from capsule



1. Solar Array
2. Shunt Regulator
3. Solar Array Drive
4. Ground Power Umbilical
5. Power Regulator Unit
6. Battery
7. Battery Bus
8. d(2)
9. d(4)
10. Bus Sense
11. Power Distribution Unit
12. V_{REF} Signal
13. Error Signal
14. Mode Controller
15. Loads

Booster Stage Engine Specifications

Engine Specifications	
Thrust (Vac.) (lb)	297583
Thrust (SL) (lb)	281620
I_{sp} (Vac.) (s)	344
I_{sp} (SL) (s)	325
Chamber Pressure	2300

Engine Weight Estimations (lb)	
Engine Assembly w/ gimbal	2230
Actuators (2)	160
Hardware	120

Critical Dimensions (in)	
Axial length of nozzle from throat to exit plane	56.22
Chamber characteristic length	87.75
Chamber diameter	15.32
Nozzle diameter	54.57
Throat diameter	9.50

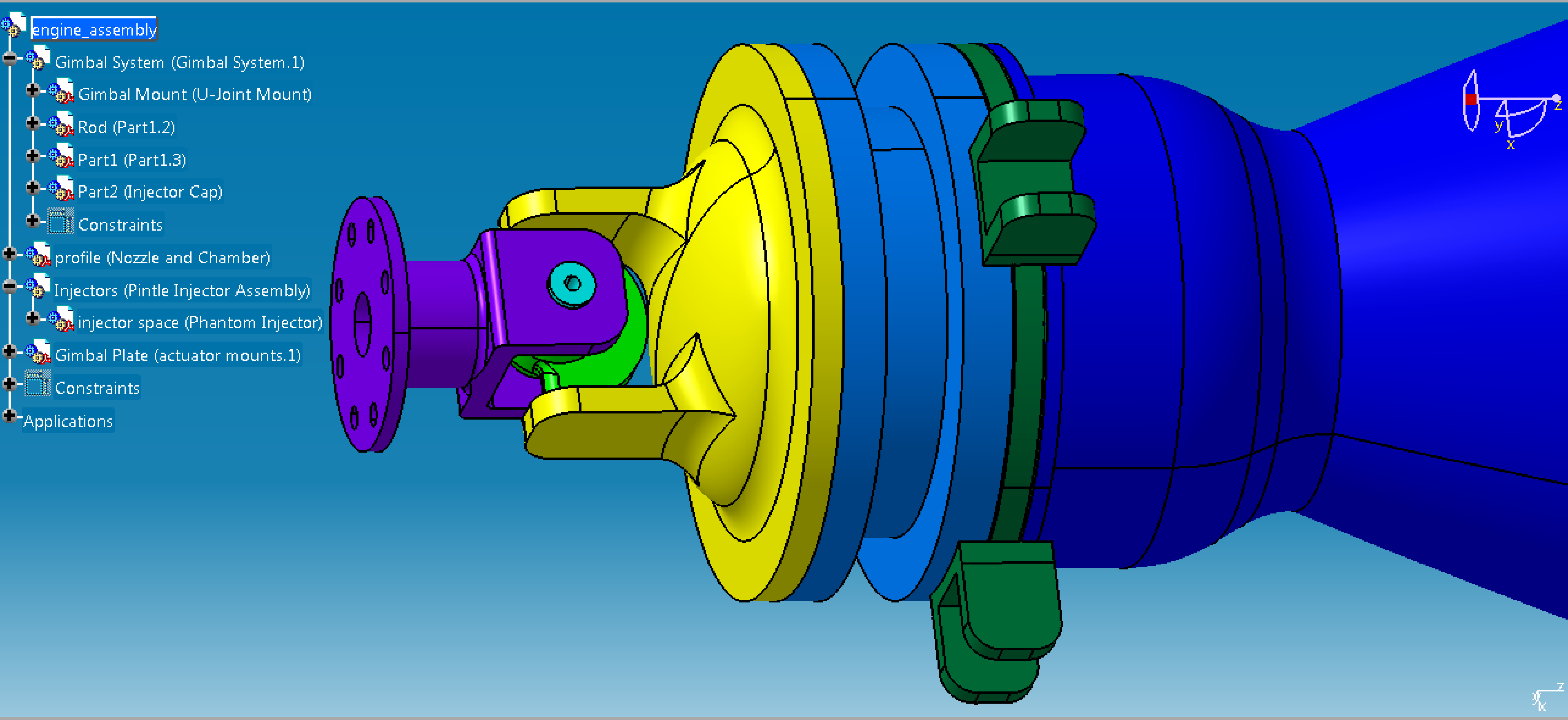
2^{nd} Stage Engine Specifications

Engine Specifications	
Thrust (Vac.) (lb)	206567
I_{sp} (Vac.) (s)	340
Chamber Pressure	2300

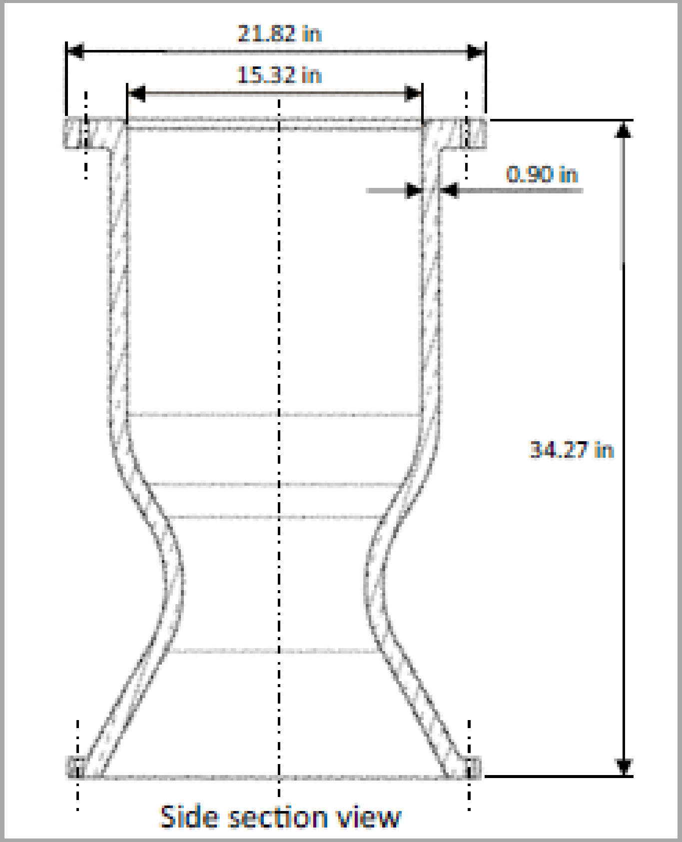
Engine Weight Estimations (lb)	
Engine Assembly w/ gimbal	1500
Actuators (2)	160
Hardware	120

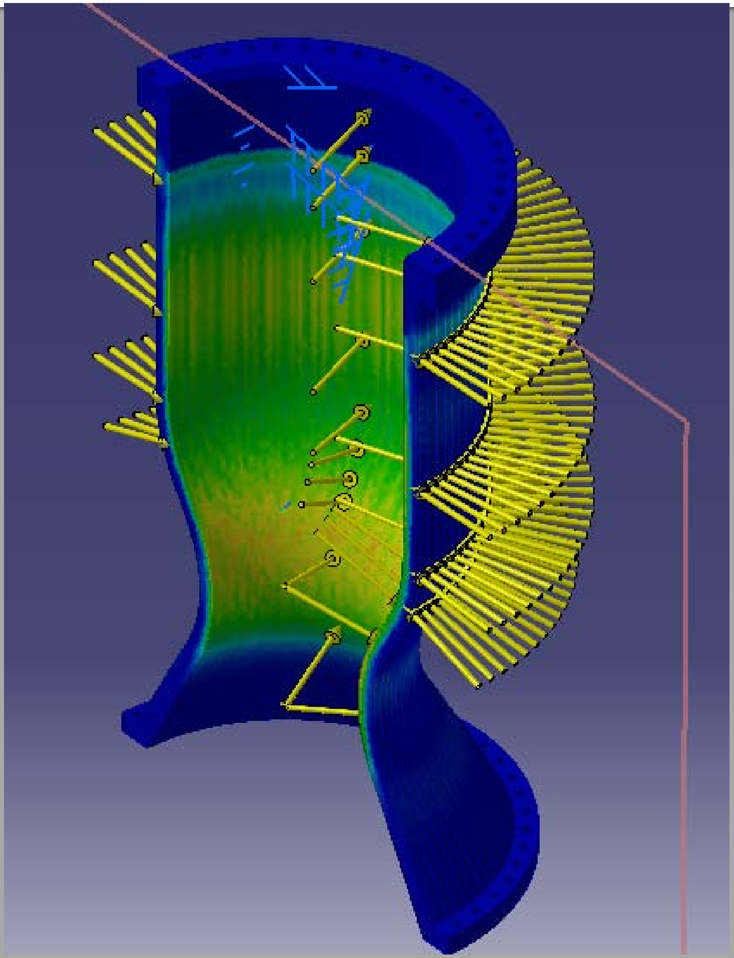
Critical Dimensions (in)	
Axial length of nozzle from throat to exit plane	56.22
Chamber characteristic length	45.00
Chamber diameter	12.76
Nozzle diameter	45.47
Throat diameter	7.91

Gimbal

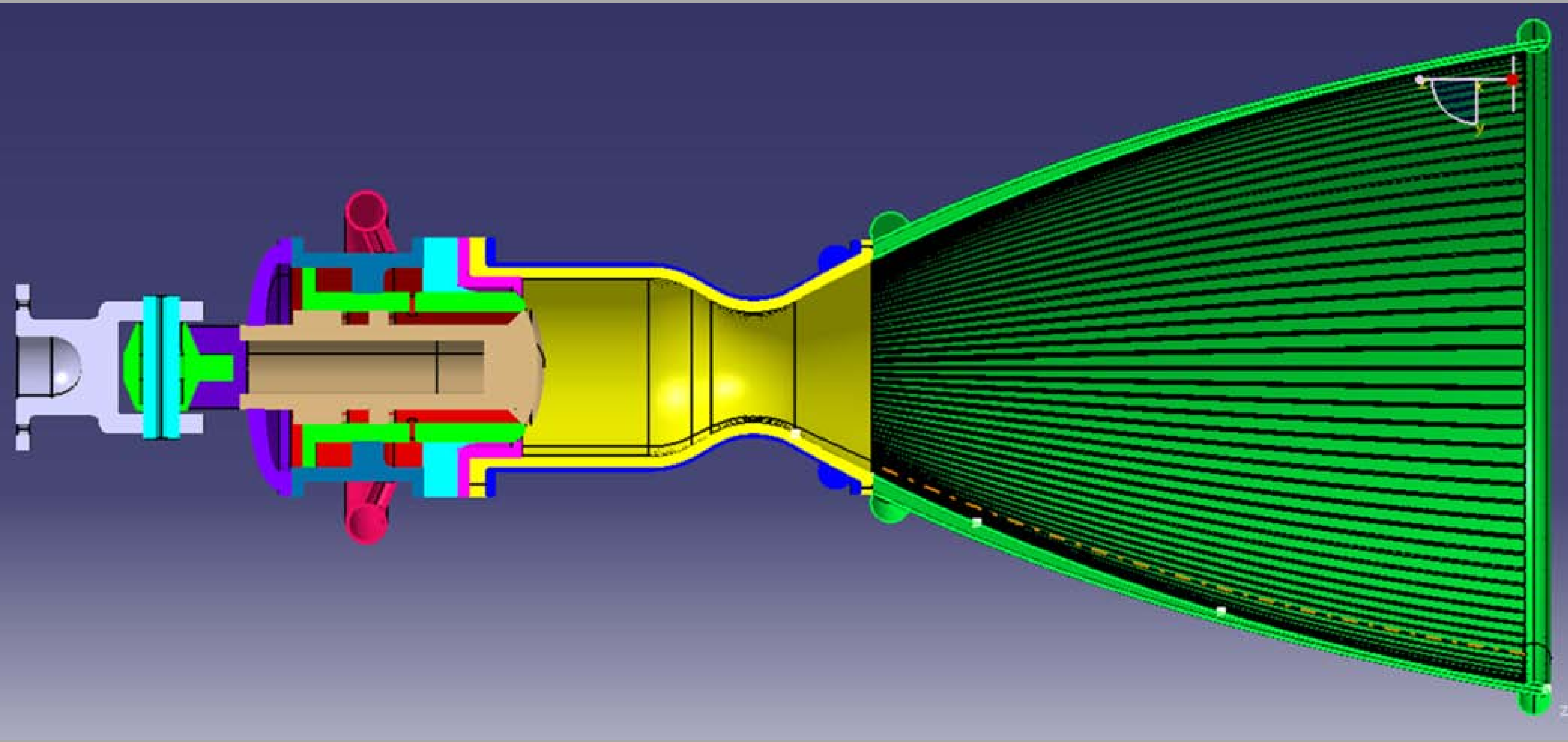

engine_assembly
Gimbal System (Gimbal System.1)
Gimbal Mount (U-Joint Mount)
Rod (Part1.2)
Part1 (Part1.3)
Part2 (Injector Cap)
Constraints
profile (Nozzle and Chamber)
Injectors (Pintle Injector Assembly)
injector space (Phantom Injector)
Gimbal Plate (actuator mounts.1)
Constraints
Applications

Combustion Chamber

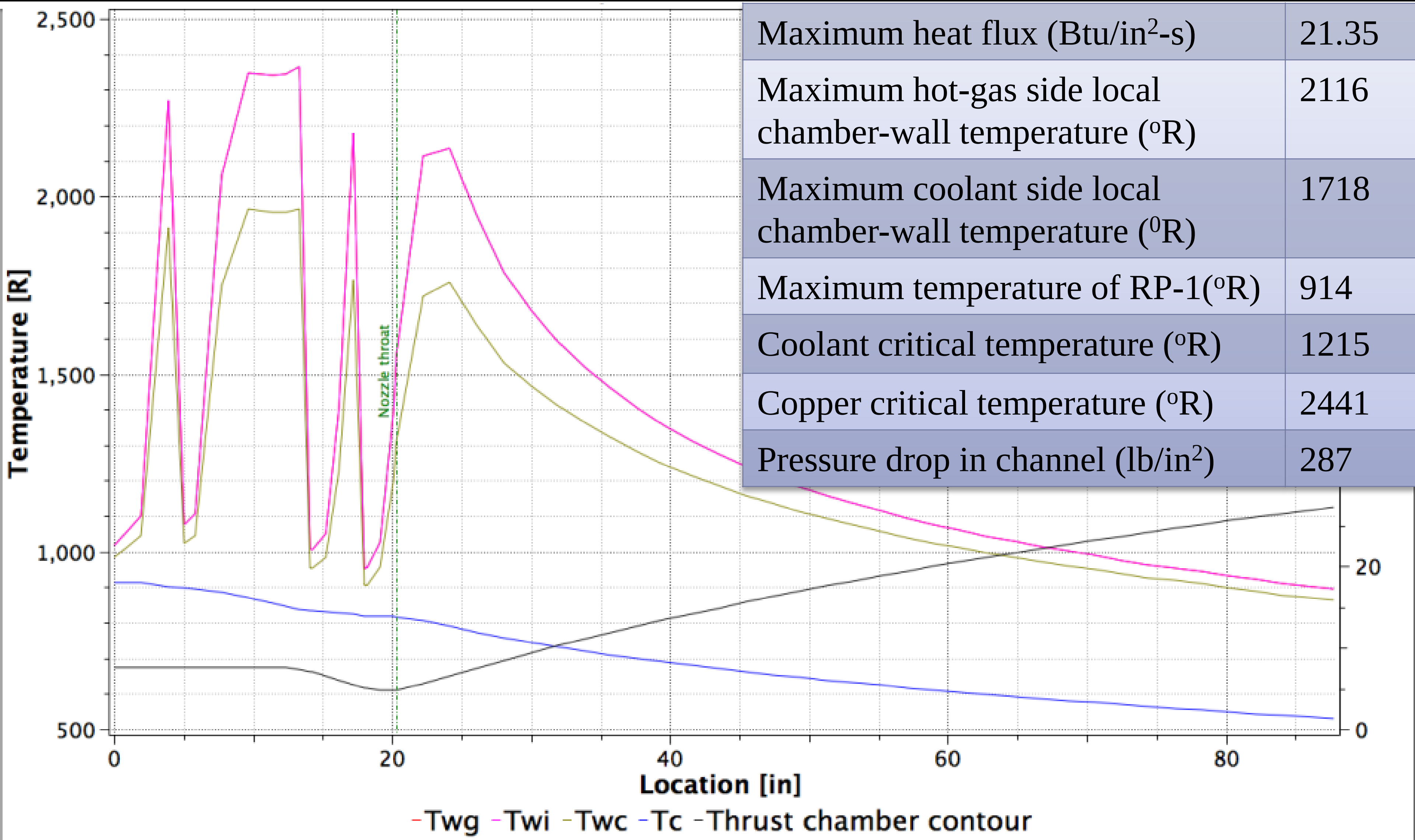




Main Engine Components

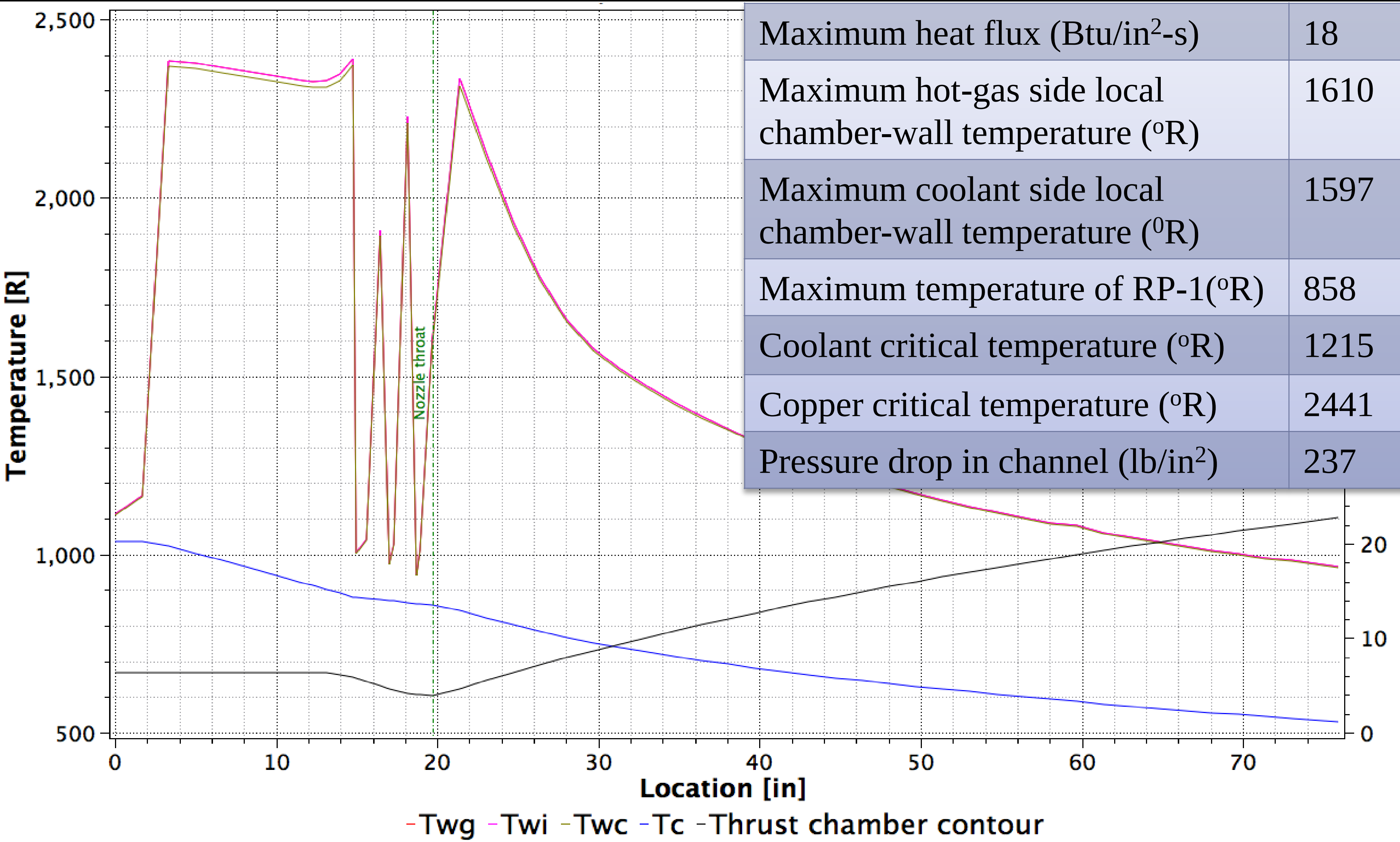


Booster Stage Engine Cooling



Maximum heat flux (Btu/in^2-s)	21.35
Maximum hot-gas side local chamber-wall temperature (°R)	2116
Maximum coolant side local chamber-wall temperature (°R)	1718
Maximum temperature of RP-1(°R)	914
Coolant critical temperature (°R)	1215
Copper critical temperature (°R)	2441
Pressure drop in channel (lb/in^2)	287

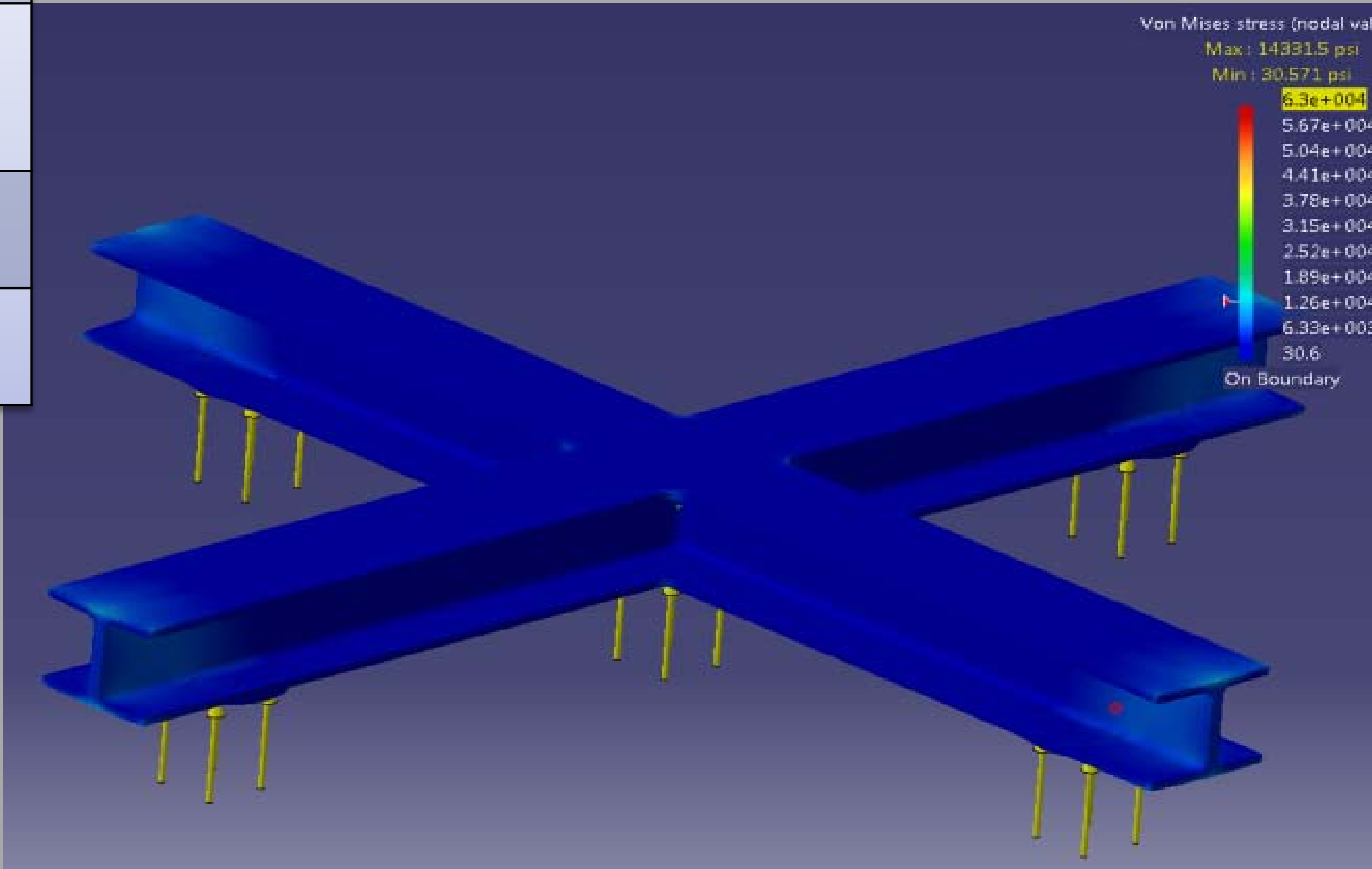
Upper Stage Engine Cooling



Maximum heat flux (Btu/in^2-s)	18
Maximum hot-gas side local chamber-wall temperature (^{o}R)	1610
Maximum coolant side local chamber-wall temperature (^{0}R)	1597
Maximum temperature of RP-1(^{o}R)	858
Coolant critical temperature (^{o}R)	1215
Copper critical temperature (^{o}R)	2441
Pressure drop in channel (lb/in^2)	237

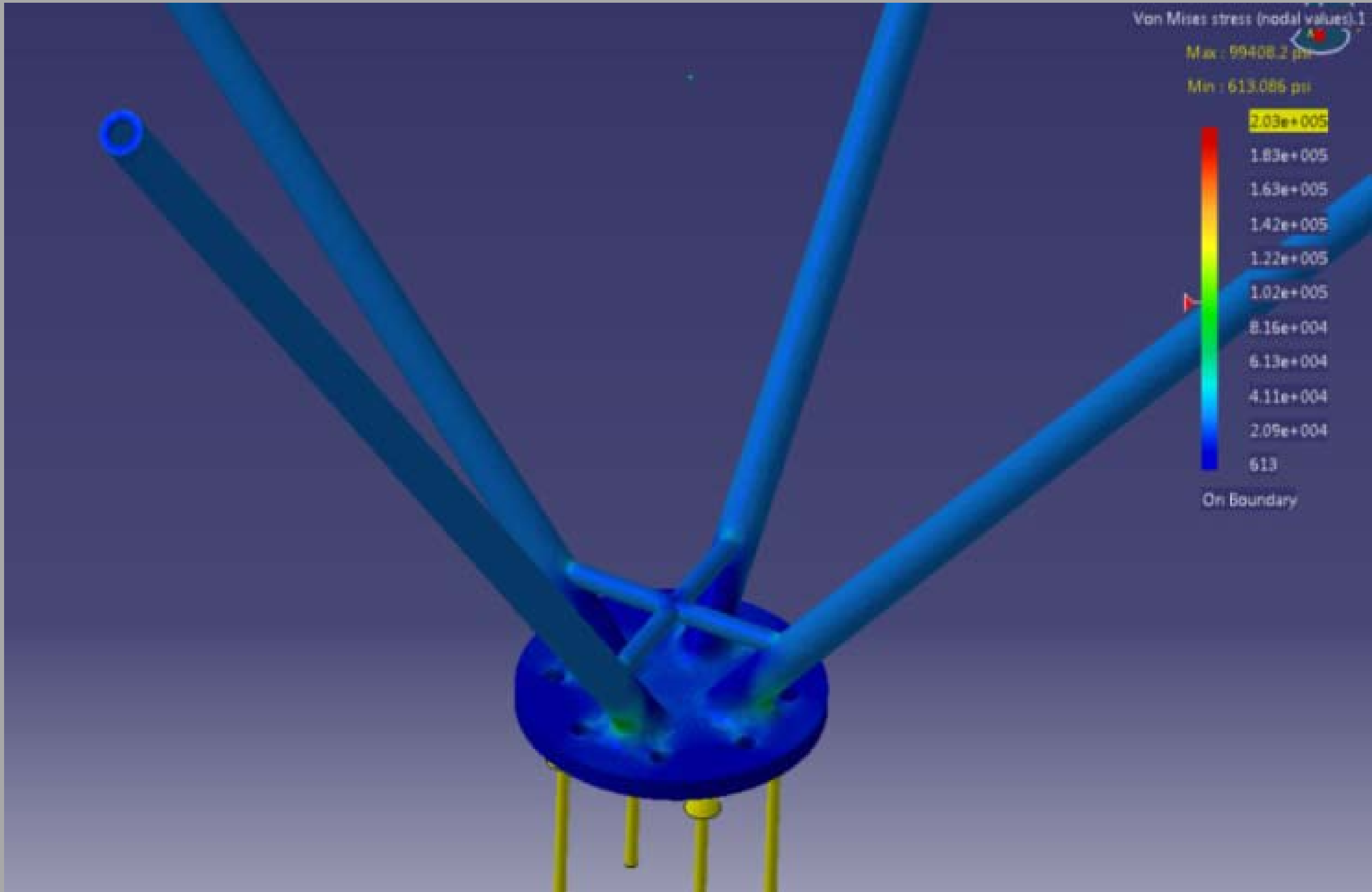
Booster Stage Engine Thrust Structure

Material: Chromoly Steel
Maximum Von Mises Stress: 13.0 ksi
Structure Mass: 1,877 kg
Combined Mass: 3,754 kg

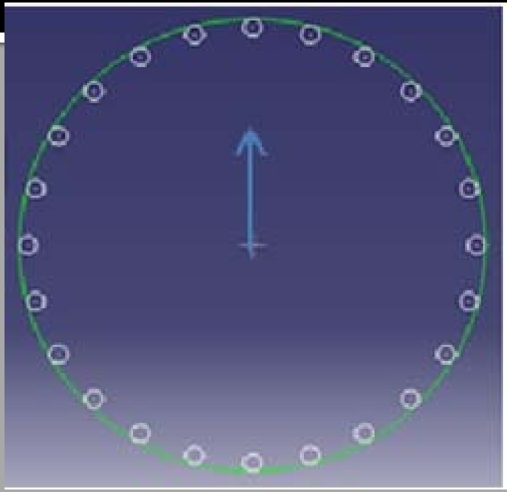


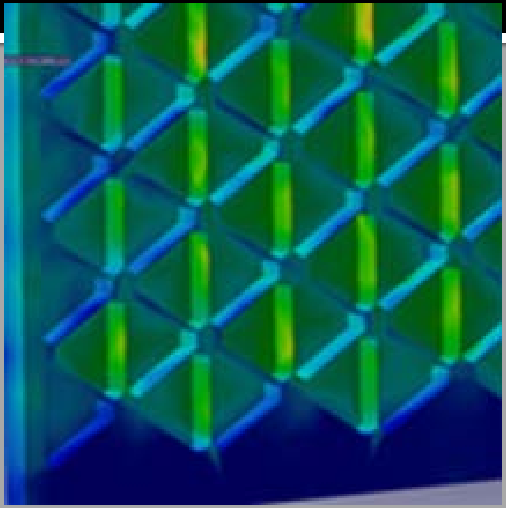
Upper Stage Engine Thrust Structure

Material: Maraging Steel
Maximum Von Mises Stress: 95 ksi
Structure Mass: 107 kg
Combined Mass: 428 kg



Construction Options



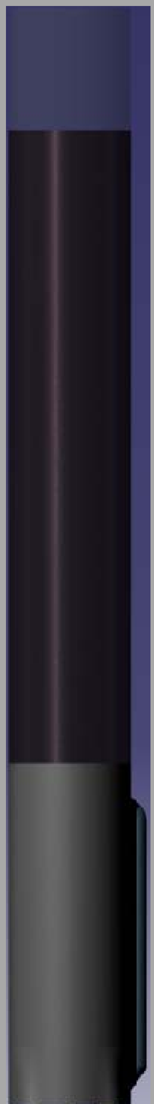


Booster RP-1	
Skin Thickness (in)	0.1046
Stringers	4.5471
Stringer Area	1.1765
Mass (kg)	7500

Booster RP1	
Skin Thickness (in)	0.1046
Triangle Height (in)	4.5471
Rib Depth (in)	1.1765
Rib Width (in)	0.1101
Mass (kg)	3200

	LOX	RP1
Pressure (in)	48.73	4.12
Thickness(in)	0.0383	0.00316

Final Tankage Statistics



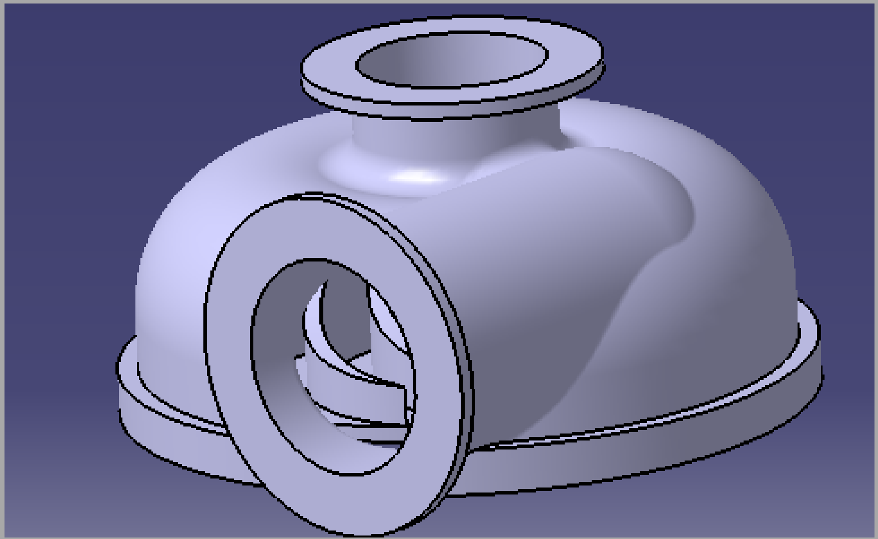
Upper Stage	Mass (kg)	Savings (kg)
Lox	1049.64	103
RP-1	967.77	95
Helium Required	75	----
Booster	Mass (kg)	Savings (kg)
Lox	2125.73	798
RP-1	1450.32	544.043
Helium Required	240	----

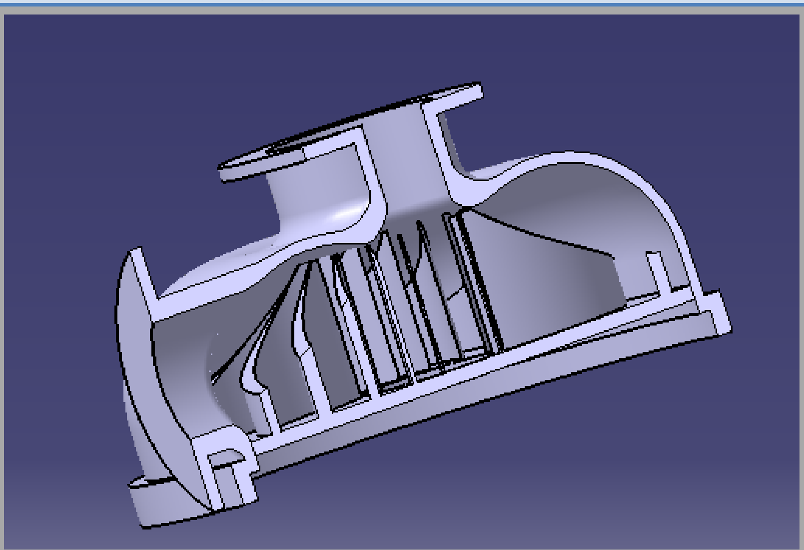
Upper Stage	Triangles	Time (days)
Lox	11856	4.24
RP1	10488	3.755
Booster	Triangles	Time (days)
Lox	37164	13.307
RP1	23940	9.40

Turbo Pump Analysis

RP-1			
WHP	131163.03 hp		
BHP	154309.44 hp		
N	8000 rpm		
T	1216292lbf*in		
Q	3.906 ft3/s		
Dsu	8.465 in		
Vin	10 ft/s		
Dh	3 in		
Do	6.75 in		
U1	235.45 ft/s	U2	685.47 ft/s
Vr1	20 ft/s	V02	649.26 ft/s
b1	1.33 in	alpha 2	1.32 deg
B1	4.86 deg	Concentration	0.85

LOX			
WHP	201892.6 hp		
BHP	237520.7 hp		
N	8000 rpm		
T	1872177lbf*in		
Q	8.73 ft3/s		
Dsu	12.65 in		
Vin	10 ft/s		
Dh	3 in		
Do	9.5 in		
U1	332.2 ft/s	U2	537.87 ft/s
Vr1	20 ft/s	V02	501.66 ft/s
b1	2.1 in	alpha 2	1.71 deg
B1	3.45 deg	Concentration	0.85



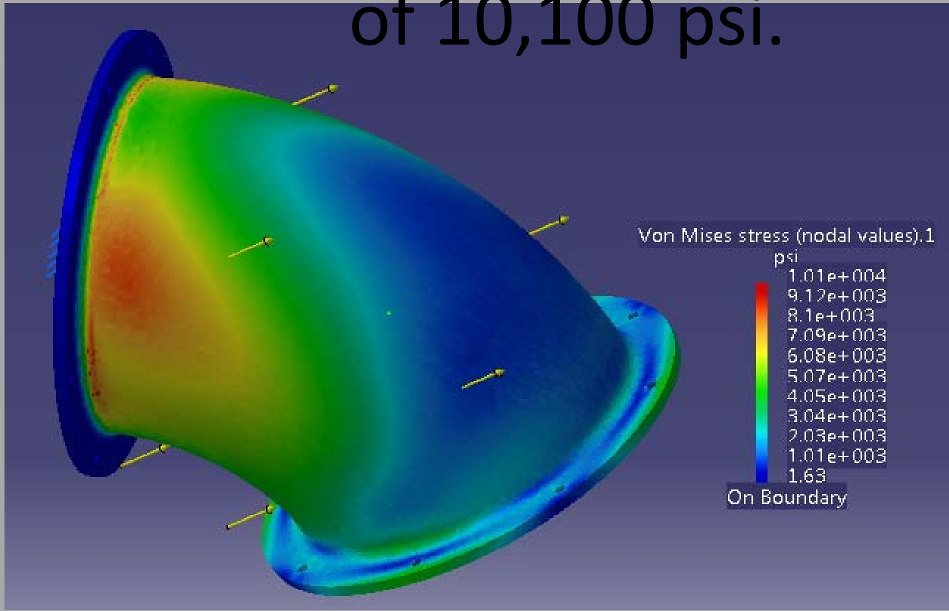


Forces and Stresses

- Stresses were estimated with an 0.125 inch wall thickness

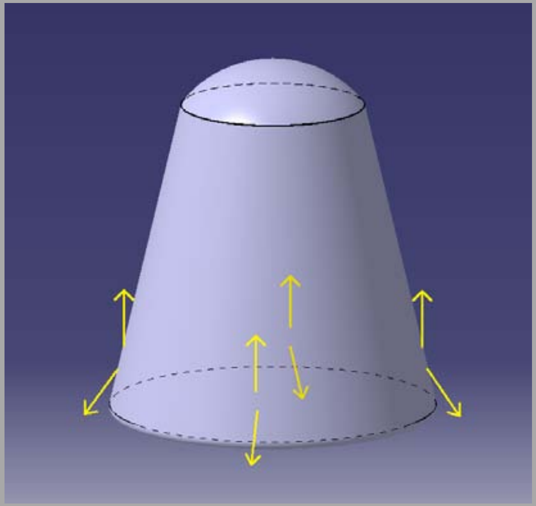
	Resultant Force (lbs)	Stress (psi)
Stage 1 LOX	11318	9367
Stage 1 RP-1	5538	5469
Stage 2 LOX	2273	5307
Stage 2 RP-1	1125	4533

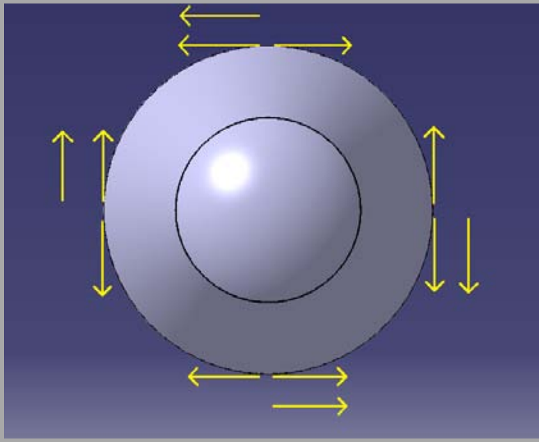
- Catia's FEA was used to verify hand calculations.
- Stage 1 LOX, max Von Mises stress of 10,100 psi.



RCS Thruster specifications

- Fuel: Monomethylhydrazine (MMH)
- Ox: Dinitrogen Tetroxide (NTO)
- O/F: 2.145
- 20 Thrusters





Thruster Parameter	Value (English)	Value (Metric)
Thrust at vacuum	96.22 lbf	428.01 N
Isp at vacuum	320.7 s	320.7 s
Oxidizer Mass Flow	0.2046 lbm/s	0.09281 kg/s
Fuel Mass Flow	0.0954 lbm/s	0.04327 kg/s
Area Expansion Ratio	50	50
Chamber Pressure	110 psi	0.7584 MPa

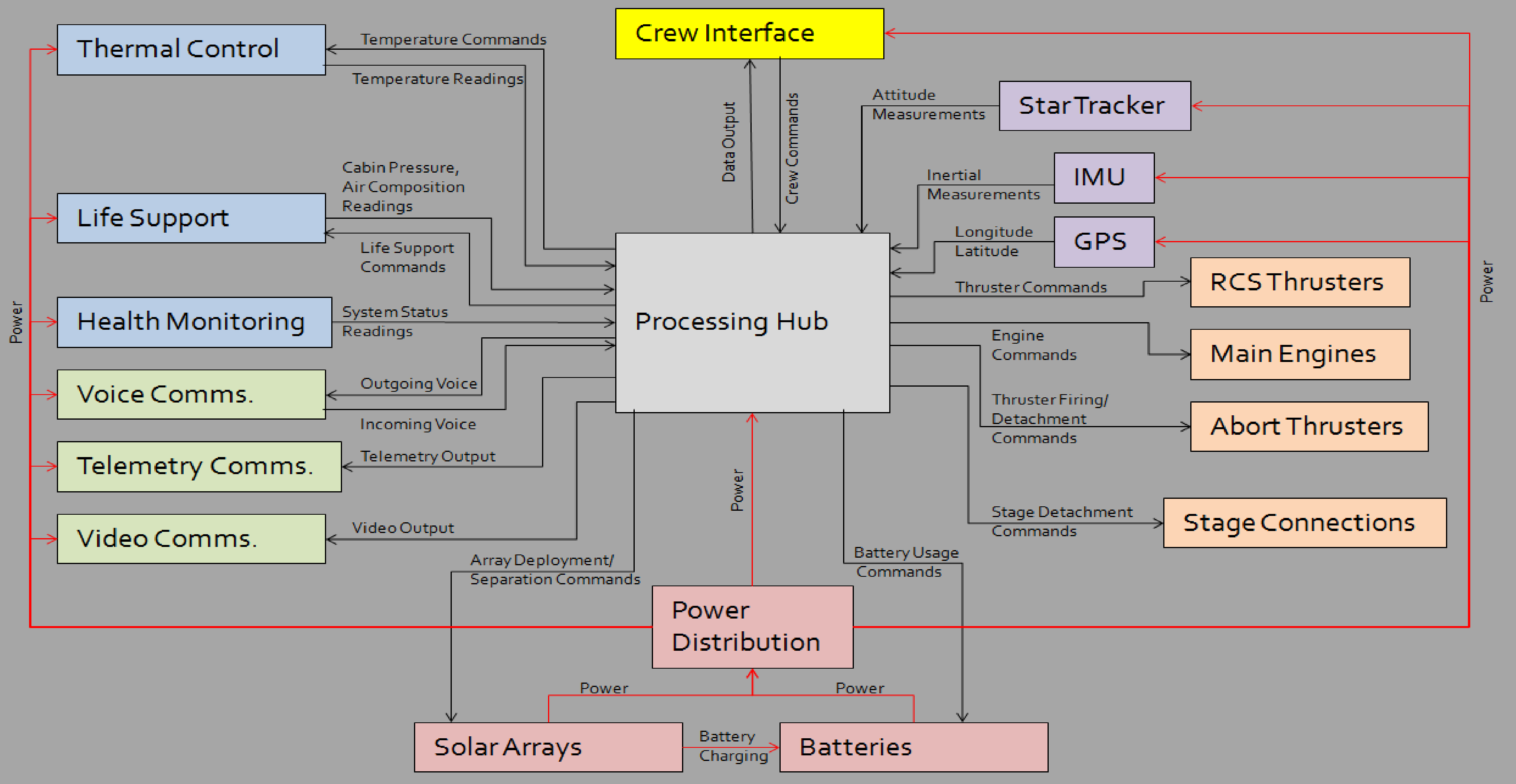
Capsule Guidance Navigation and Control (GNC)

- Sensors:
  - Star Tracker: Sodern SED26
  - IMU: Honeywell MIMU
  - GPS: Surrey SGR-10

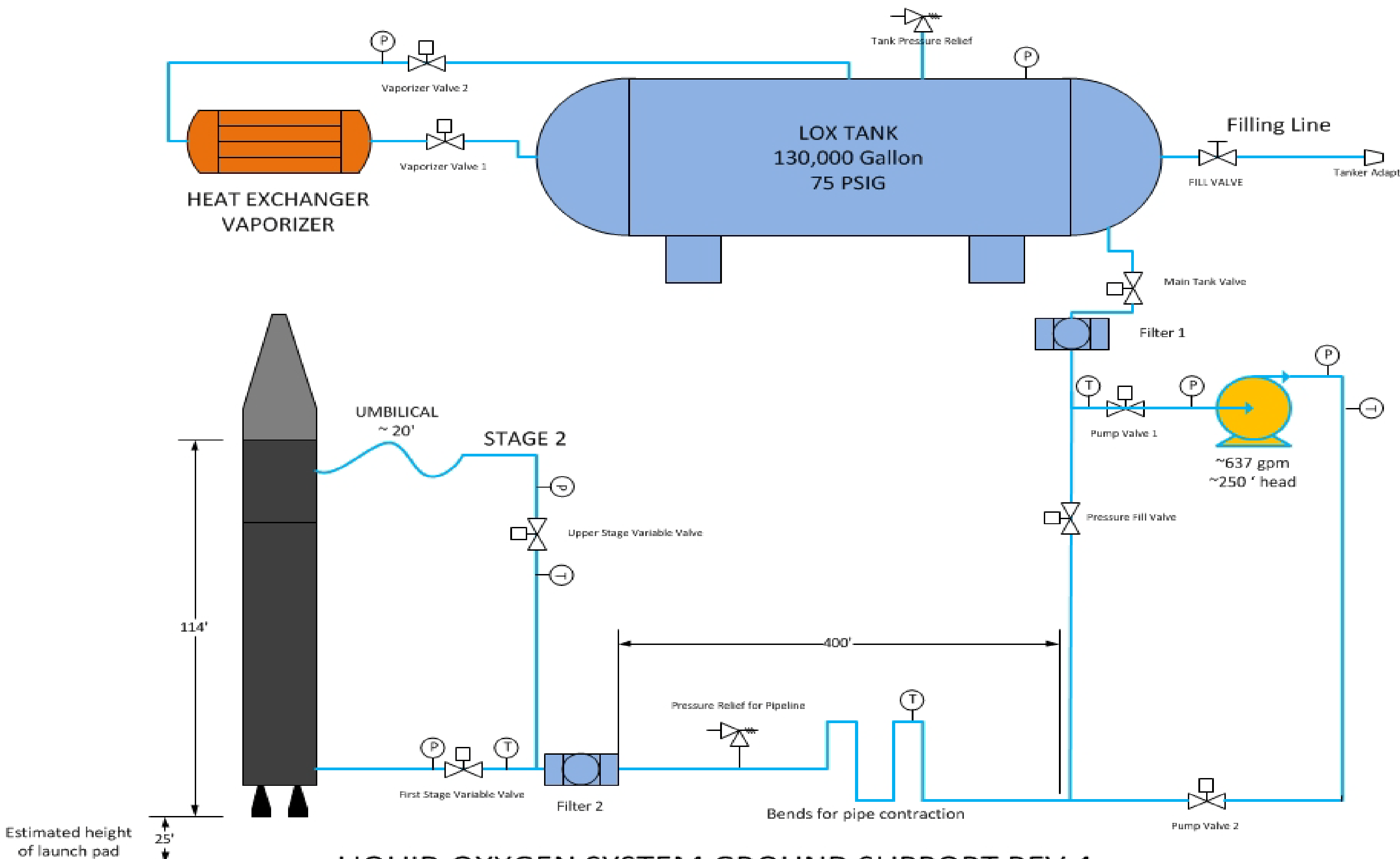
- QUEST Algorithm

Picture Source: http://ars.els-cdn.com/content/image/1-s2.0-S127096381100201X-gr007.jpg

Avionics Architecture



Ground Support System - LOX



LIQUID OXYGEN SYSTEM GROUND SUPPORT REV 4

Ground Support System – RP-1

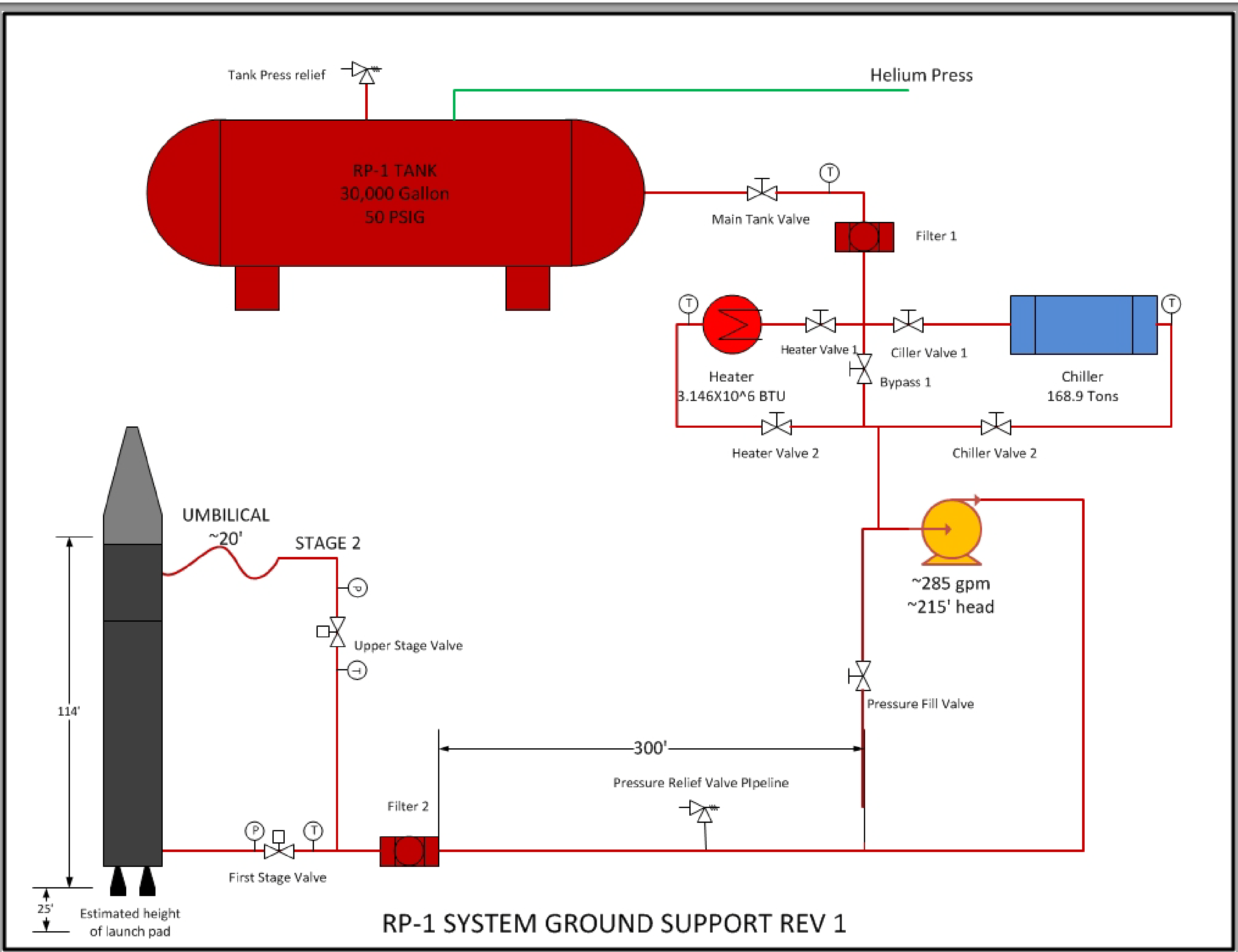
Launch Temps
36-99F

$Q = cm\Delta T$

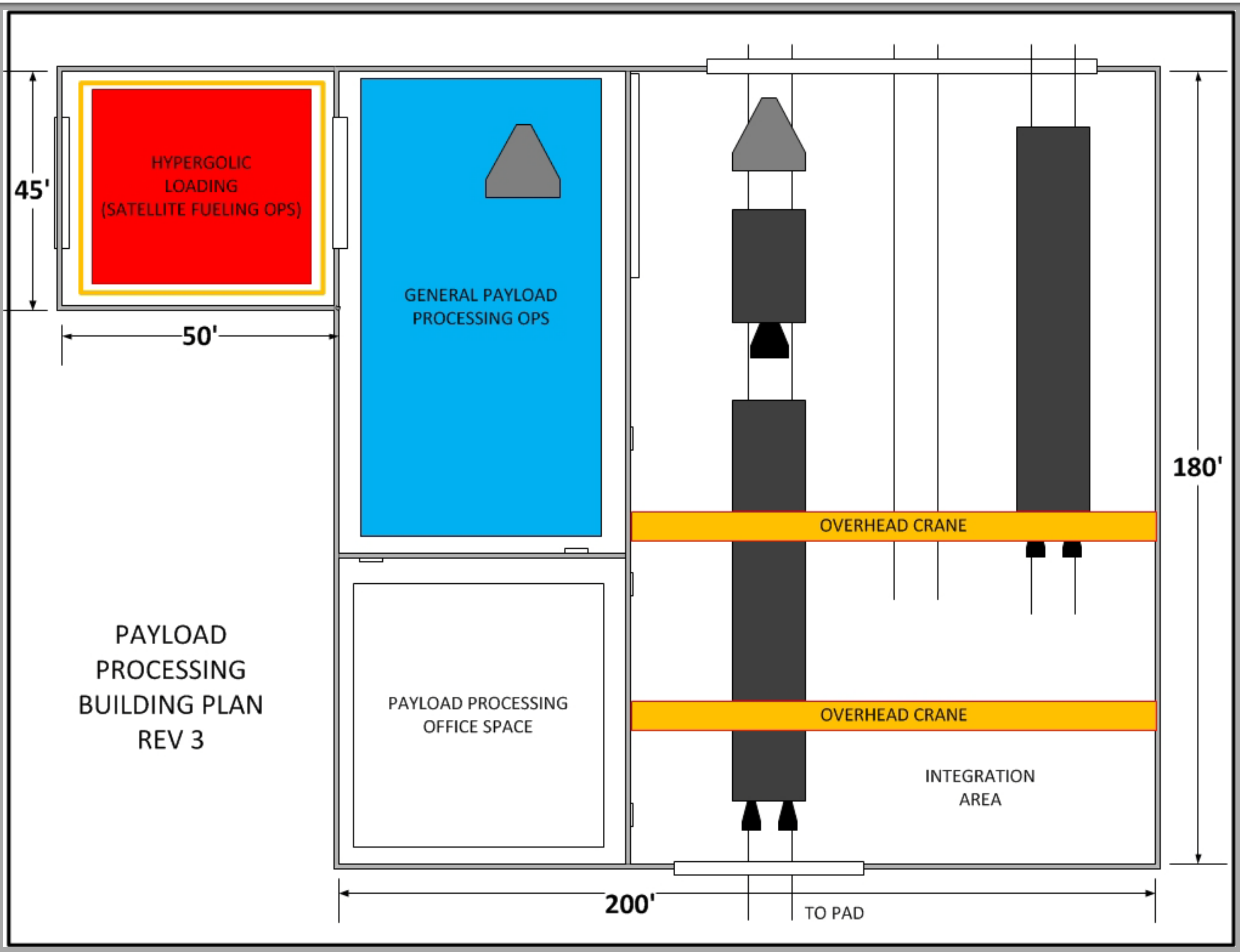
Heater
$3.146\text{x}10^6$ BTU

Chiller
$3.04\text{x}10^6$BTU

(168.9 Tons)

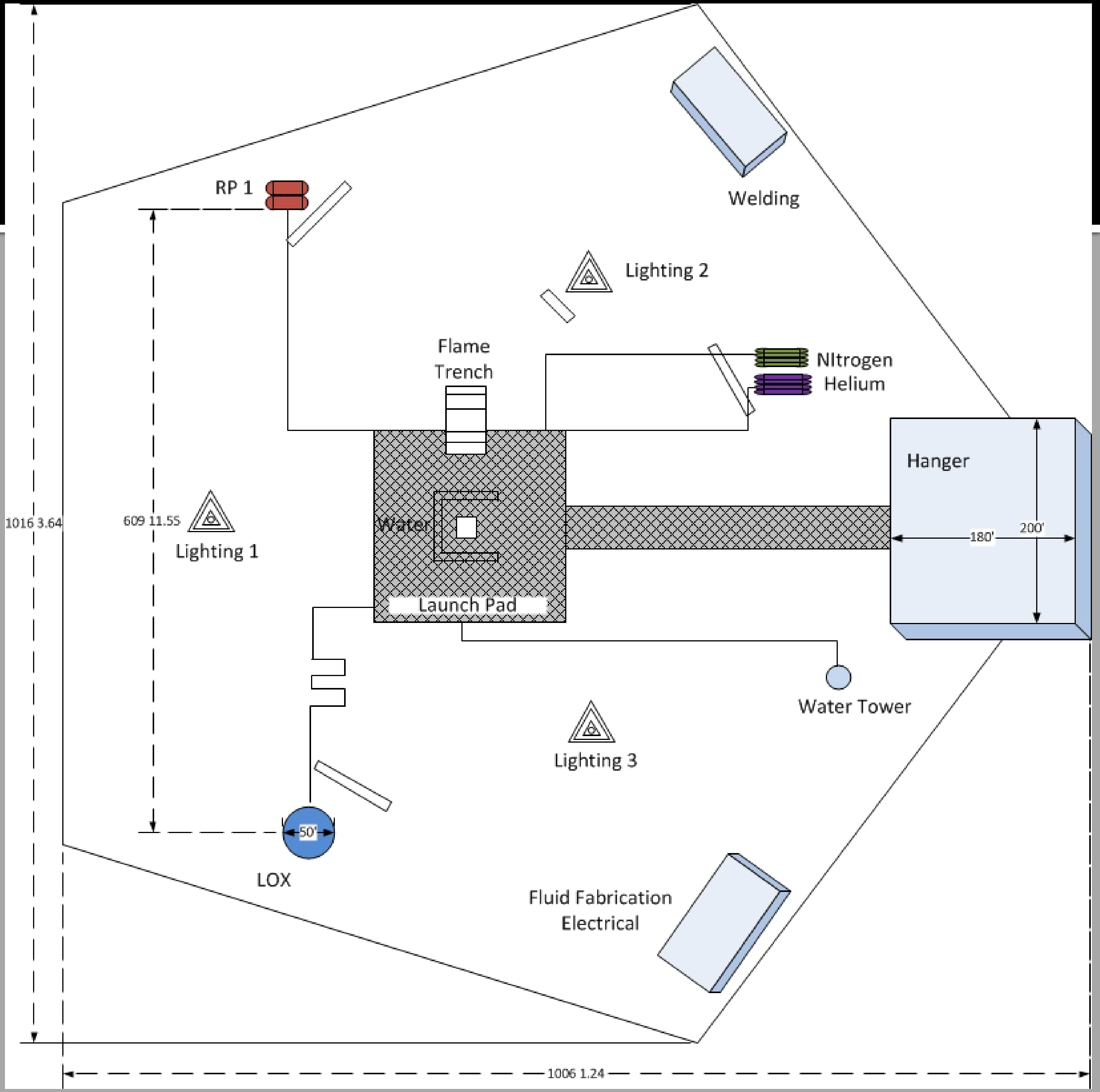


Payload Processing



3rd Rail for vehicle turnaround

Pad Overview



THE SKY IS NO LONGER THE LIMIT

Questions? / Back Up Slides