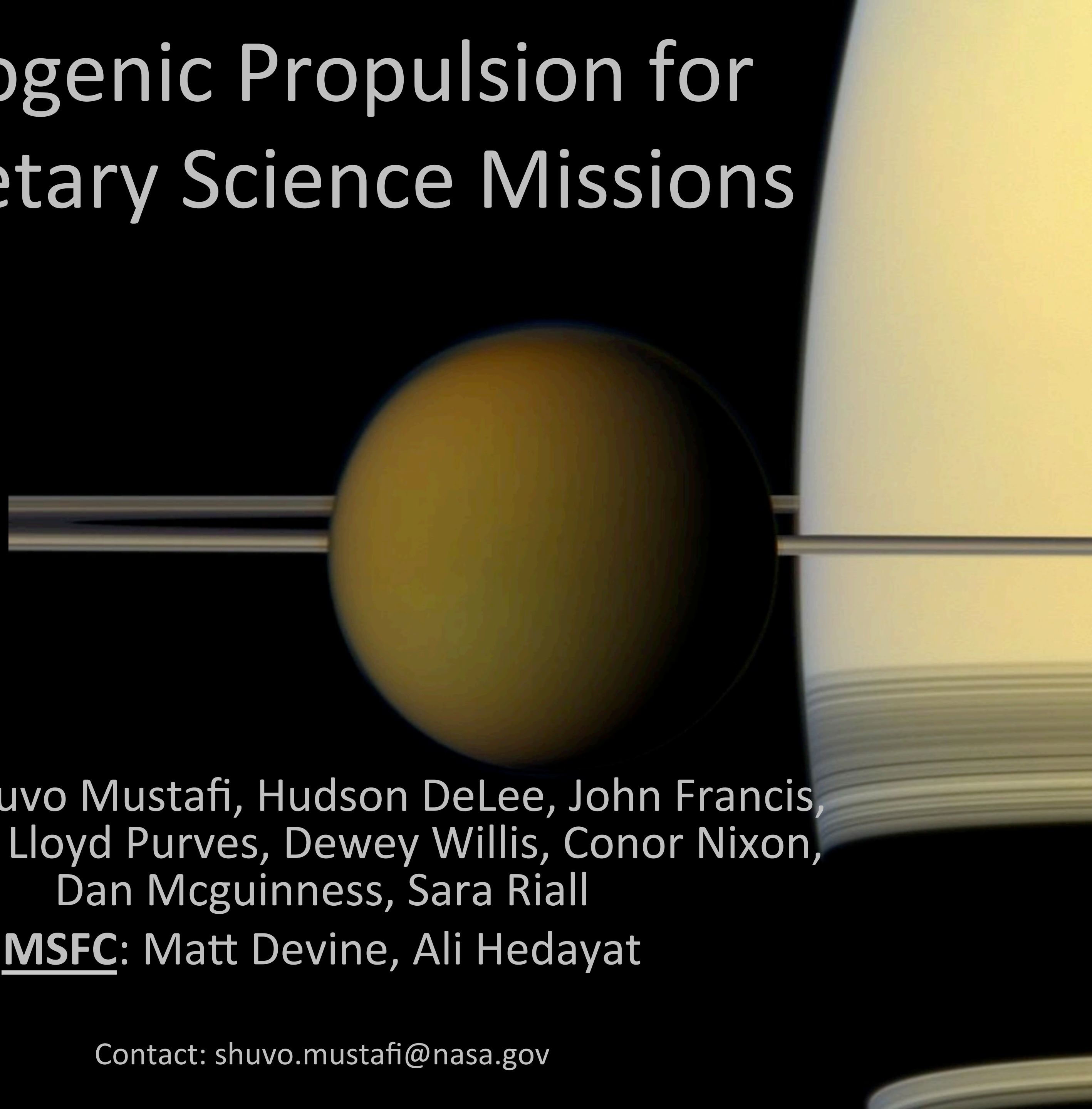
Cryogenic Propulsion for Planetary Science Missions



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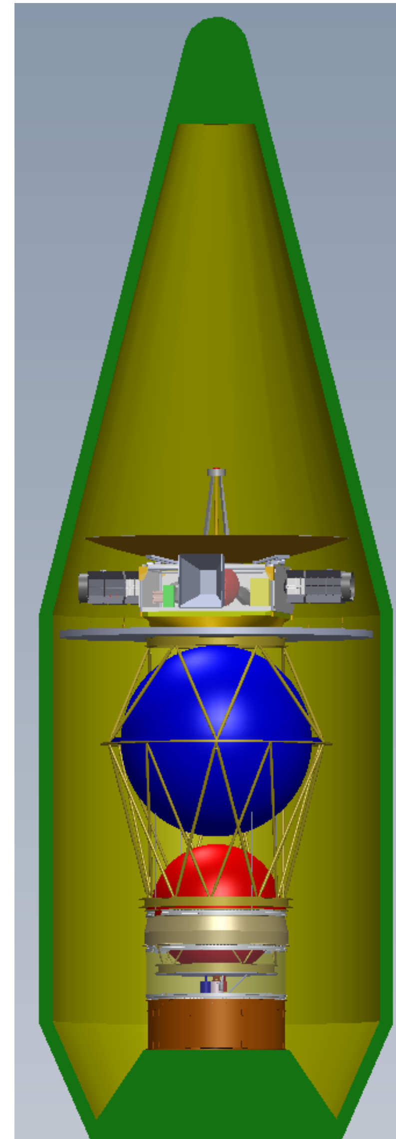
Cryogenic Propulsion for Planetary Science Missions

$$m_{Propellant} = m_{Dry}\left[e^{\Delta V/(g I_{sp})} - 1\right]$$

$$I_{sp},\ LH2+LO2 = 420\text{s} - 460\text{s}$$

$$I_{sp},\ MMH+NTO = 310\text{s} - 329\text{s}$$

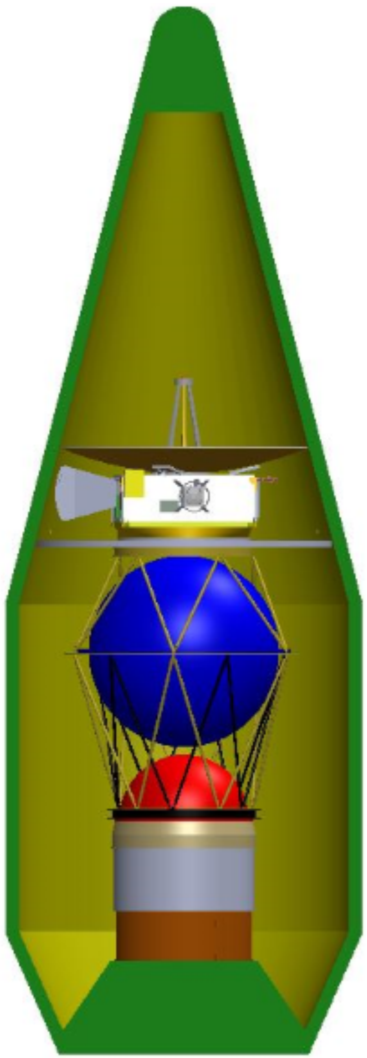
- LH2 + LO2 Propulsion systems provide the highest specific impulse of any practical chemical propulsion system
- LH2+LO2 not currently employed in planetary science missions due to historic limitations in cryogenic storage
- New storage technologies such as advanced MLI, pre-launch subcooling, and smart spacecraft design will allow passive long-term storage of cryogenic propellants for multi-year planetary science missions
- Design Study: Compared impact of Cryogenic LH2+LO2 propulsion system (I_{sp} = 438s) Vs. Hypergolic MMH+NTO (I_{sp} = 329s) propulsion system on a representative mission to Titan:
  - the Titan Orbiter Polar Surveyor (TOPS) mission



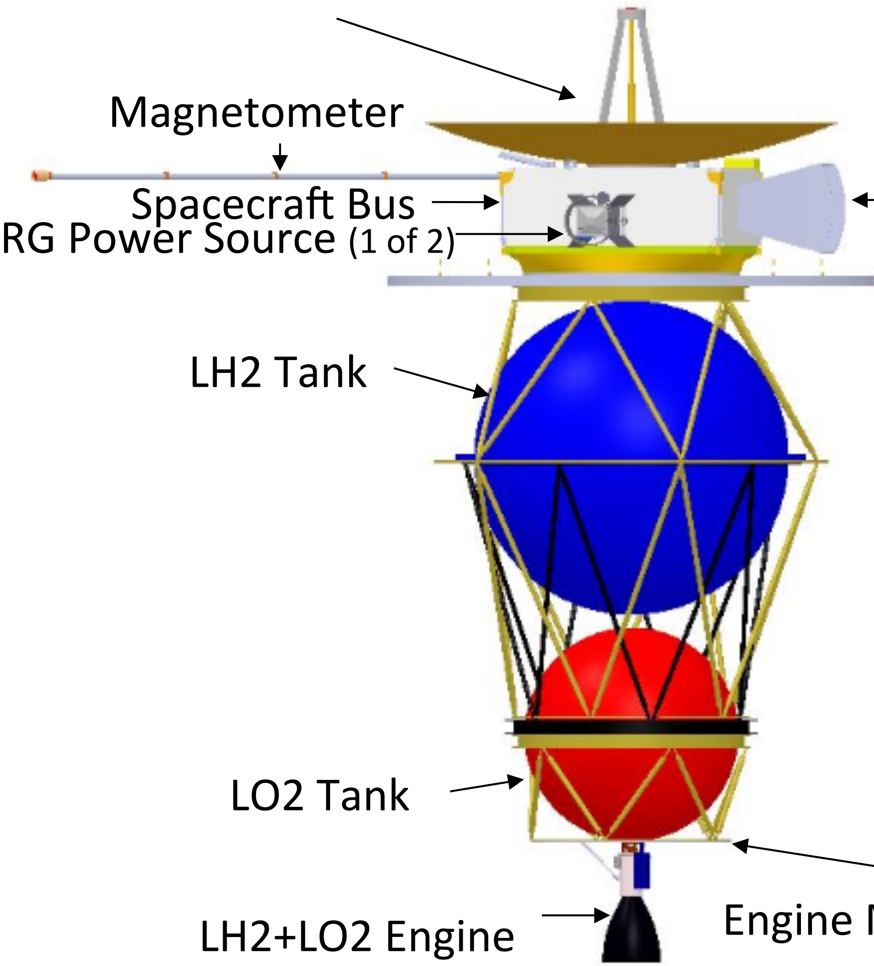
TOPS Mission Parameters

- Mission Duration: 10.5+ years
- Cryogenic Propellant Storage Mission: 8.5+ Years
- Launch in 2022
  - Jupiter not available for gravity assist
- ΔV = 5887 m/s
- 7 Engine Burns
  - Shortest Burn = 2.2 min.
  - Longest Burn = 56 min.
- Launch on an existing Atlas Launch Vehicle
- Science Payload Mass = 53.3 kg
- No Active Cooling during Mission

TOPS Spacecraft



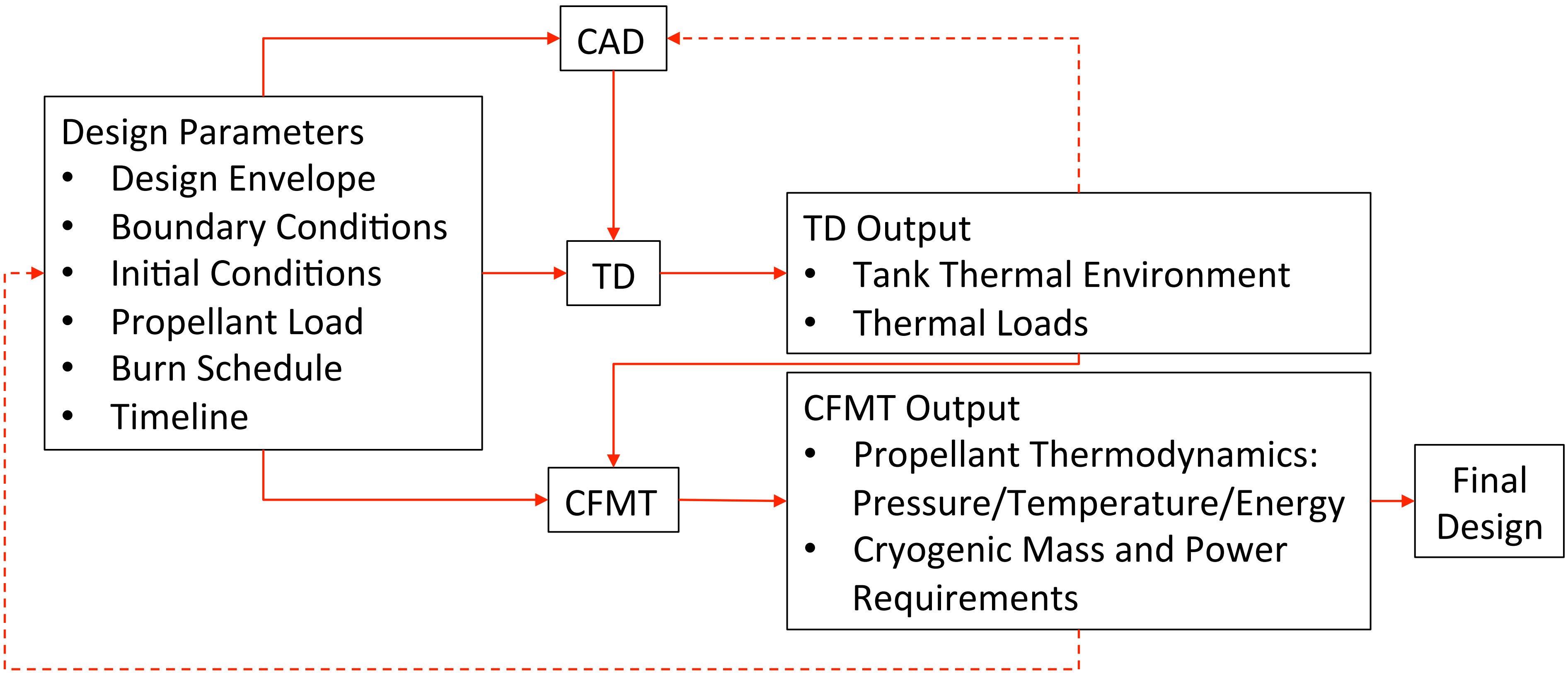
TOPS Spacecraft Stowed in Atlas AV 551



TOPS Spacecraft Deployed

Analysis Methodology

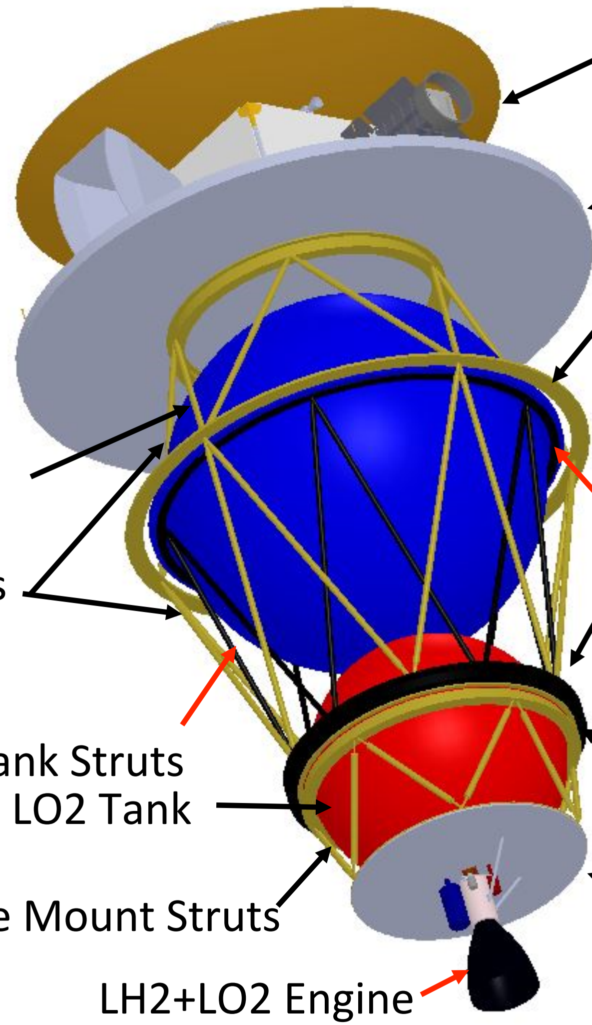
- CAD: Creo and Solid Works
- Heat Transfer: Thermal Desktop (TD)
- Fluid Condition: Cryogenic Fluid Management Tool (CFMT) - GSFC Spreadsheet and REFPROP Based Tool



Cryogenic Storage Strategies

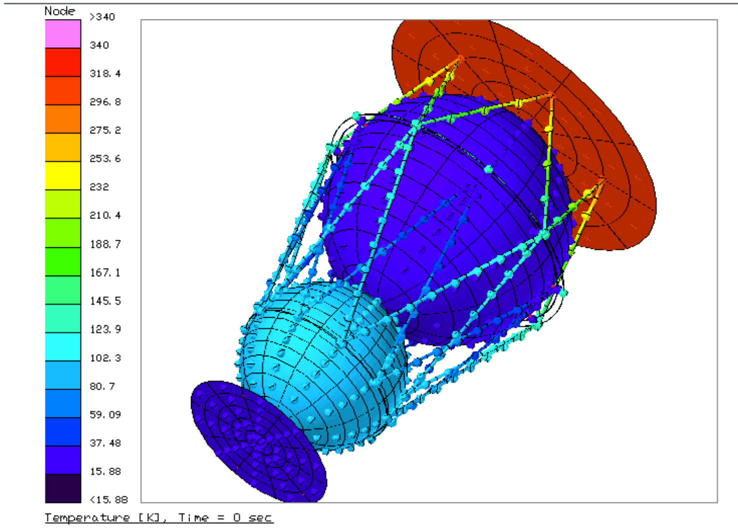
- Low Conductivity Struts:
  - T300 with low emissivity Aluminum Tape
  - Struts Implemented to have LH2 Tank at Maximum Conductive Isolation via LO2 Tank Stage to Spacecraft Bus or Launch Vehicle Payload Adapter Fairing
- Advanced MLI for LO2 and LH2 Tank
  - 5 layer Load Responsive MLI (LRMLI) for Convective Isolation on the Launch Pad
  - 40 layer Integrated MLI (IMLI) for Radiative Isolation
    - LRMLI and IMLI manufactured by Quest Thermal Group
- Smart Propellant Stacking and Smart Sunshield/Orientation:
  - Multi-layer low solar absorptivity
  - Nominally spacecraft bus will point towards sun
  - Thermal design can accommodate short durations of increased heat input from sun views and engine burns during burn and communication maneuvers
- Fluid Condition
  - LO2: Launched normal boiling point. Densifies slowly during interplanetary phase of mission.
  - LH2: Launched subcooled. Warms slowly during interplanetary phase of mission
    - LH2 subcooling can be provided by a launch pad cryocooler
      - Eg. Turbo-Brayton Cryocooler 400W@15 K Cooler: Estimated Mass: 780 kg Estimated Power: 32kW

TOPS LH2+LO2 Propulsion Features



Thermal Loads

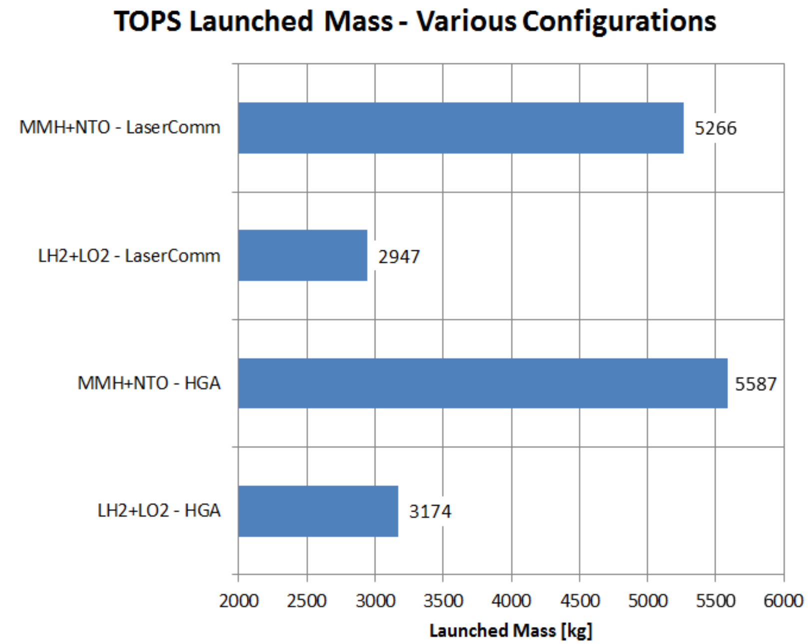
- Duration of Propellant Storage Mission >8.5+ Years
- LO2 Tank
  - Deep Space Nominal Heat Loss: 42 mW
  - No LO2 loss due to phase change
- LH2 Tank
  - Deep Space Nominal Heat Gain = 71 mW
  - Maximum Heat Input During Burns = 191 W
  - Duration of Longest Burn < 57 min.
  - Minimal 44kg loss of LH2 due to phase change.
- LH2+LO2 Launched Mass Savings over MMH+NTO for TOPS mission = 2300+ kg (43% mass reduction)



TOPS Launch Vehicle Performance

	LH2+LOX - HGA	MMH+NTO - HGA	LH2+LOX - LaserComm	MMH+NTO - LaserComm
Total Δ V	5887	5887	5887	5887
Dry Mass - Nominal [Kg]	739	878	685	828
Dry Mass with 25% Dry Mass Contingency [Kg]	880	1053	812	991
Launch Mass with 25% Dry Mass Contingency [Kg]	3174	5587	2947	5266
AV 431 - Separated Launch Limit [Kg]	2922	2922	2922	2922
AV 431 - Separated Launch Mass Margin [%]	-8	-48	-1	-45
AV 541 - Separated Launch Limit [Kg]	3200	3200	3200	3200
AV 541 - Separated Launch Mass Margin [%]	1	-43	9	-39
AV 551 - Separated Launch Limit [Kg]	3525	3525	3525	3525
AV 551 - Separated Launch Mass Margin [%]	11	-37	20	-33

TOPS Comparison of LH2+LO2 vs Hypergols



- **LH2+LO2 provides the highest specific impulse of any practical chemical propulsion system.**
- **For the TOPS Mission this means a 43% reduction in launched mass. This mission can be completed using an Atlas Launch Vehicle using LH2+LO2 but not with MMH+NTO.**
- **LH2+LO2 can enable missions that deliver/recover substantially larger masses to/from the target destinations, or launch the mission on smaller and cheaper launch vehicles, or both.**
- **Subcooling saves a further 30 kg of boil-off H2 mass that can be directly used for payload.**
    - **56.4% of Science Payload Mass of 53.3 Kg**
        - **Not including secondary mass savings from smaller tank, less insulation, less support structure, less propellant. Accounting for this leads to increased reduction in launched mass.**

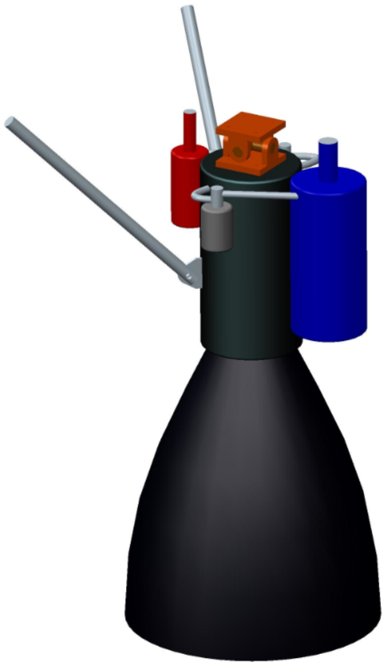
Parametric Mass Savings of LH2+LO2 over MMH+NTO

Launch Mass Savings for using LH2+LO2 Vs MMH+NTO (MEV) [kg]			
	ΔV [m/s]		
Non-Main Propulsion Dry Mass (CBE) [kg]	**2500**	**5000**	**7500**
250	118	843	3,664
500	255	1,469	6,251
1000	529	2,721	11,425

LH2+LO2 Main Engine

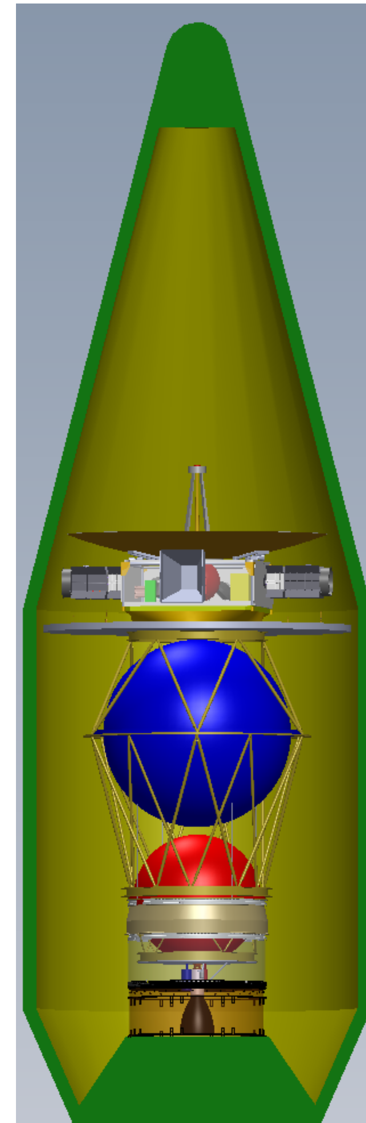
LH2 + LO2 Main Engine Needs to be developed

- Thrust: 890 N
- 438 s Isp
- Area Ratio: 150:1
- Chamber Pressure: 621 kPa
- Mixture Ratio: 4.5
- 7 Burns
- Longest Burn 56+ Minutes.
- Pump Fed
  - Brushless DC Motor
- Active Cooling Circuits for autogenous repres
- Gimballed for Thrust Vector Control



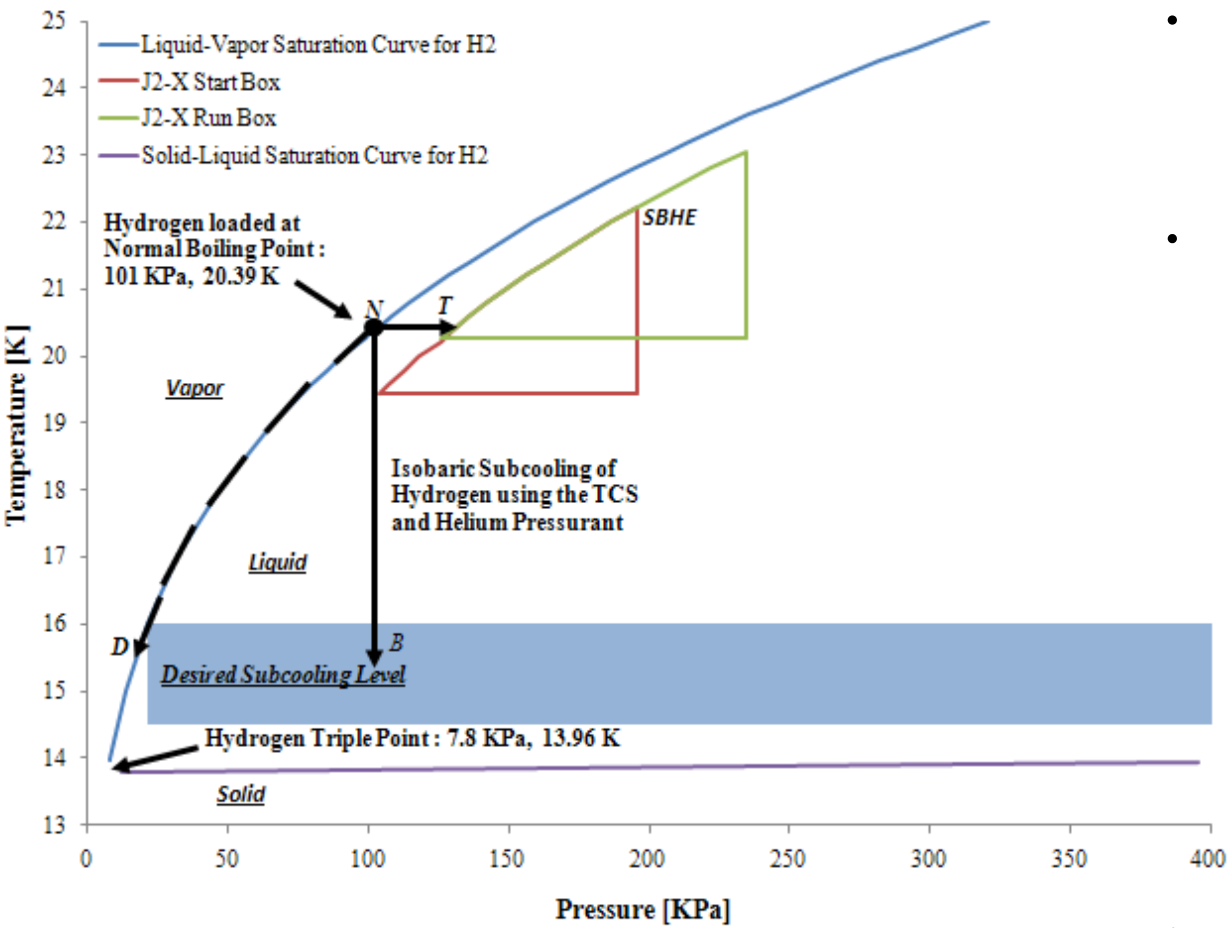
Summary: Cryogenic Propulsion for Planetary Science Missions

- Cryogenic LH2+LO2 Propulsion provides high specific impulse chemical propulsion for planetary science exploration
- Provide high ΔV and high delivered and high returned mass to and from planets, moons, asteroids, comets with lower spacecraft wet mass.
- For the TOPS mission, passively cooled LH2+LO2 reduces launched spacecraft mass by 43% and allows for launch on an Atlas launch vehicle. The same mission cannot be performed using a MMH+NTO propulsion and an Atlas launch vehicle.
- Subcooling cryogenic propellants on the launch pad using a cryocooler enables multi-year storage of LH2 without adding launched mass. For the TOPS Mission Subcooling saved LH2 boil-off mass that amounts to 56% of science payload mass.
- LH2+LO2 Propulsion Development Required:
  - 890 N LH2+LO2 Engine
  - Implementation of LRMLI and IMLI on 5500 to 6500 L Tanks.
  - Launchpad Subcooling of LH2
- TOPS Mission and other planetary science missions can be accomplished without any in-space active cooling.



Backup Slides

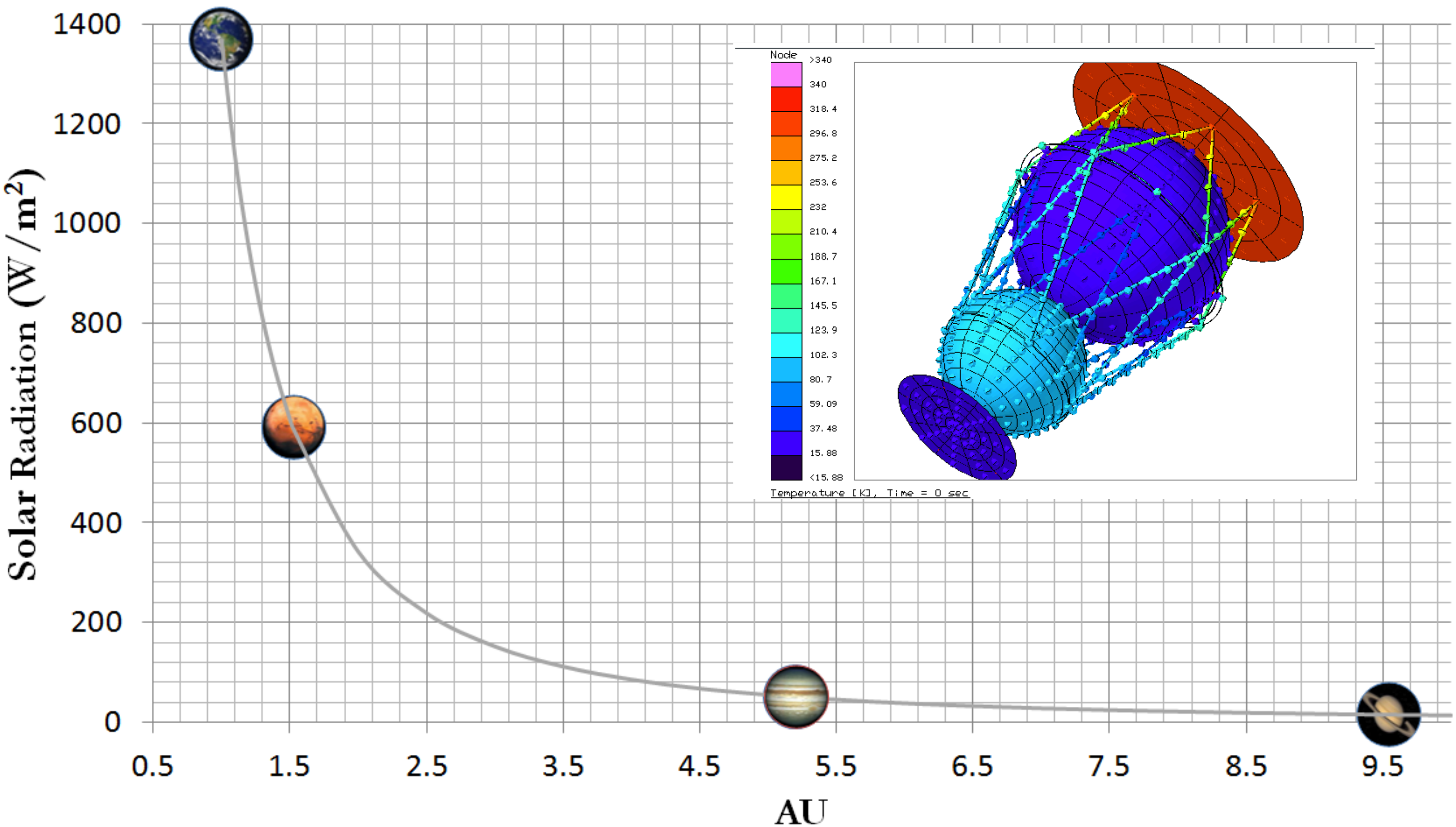
Pre-Launch Isobaric Subcooling for Storage



- *Objective:* Delay venting of the cryogen as long as possible.
- **Fluid Conditioning**
  - Engine Start Box High End (SBHE)
  - Fluid at Normal Boiling Point (N)
  - Isobaric Subcooling (B)
    - Proposed fluid conditioning method
- **Physics**
  - Substantially lower heat flux in-space than in-atmosphere exploited or enhanced
    - Dominant in-space load < 0.25 W/m^2
    - Dominant in-atmosphere load >63 W/m^2
  - Available heat capacity of the stored cryogen - Unexploited
    - Heat Capacity from N to SBHE = 18.2 KJ/Kg
    - Heat Capacity from B (@ T=16 K) to SBHE = 55.0 KJ/Kg
  - Isobaric Subcooling to 16 K allows hydrogen to absorb ~ 3x the energy before venting has to be initiated => hold time before venting for isobaric subcooling is ~ 3x
- Pre-launch Subcooling using launch pad subcoolers or a thermodynamic cryogen subcooler

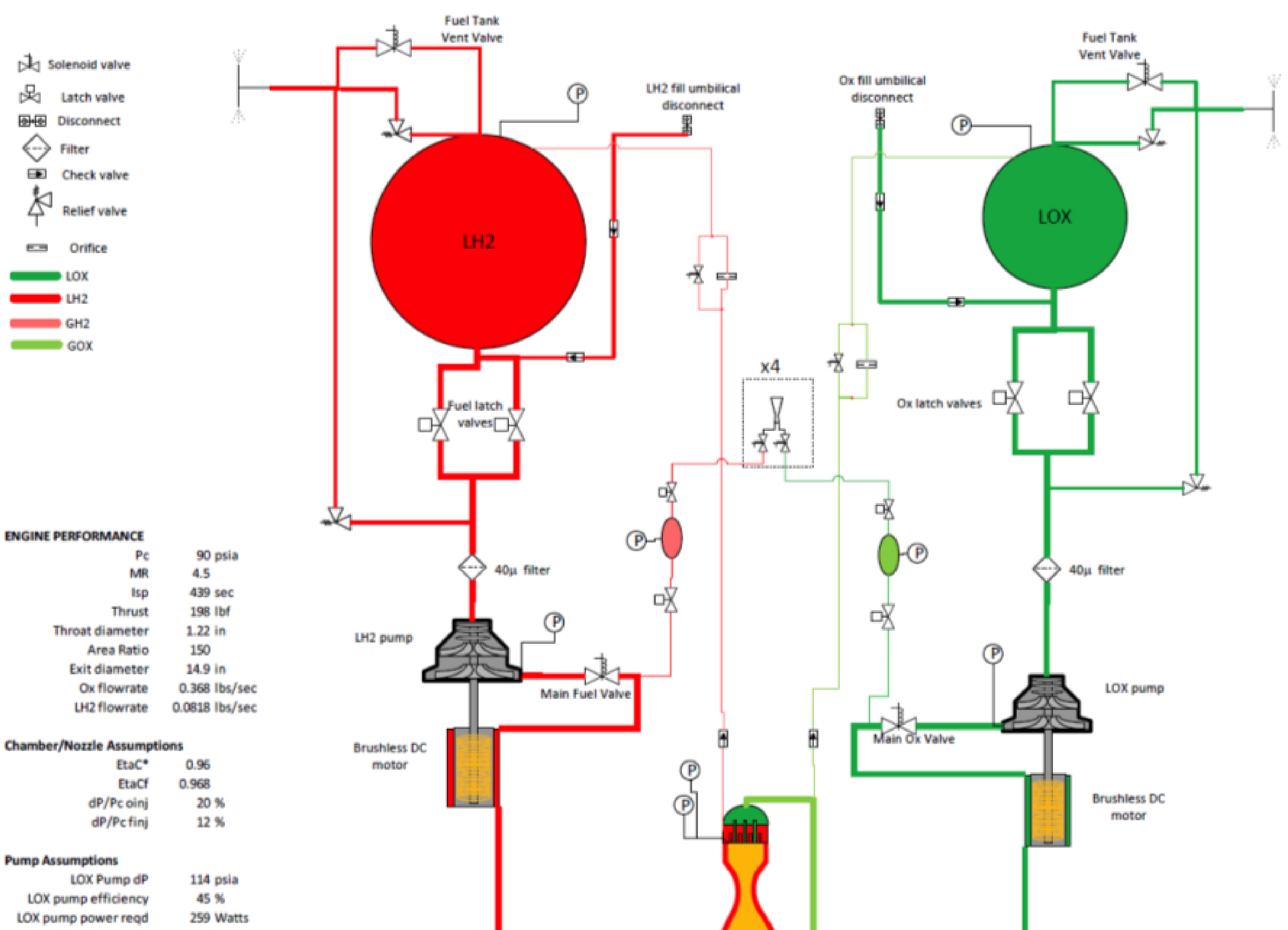
•RL-10s operated with densified hydrogen
•Other Engines would have to be qualified

LH2+LO2 Storage



Combination of Smart Cryogenic Design with Subcooling and Lowering Solar Flux (artificially and naturally) allows long term storage of LH2+LO2 for Planetary Science propulsion

TOPS Main Propulsion System



ENGINE PERFORMANCE

Pc	90 psia
MR	4.5
Isp	439 sec
Thrust	198 lbf
Throat diameter	1.22 in
Area Ratio	150
Exit diameter	14.9 in
Ox flowrate	0.368 lbs/sec
LH2 flowrate	0.0818 lbs/sec

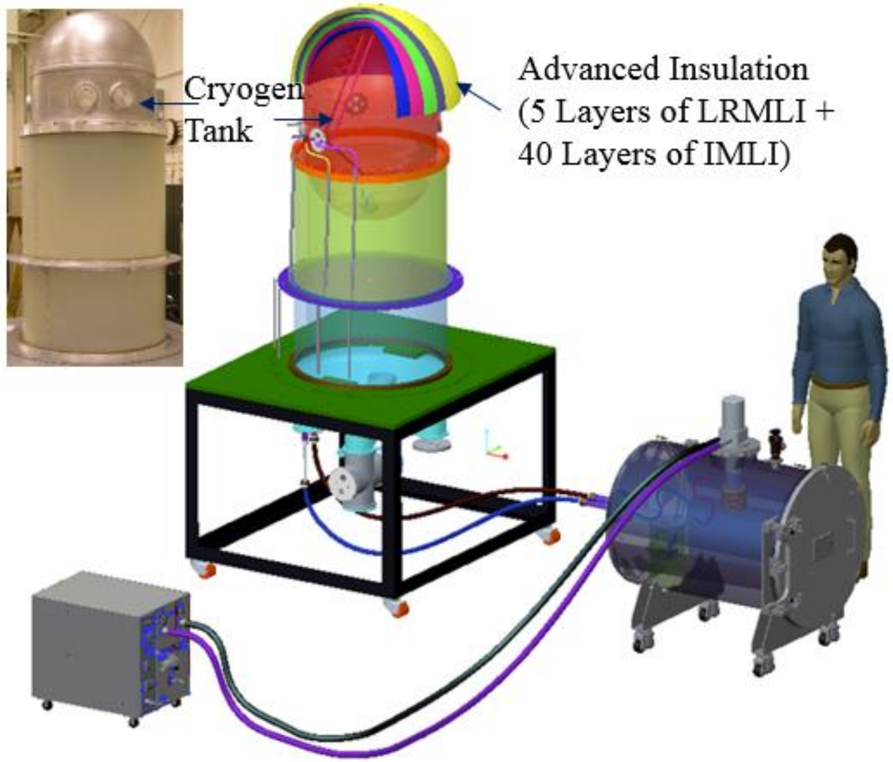
Chamber/Nozzle Assumptions

EtaC*	0.96
EtaCf	0.968
dP/Pc oinj	20 %
dP/Pc finj	12 %

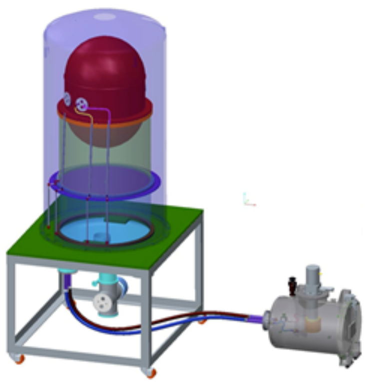
Pump Assumptions

LOX Pump dP	114 psia
LOX pump efficiency	45 %
LOX pump power reqd	259 Watts

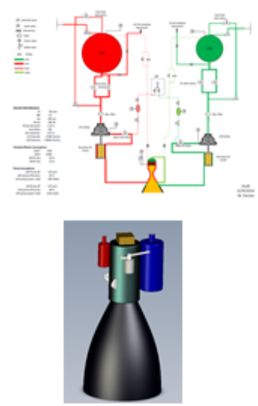
Cryogen Storage Demonstration



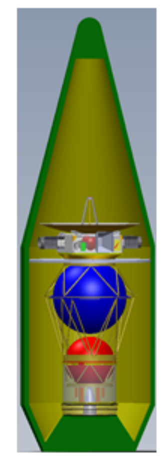
Roadmap



2015: TRL 5



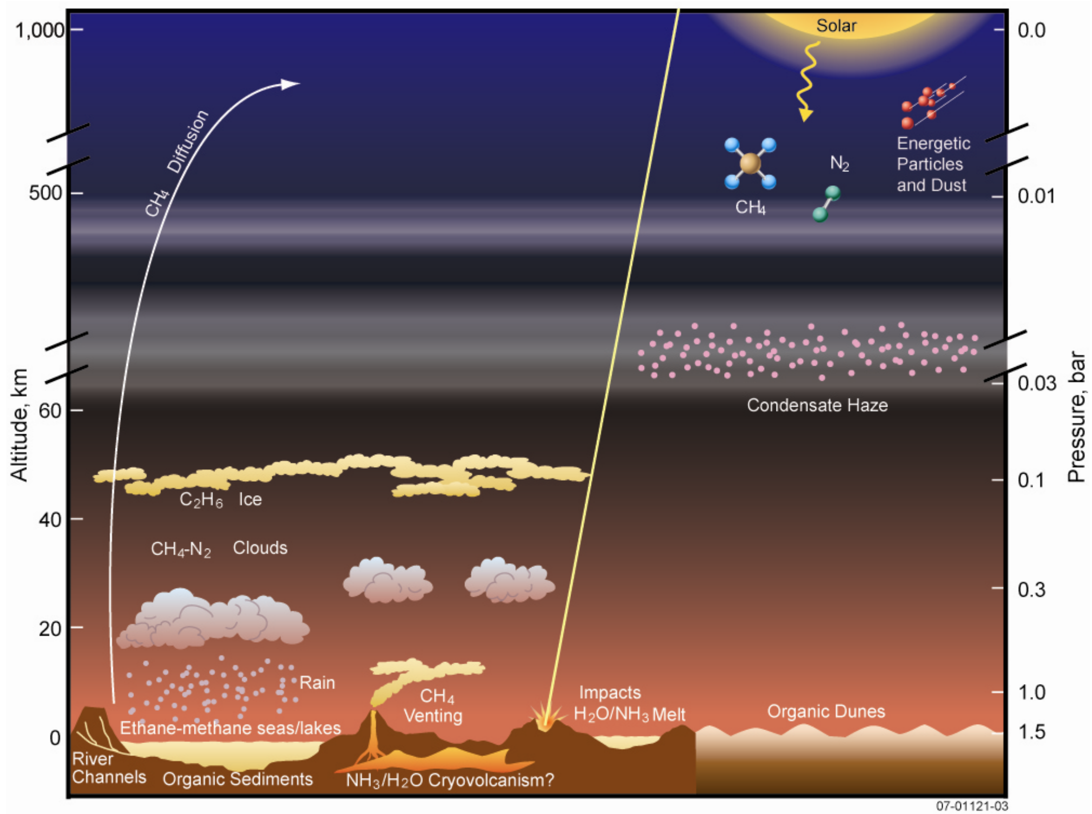
2017: TRL 6



2022: TRL 9

TOPS Science

- Titan's has similarities to Earth
  - 95% N_2 and 1.5 bar pressure at surface
  - Evaporation and Precipitation of Methane similar to Water Vapor Cycle
  - Methane is source of active photochemistry that produces haze and net greenhouse effect of 12K
- Differences
  - Surface Temperature 93K
  - Precipitation of Methane
  - Ethane/Methane seas and lakes
- TOPS Orbit
  - TOPS would place the first spacecraft in polar orbit around Titan
  - First global multi-spectral and radar maps of the surface
- TOPS Science Goals
  - Complete crater counts, yielding surface age estimates for different terrains
  - Lake composition and morphology studies
  - Search for volcanic/endogenic/tectonic activity
  - Meteorology – Clouds and Haze



NASA/JHU/APL, from "Titan Explorer" Mission Study, Lorenz et al., 2008