Cryogenic Propulsion for the Titan Orbiter Polar Surveyor

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• TOPS Science Goals
• TOPS Spacecraft
• Thermal Design and Analysis
• Conclusions
TOPS Science

• Titan’s has similarities to Earth
  – 95% N₂ 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
TOPS Mission Parameters

- Mission Duration: 10.5+ years
- Cryogenic Propellant Storage Mission: 8.5+ Years
- Launch in 2022
  - Jupiter not available for gravity assist
- $\Delta V = 5887$ 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
TOPS Spacecraft

(a) Sunshade
(b) LH2 Tank
LO2 Tank
LH2+LO2 Engine
Spacecraft Bus
Magnetometer
High Gain Antenna and Radar
ASRG Power Source (1 of 2)
Spectroscopic Imager
Sunshade
Engine Mounting Plate
Thermal Analysis

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

Design Parameters
- Design Envelope
- Boundary Conditions
- Initial Conditions
- Propellant Load
- Burn Schedule
- Timeline

CAD

TD Output
- Tank Thermal Environment
- Thermal Loads

CFMT Output
- Propellant Thermodynamics: Pressure/Temperature/Energy
- Cryogenic Mass and Power Requirements

Final Design

5/29/2018
Cryogenic Storage Strategies

• 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

• LOx 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

• Sunshield and 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 Truss Structure
Thermal Loads

- Duration of Propellant Storage Mission >8.5+ Years

- LOx Tank
  - Deep Space Nominal Heat Loss: 42 mW

- LH2 Tank
  - Deep Space Nominal Heat Gain = 71 mW
  - Maximum Heat Input During Burns = 191 W
  - Duration of Longest Burn < 57 min.
### TOPS Launch Vehicle Performance

<table>
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<th>LH2+LOX - HGA (Kg)</th>
<th>MMH+NTO - HGA (Kg)</th>
<th>LH2+LOX - LaserComm (Kg)</th>
<th>MMH+NTO - LaserComm (Kg)</th>
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<td>Total ΔV</td>
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<td>Dry Mass - Nominal</td>
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<td>Dry Mass with 25% Contingency</td>
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TOPS Comparison of LH2+LOx vs Hypergols

- LH2+LOx 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+LOx 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.

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Summary: Cryogenic Propulsion for Planetary Science Missions

• Cryogenic LH2+LOx 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+LOx 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+LOx Propulsion Development Required:
  – 890 N LH2+LOx 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 using 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/m²
    - Dominant in-atmosphere load > 63 W/m²
  - 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

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

- **Pre-launch Subcooling using launch pad subcoolers or a thermodynamic cryogen subcooler**
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.
LH2 + LOx Main Engine Needs to be developed

- Thrust: 890 N
- 440 s lsp
- 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
TOPS Main Propulsion System

ENGINE PERFORMANCE
- $P_c$: 90 psia
- $M_R$: 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 lb/sec
- LH2 flowrate: 0.0818 lb/sec

Chamber/Nozzle Assumptions
- $E_{th}$: 0.06
- $E_{sc}$: 0.068
- $dP/P_c$ (in): 20%
- $dP/P_c$ (fin): 12%

Pump Assumptions
- LOX Pump $P$: 114 psia
- LOX pump efficiency: 45%
- LOX pump power reqd: 259 Watts
- LH2 Pump $P$: 127 psia
- LH2 pump efficiency: 40%
- LH2 pump power reqd: 1118 watts

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Subcooling Demonstration

Cryogen Tank

Advanced Insulation
(5 Layers of LRMLI + 40 Layers of IMLI)
Roadmap

2015: TRL 6

2016: TRL 6

2017: TRL 6

2022: TRL 9