A Heat and Mass Transfer Model of the Orion European Service Module Propulsion Sub-System

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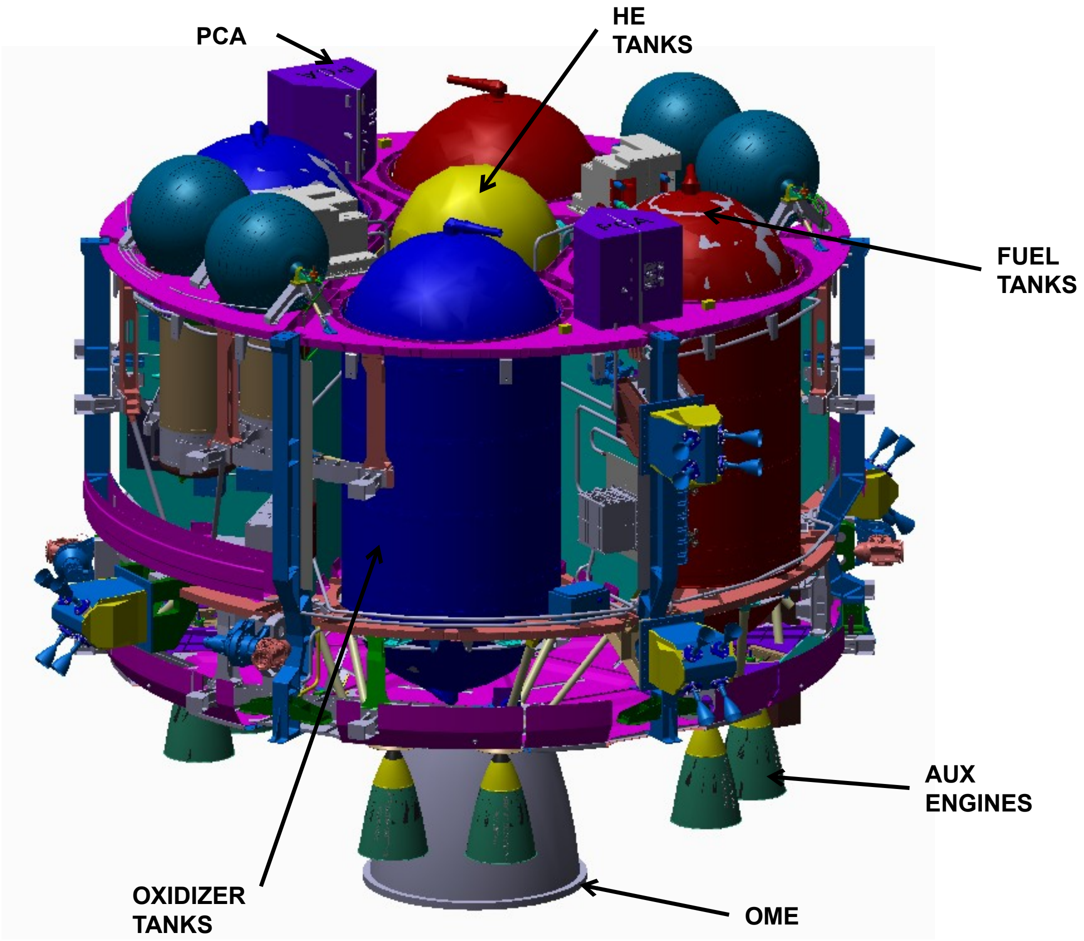
Supported by the European Service Module Propellant Integration Team Project

Orion European Service Module Thrusters

- Hypergolic, pressure fed, common supply
- 1x Space Shuttle Orbital Maneuvering System (OMS) AJ10-190
  - 27 kN (6000 lbf) thrust with TVC
  - AM1 engine a spaceflight veteran:
    19 missions, 89 burns.
- 8x Auxiliary thrusters (PlusX), European ATV heritage
  - 490 N (110 lbf), no TVC
  - Trajectory corrections
  - Backup to OMS
- 24x Reaction Control System thrusters, ATV heritage
  - 220 (50 lbf) thrust
  - 12 nominal, 12 backup
  - 6 clusters of 4 thrusters

Propulsion Subsystem (PSS)

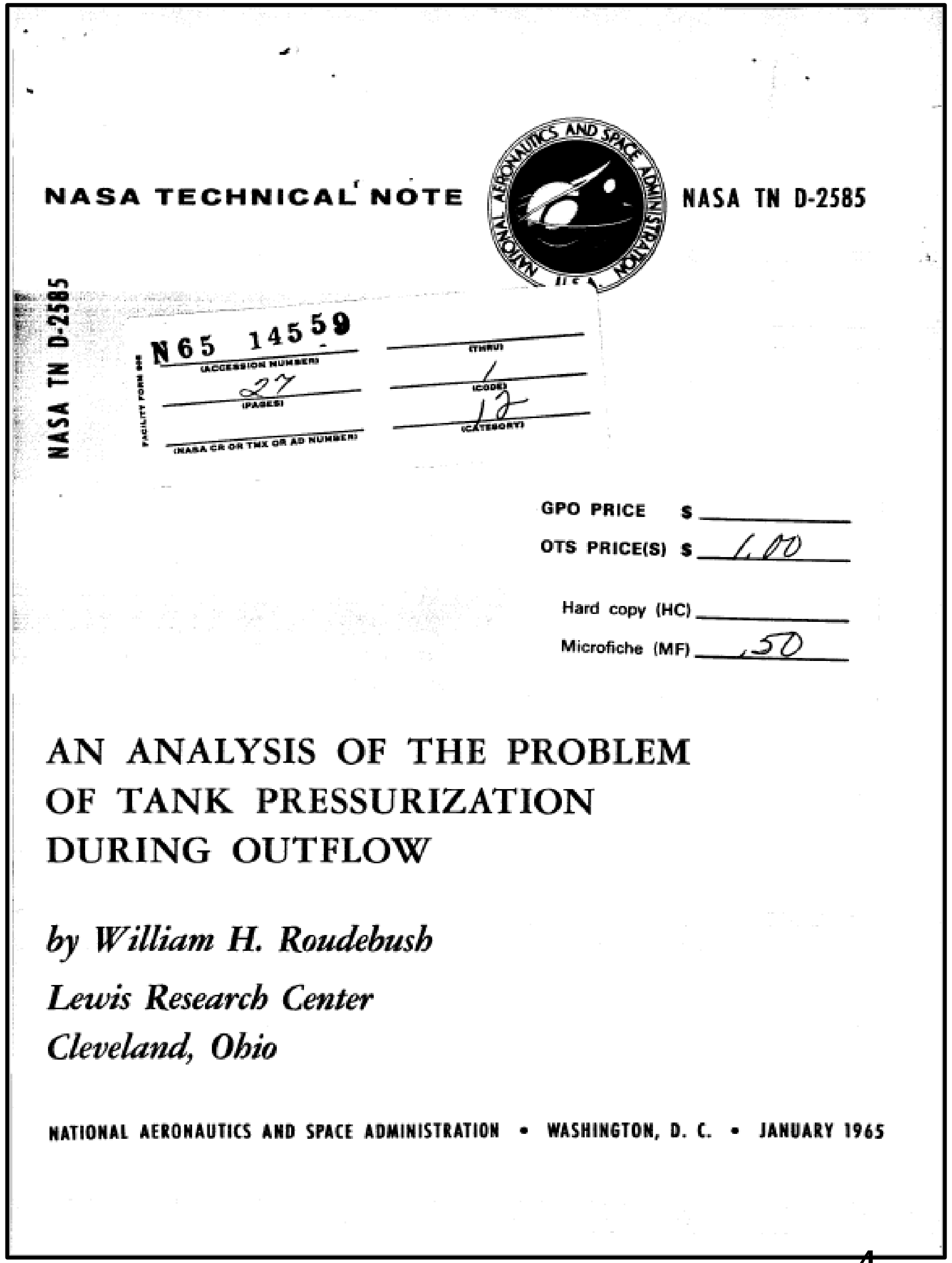
- Two helium tanks
  - 300 L, 0.41 meter radius
  - Up to 400 bar pressure
  - Cross-feed as backup (for AM2+)
- Four propellant tanks
  - 2 m^3 each, ~10 tons total propellant
  - Two tanks mixed oxides of nitrogen (MON)
  - Two tanks monomethyl hydrazine (MMH)
  - Serial configuration
- Solenoid valves and electronic pressure regulation
  - Programmable set-points, 17 bar nominal



Prior Art

Time stepping methods for analyzing spacecraft propulsion systems

- An Analysis of the Problem of Tank Pressurization During Outflow
  NASA TN D-2585 (1965)
- Modeling of the Intelsat VI bipropellant propulsion subsystem AIAA-1993-2518
- Development and Validation of Fluid Thermodynamic Models for Spacecraft Propulsion Systems (Journal of Propulsion and Power 2001)



NASA TECHNICAL NOTE NASA TN D-2585

NASA TN D-2585

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AN ANALYSIS OF THE PROBLEM OF TANK PRESSURIZATION DURING OUTFLOW

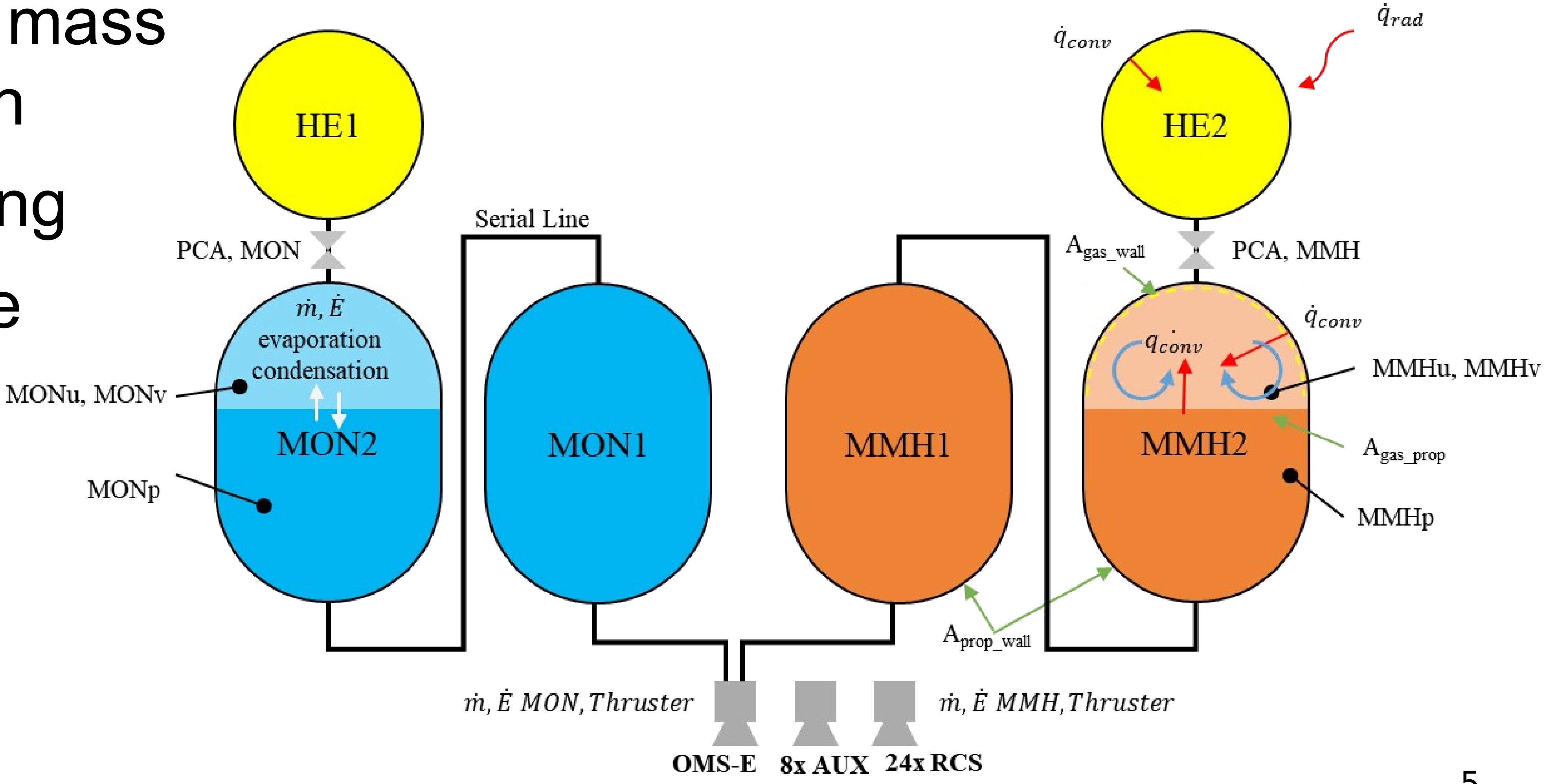
by William H. Roudebush

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1965

NASA GRC Heat and Mass Transfer (HMT) Code

- Energy and mass conservation
- Time-stepping
- Steady-state
- 1-D
- MATLAB
- ~150 state variables



Propellant Vaporization and Heat Transfer

- Propellant is a large mass in thin-walled titanium tanks
  - Heat transfer between liquid propellant and ullage gas
  - Heaters add energy to when propellant falls below 20ºC
  - No other heat exchanged with environment currently modeled
  - Evaporation and condensation assumed instantaneous to maintain saturated vapor
- Geometry changes affect heat transfer
  - During coast, ullage assumed to be a spherical bubble in center of tank
  - During thrusting, circular interface between ullage and liquid
- Observations
  - Ullage cools as it expands during engine firing
  - Ullage warms as helium is added during pressurization
  - Thermal mass leads to slow changes in liquid temperature

Nitrogen Tetroxide Venting
(from 1960s NASA Safety Video)

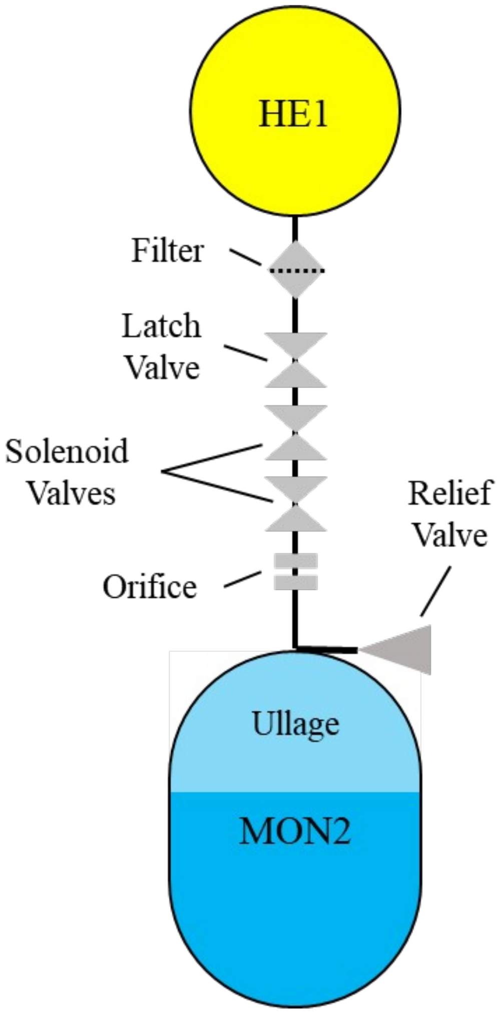
Helium and COPV Heat Transfer

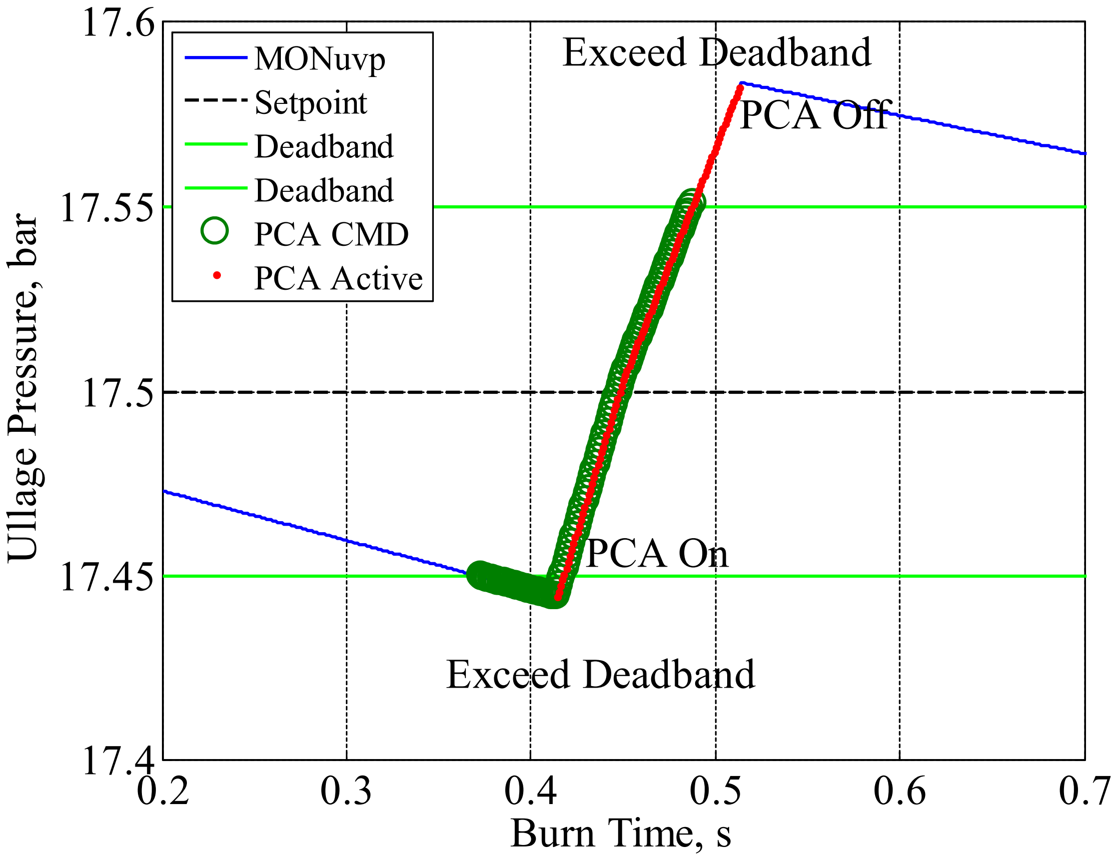
- High pressure helium gas used to maintain pressure in propellant tanks
  - Conductive heat transfer between COPV and helium gas
  - Radiative heat transfer between environment and COPV
- Observations
  - Large tank mass compared to mass of gas
  - Thermal mass of COPV significant
  - Helium cools as it expands

Example COPVs

Electronic Pressure Regulator

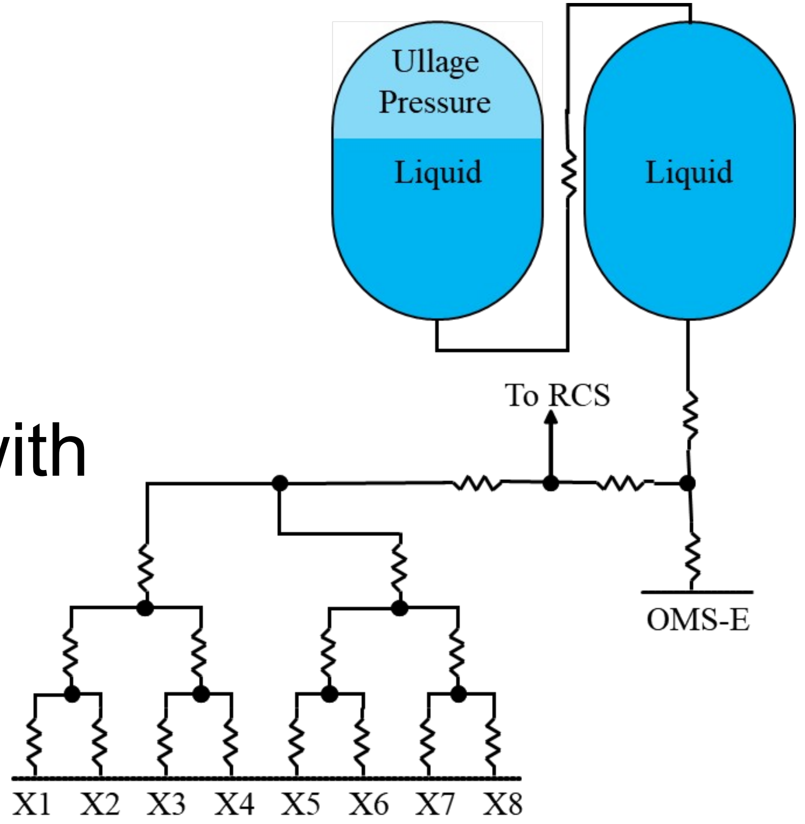
- Pressure Control Assembly (hardware)
- Pressure Regulation Unit (avionics)
- Latch valve enables system
- High-pressure solenoid valves
  - Setpoint, deadband
  - Timing, overshoot
- Orifice throttles flow
  - Choked and unchoked flow simulated, plus secondary losses

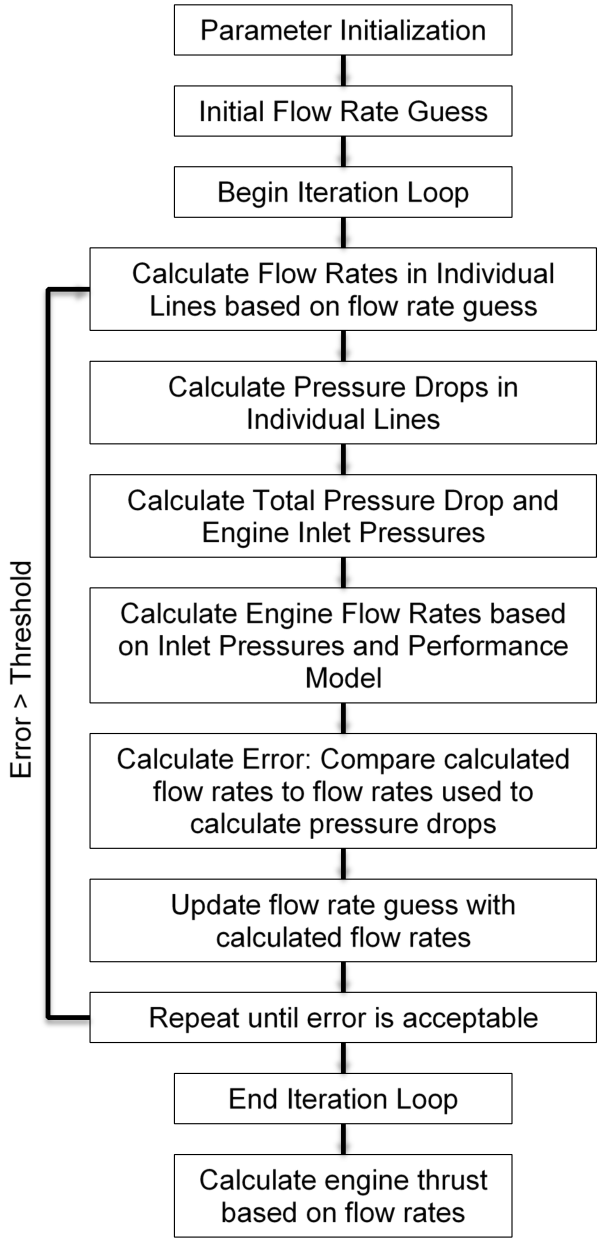




Piping Flow Model

- Network of fluid resistance coefficients
- Solved at each time step
  - Accounts for changing ullage pressure
  - Fluid density changes with temperature
- Momentum neglected





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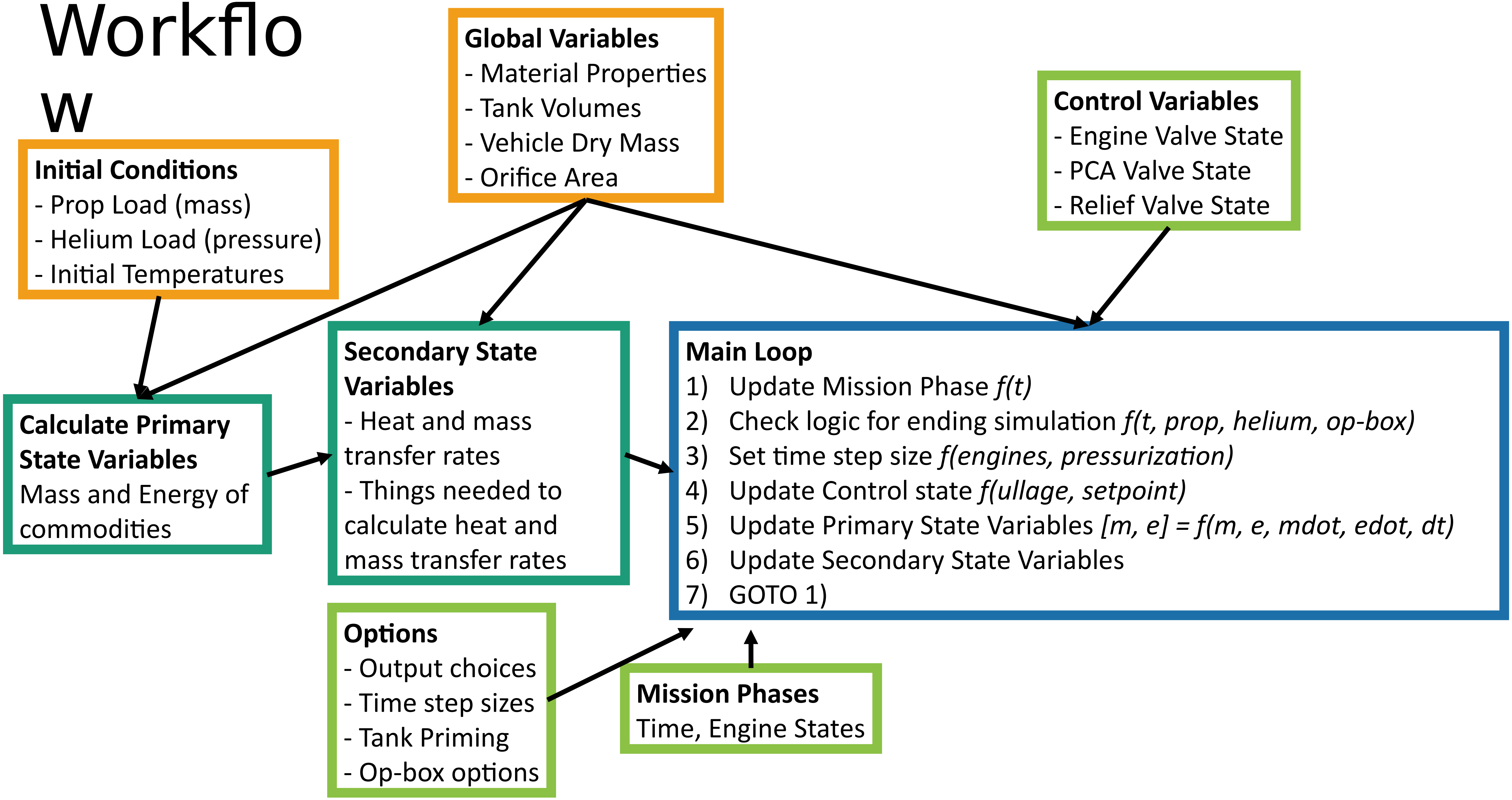
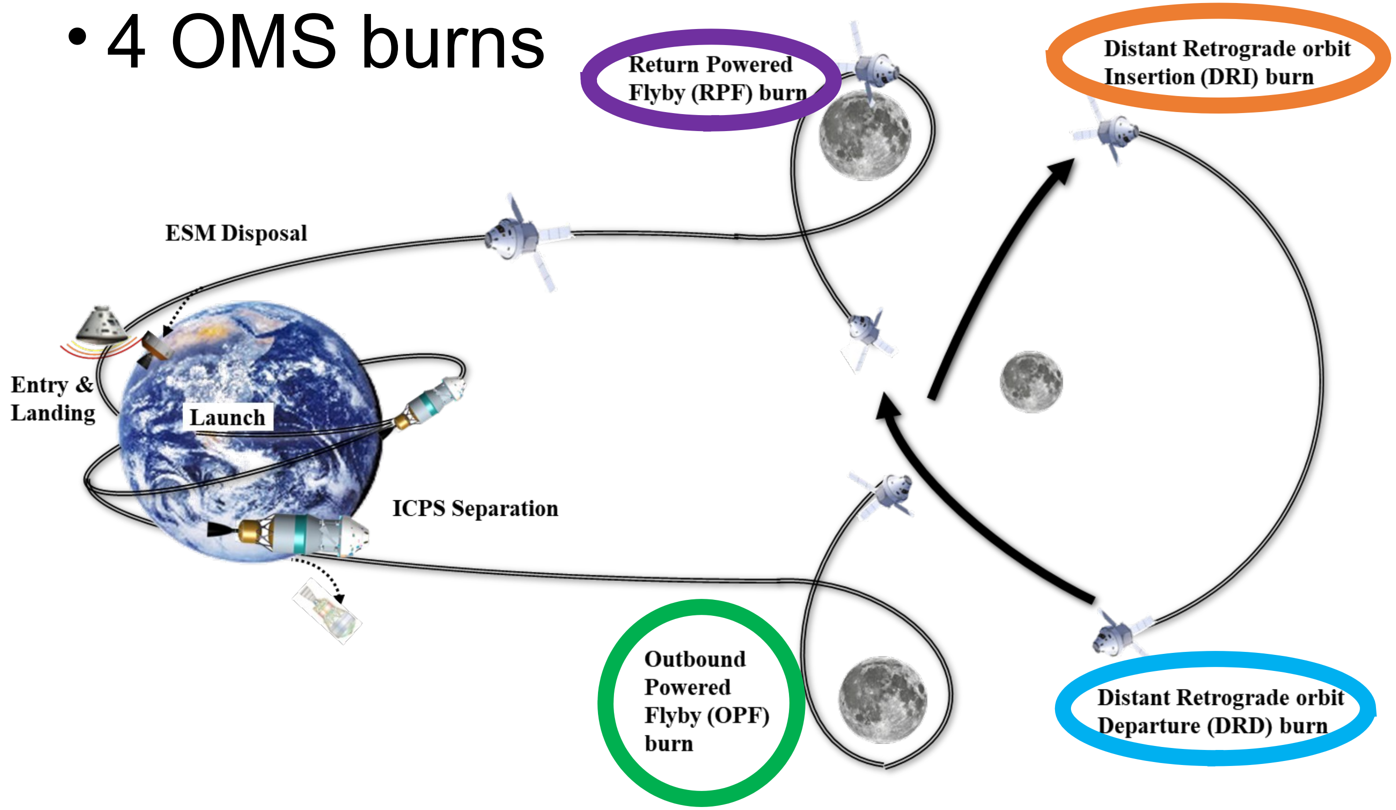

Global Variables
- Material Properties
- Tank Volumes
- Vehicle Dry Mass
- Orifice Area
Control Variables
- Engine Valve State
- PCA Valve State
- Relief Valve State
Initial Conditions
- Prop Load (mass)
- Helium Load (pressure)
- Initial Temperatures
Calculate Primary State Variables
Mass and Energy of commodities
Secondary State Variables
- Heat and mass transfer rates
- Things needed to calculate heat and mass transfer rates
Main Loop
1) Update Mission Phase f(t)
2) Check logic for ending simulation f(t, prop, helium, op-box)
3) Set time step size f(engines, pressurization)
4) Update Control state f(ullage, setpoint)
5) Update Primary State Variables [m, e] = f(m, e, mdot, edot, dt)
6) Update Secondary State Variables
7) GOTO 1)
Options
- Output choices
- Time step sizes
- Tank Priming
- Op-box options
Mission Phases
Time, Engine States

Example Mission

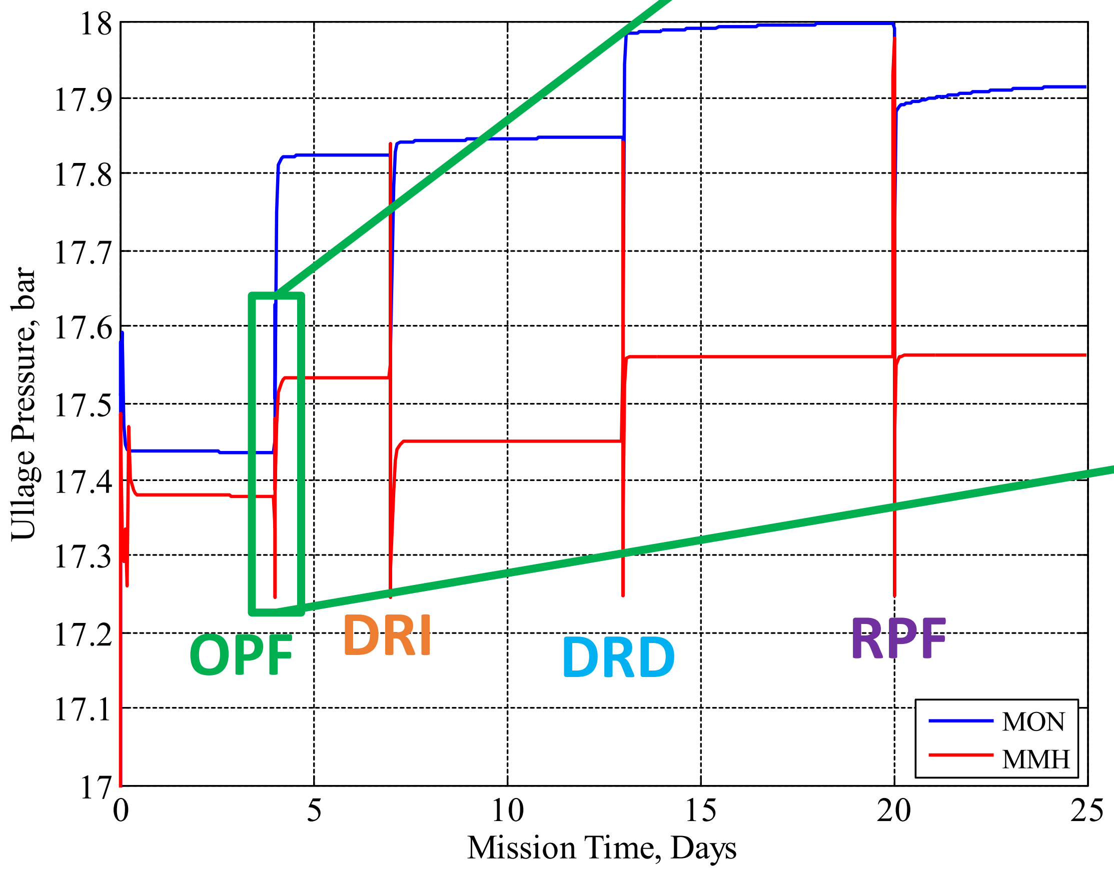
Δt OMS/PCA = 0.001 s
Δt Aux/RCS/100 s after burn = 0.1 s
Δt coast = 100 s
O(10 m) Simulation Time

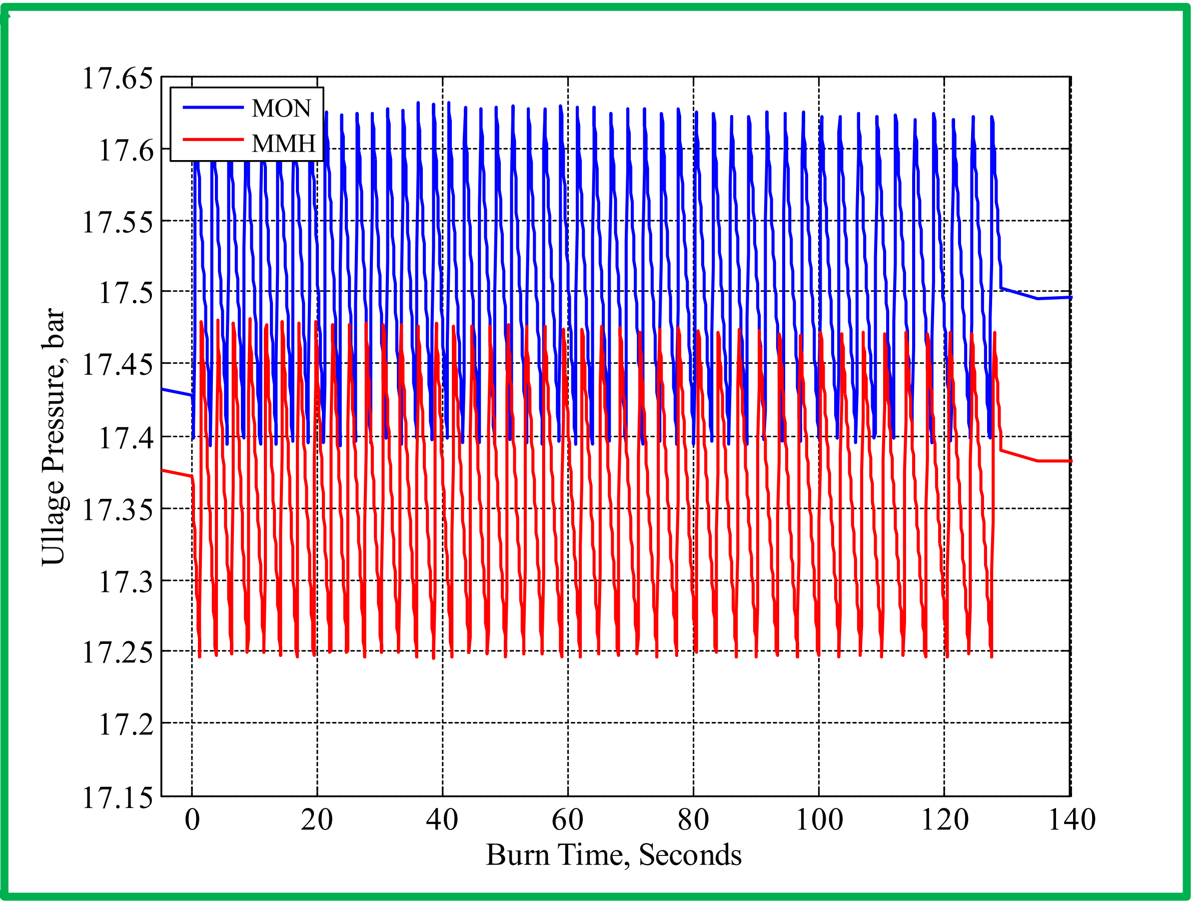
- 25 day (1-orbit) Distant Retrograde Orbit
  (43 day (2-orbit) mission also possible)
- 4 OMS burns



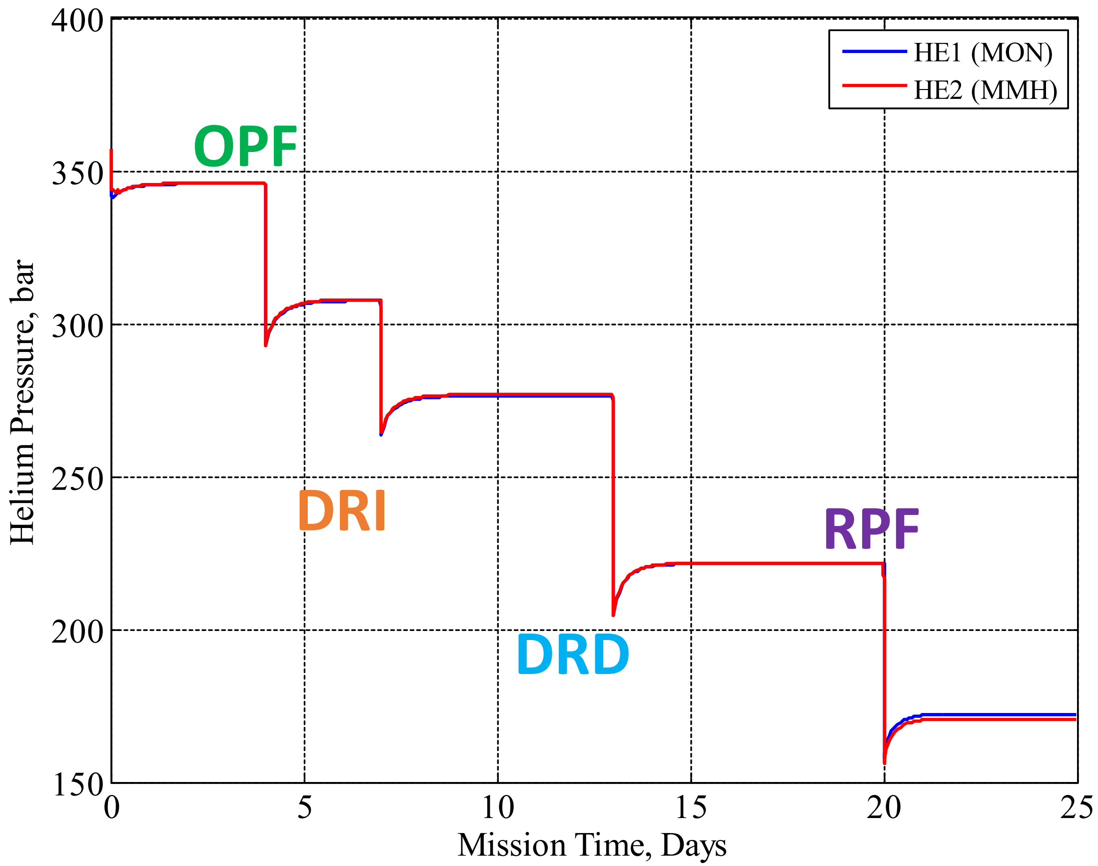
Mission Phase	Phase Duration		Mission Elapsed Time (s)	OMS Firing
Separation from Upper Stage	120	Seconds	120	0
Prime Tanks	10	Seconds	130	0
Coast	4	Days	345600	0
OPF	129	Seconds	345729	1
Coast	3	Days	604800	0
DRI	113	Seconds	604913	1
Coast	6	Days	1123200	0
DRD	199	Seconds	1123399	1
Coast	7	Days	1728000	0
RPF	195	Seconds	1728195	1
Coast	5	Days	2160000	0

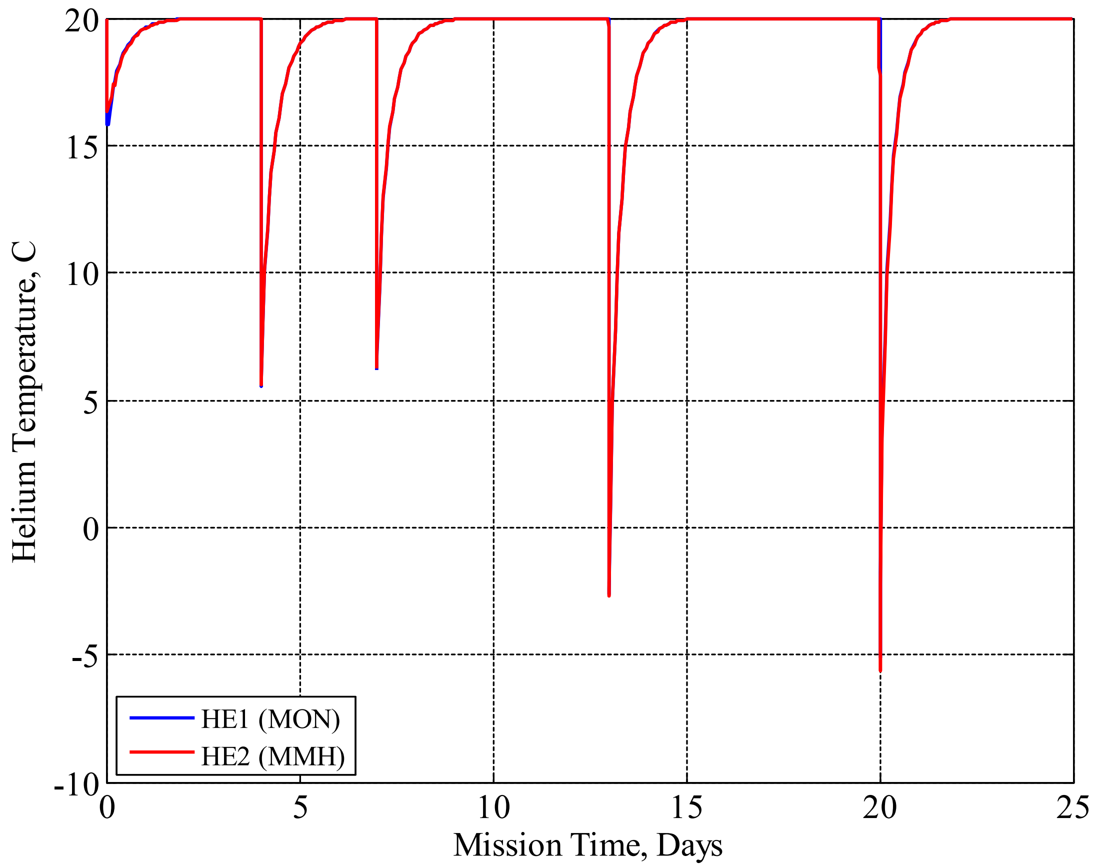
Example Results: Ullage Pressure



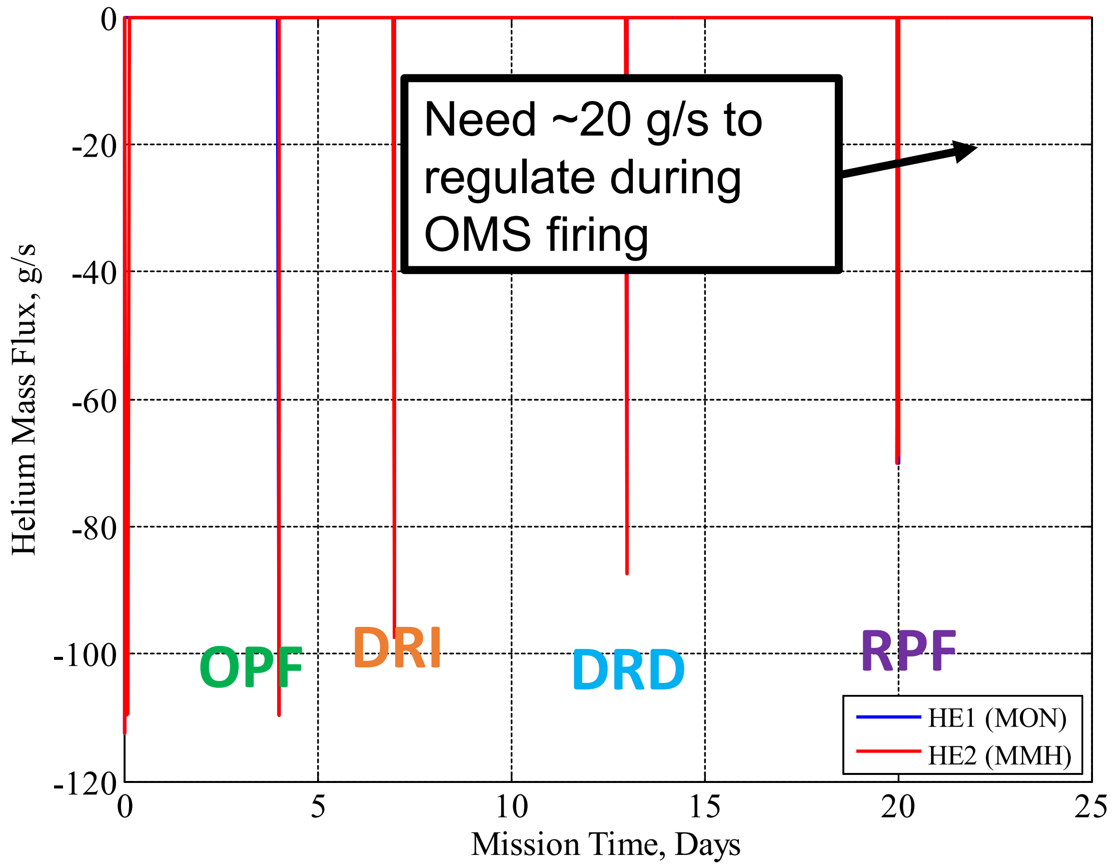


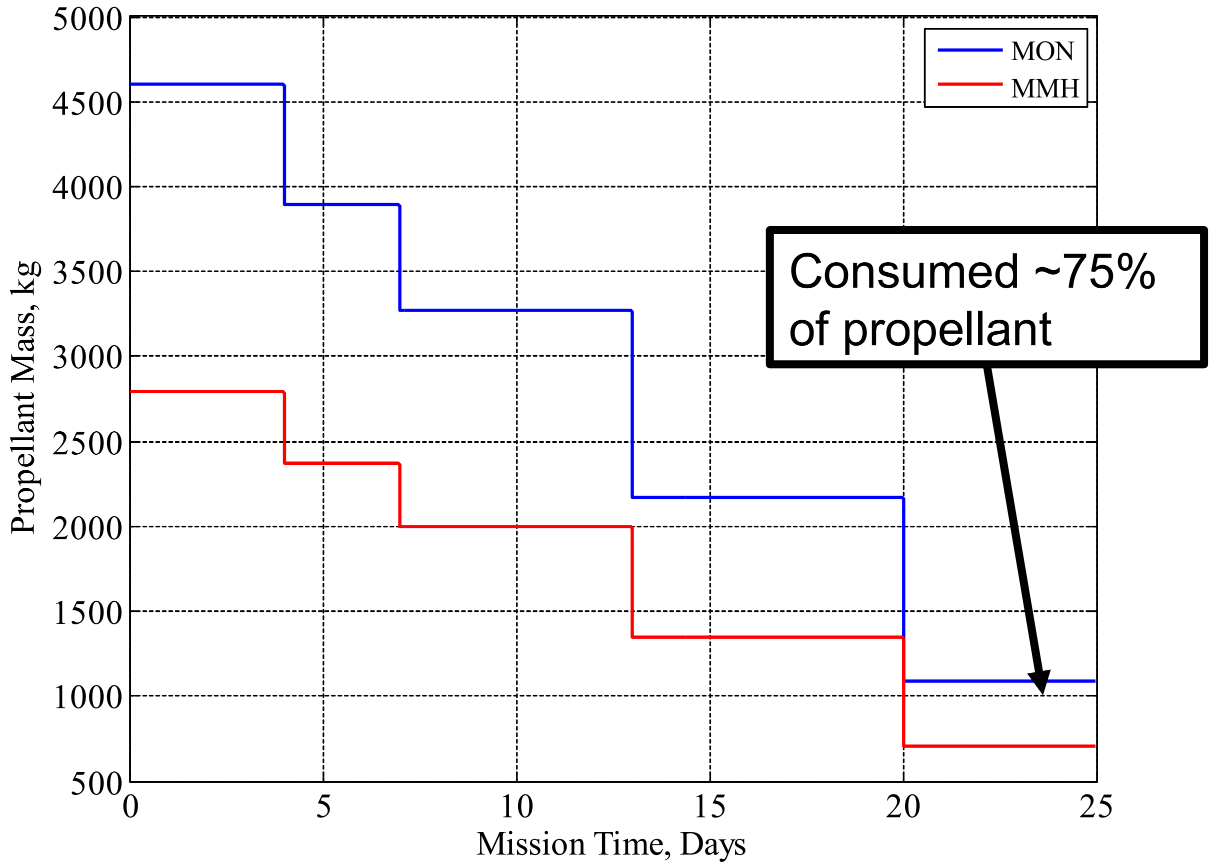
Example Results: Helium Pressure and Temperature





Example Results: Helium Mass Flux and Prop Mass





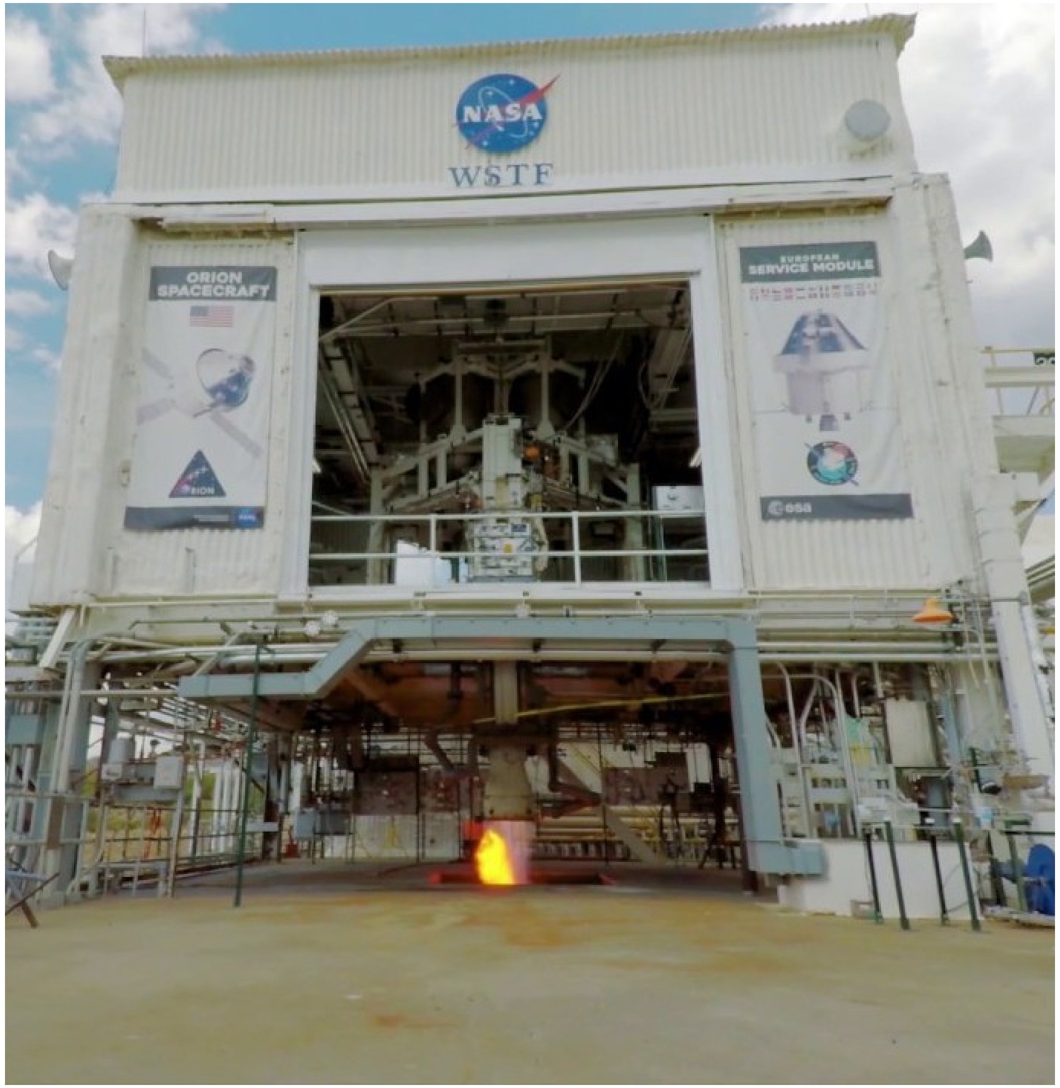
Summary

- A tool for modeling the thermodynamic state of the ESM PSS has been developed
- Code is fast, flexible and relatively easy to modify
- Multiple applications
  - Commodity consumption
  - Capabilities evaluation
  - Mass gauging
  - Avionics simulation

AM1 Orion and SM at NASA GRC
Plumbrook Station Vacuum Chamber

Future Work

- Helium solubility in propellants
- Timescales for vapor equilibrium
- Conductive/radiative heat transfer between components, sun exposure, mission, firing
- Individual propellant tanks



ESM Propulsion Qualification Module
Test Firing at White Sands Test Facility

Acknowledgements

- Former NASA GRC engineer **Aaron Schinder** developed the initial version of the HMT code
- Technical Guidance by **Jon Millard**, Prop Integration Engineering Team Lead
- GRC Propulsion Division sponsored conference participation

NASA GRC Aircraft Hanger

Questions?