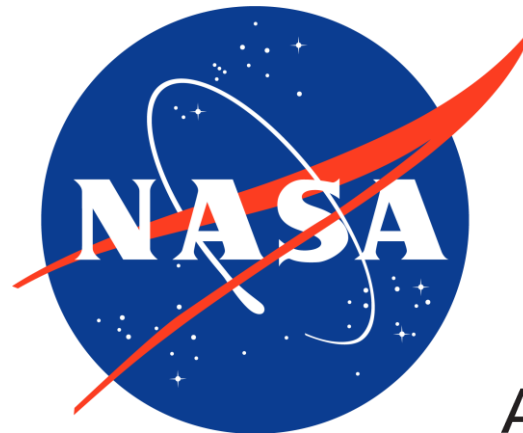


In-Situ Alternative Propellants for Nuclear Thermal Propulsion Systems

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Introduction

- Water, ammonia, and carbon oxides have been found on the Moon and our current technology has the capability to extract and process these resources. [1]
  - This will make reusable space transportation vehicles possible.
- Nuclear thermal propulsion (NTP) engines can theoretically use any fluid as a propellant provided that significant core material degradation does not occur.
- Analysis is currently underway to understand how water and ammonia impact NTP engine performance.
- Water/ammonia NTP engine performance will help determine mission architectures that could be more beneficial than both chemical and hydrogen-NTP.



Challenges with Hydrogen

- Hydrogen can provide a high specific impulse (I_{sp}) of ~900 seconds in NTP engines.
- Hydrogen has some unfavorable properties:
  - Low Boiling Temperature (20 K)
  - Low liquid density (7.1% to 8.6% that of water)
  - High specific heat capacity (3.5 times greater than that of water)

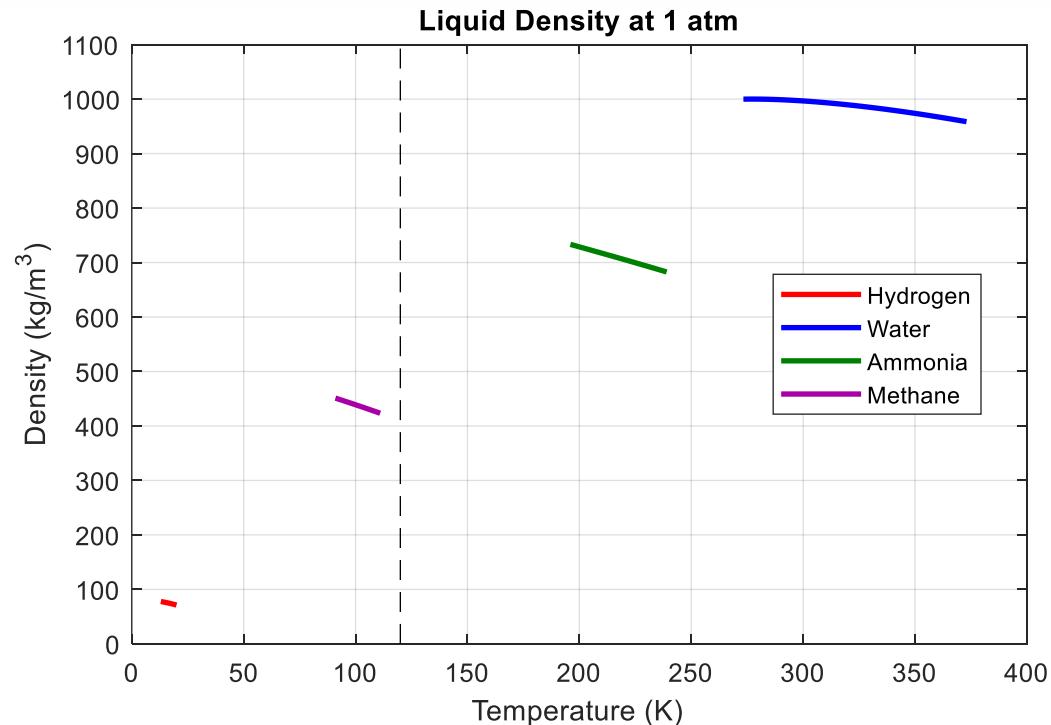


Figure 1: Propellant Liquid Densities

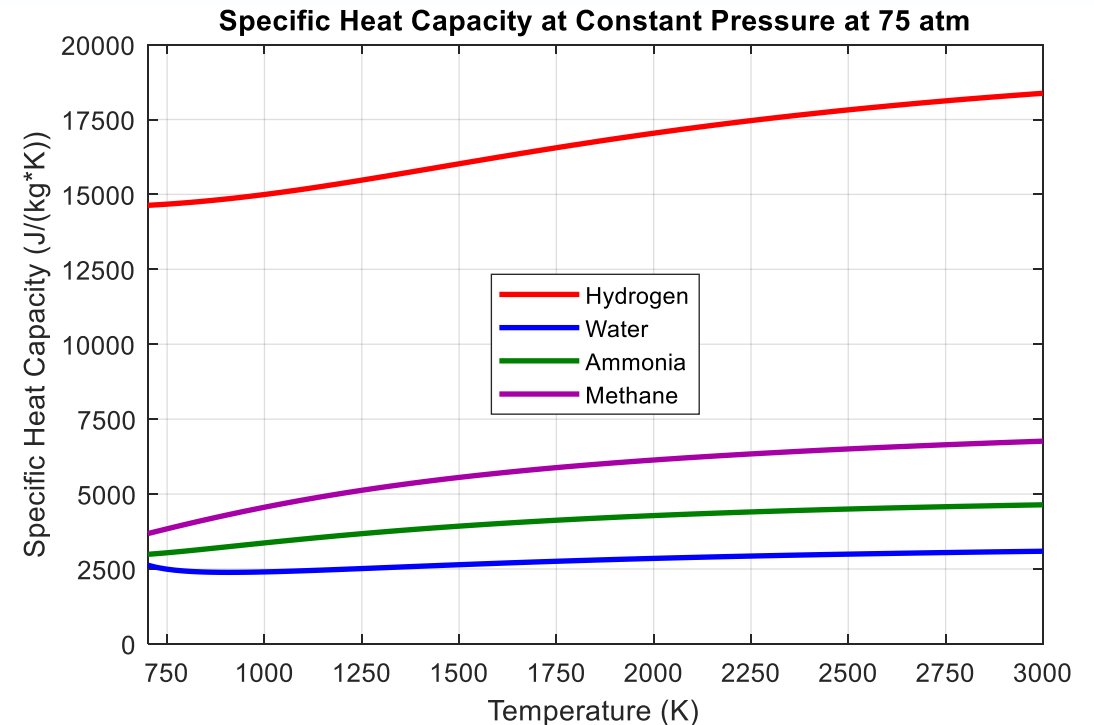


Figure 2: Propellant Gaseous Specific Heat Capacities

A Simpler Vehicle Architecture

- Denser and non-cryogenic propellant will reduce tank size and dry mass.
- Wider liquid phase temperature range does not require precise thermal management.
- Lower specific heat capacity will decrease the reactor power level given a thrust level or increase the thrust level given a reactor power level.
- This type of propellant:
  - Yields lower I_{sp}
  - Increases initial vehicle wetted mass resulting in longer burn times.
  - If reusability is considered, partially tanked stages/vehicles can be sent from Earth.
  - Decreases dry mass and thus cost.



Energy Limited Propulsion Systems 1

- Encompasses both NTP and electrical propulsion.
- The purpose of any transportation system is to get something from point A to point B.
- The Ideal Rocket Equation provides information about a single mission and focuses on propellant mass.
- Assuming propellant availability on the Moon and spacecraft reusability, a different parameter should be used.
- In electrical and NTP engines, the propulsion system introduces energy into the propellant rather than chemical engines where the energy is inside the propellant.
- This energy can be adjusted to meet mission parameters.
- Electrical propulsion is power limited (limited by wattage) while NTP is energy limited (limited by joules).



Energy Limited Propulsion Systems 2

- $E_{tot} = \frac{1}{2} m_{prop} V_e^2 = \frac{1}{2} m_{prop} (I_{sp} g_0)^2$
- Specific energy $E_{sp} = \frac{E_{tot}}{m_{dry}}$:
  - PER TRIP
  - In chemical propulsion, $E_{sp} = \frac{E_{tot}}{m_{prop}}$.
  - Scales with m_{dry} in electrical propulsion systems
- In NTP systems, 1 kg of ^{235}U will produce 86.4 TJ of energy. Therefore, the total energy OF THE VEHICLE ☞ depends on the total mass of usable ^{235}U inside the NTR core.
- ☞ can be divided by the number of desired flights to yield E_{tot} while m_{dry} remains constant.
- In the NASA-AR HALEU NTP engine, based on BWXT's reactor parameters, the total usable ^{235}U mass will yield ☞ of about 30 TJ.

By replacing m_{prop} with $\frac{2E_{tot}}{(I_{sp}g_0)^2}$ from kinetic energy,

the Ideal Rocket Energy Equation is obtained:

$$\frac{m_{payload}}{m_{dry}} = \frac{\frac{2E_{sp}}{(I_{sp}g_0)^2}}{\exp\left(\frac{\Delta V}{I_{sp}g_0}\right) - 1} - 1$$

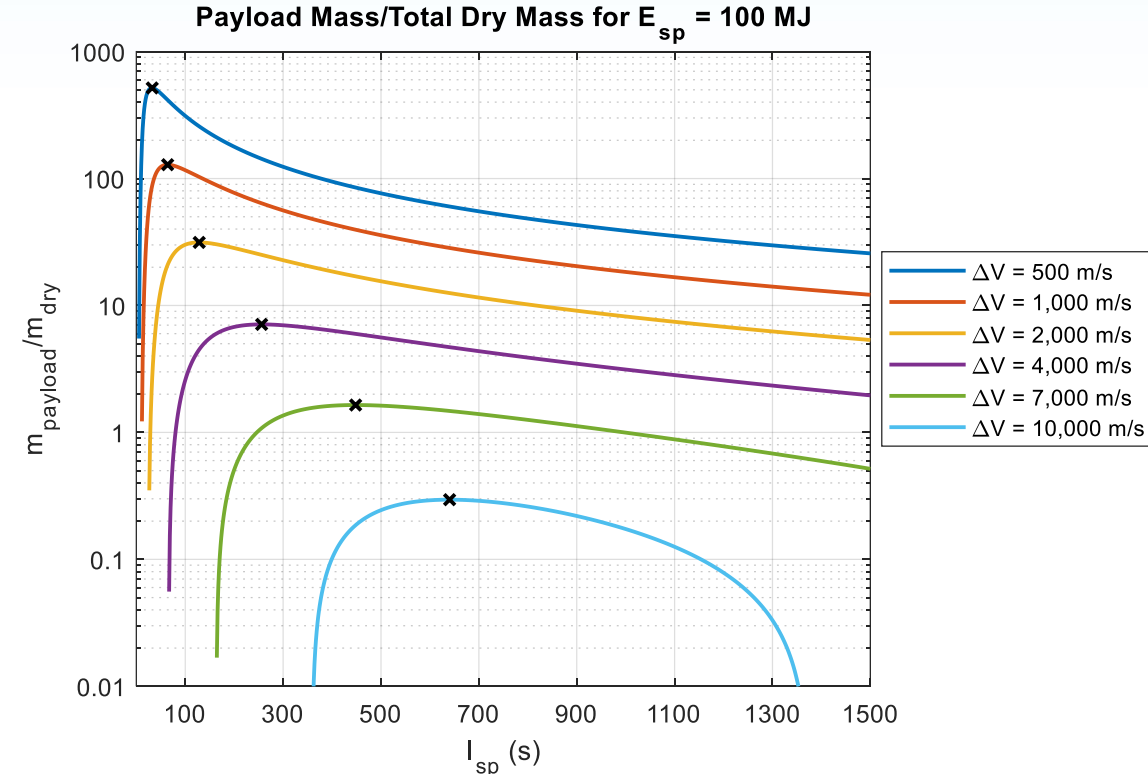


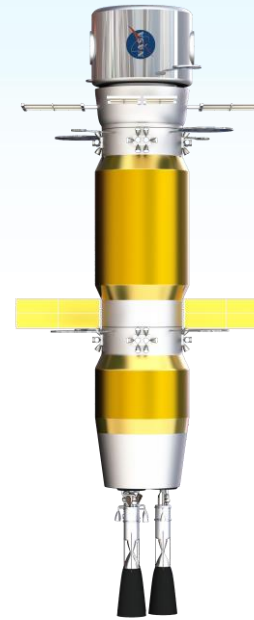
Figure 3: Relations among Specific Impulse, Delta-V, and Payload to Dry Mass Ratio

Energy Limited Propulsion Systems 3

The $I_{sp_{opt}}$ concept can be explained with a Mars Transfer Vehicle for a conjunction class mission that has a ΔV of 4200 m/s and E_{tot} of 3 TJ (1 TJ per engine).



- Hydrogen NTP
- I_{sp} of 875 seconds
- 4 stages
- 5 SLS aggregation launches
- Will be able to perform 1st mission after aggregation
- 6 Lunar launches for reusability
- Requires propellant grade water and electrolysis plants



- Ammonia NTP
- I_{sp} of 360 seconds
- 2 stages
- 3 SLS aggregation launches
- Requires additional 12 Lunar launches to perform 1st mission
- 15 Lunar launches for reusability
- Requires an ammonia scrubber which is already in the considered architecture.

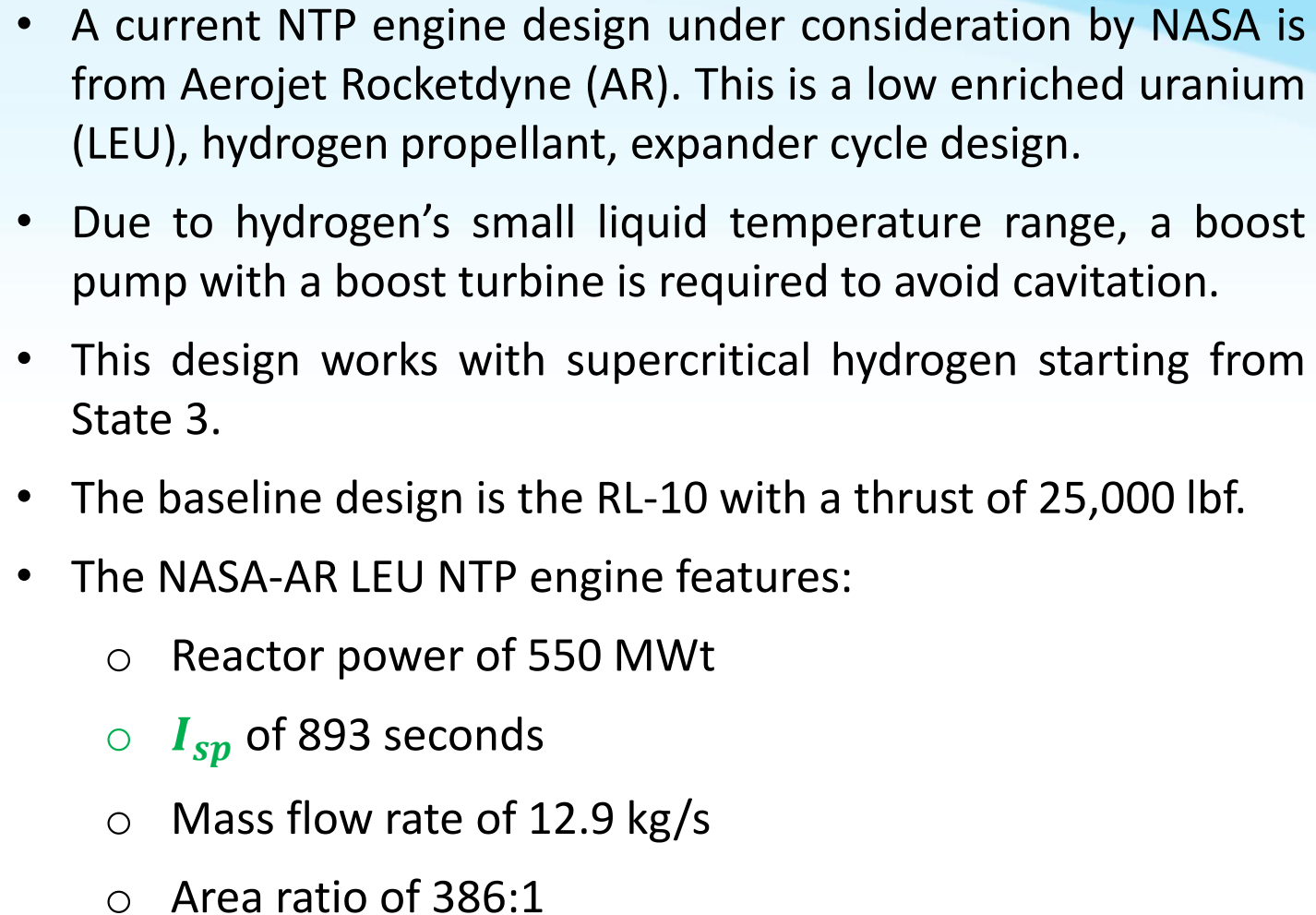
This study will address the question of, “*Is trading no electrolysis plants for more Lunar launches advantageous?*”

Operation Time Limited Propulsion Systems

- Total operational time $\mathcal{T}$ is a function of both chemistry and temperature
- $\mathcal{P}$ is the hard limit inherent to NTP engines and another limit is the maximum design power $\mathcal{Q}$.
- $\mathcal{P}$ will provide an operational time of over 15.7 hours.
- Ammonia has not shown any significant adverse reactions with the baseline Tungsten and ZrC coating.
- Water is highly reactive at high temperatures, so Silicon Carbide (SiC) will need to be used for fuel element coatings.
- At NTP flow rates and pressures, this coating will only survive a single flight [51-54].
- Bringing T_s down will bring I_{sp} down but increasing thrust up to the $\mathcal{Q}$ limit could bring the $\mathcal{T}$ and $\mathcal{P}$ limits closer together.



A diagram of a red cylindrical tank labeled "LH2 Tank". The tank is partially filled with a red liquid, indicated by a horizontal line. A blue arrow points upwards from the bottom left of the tank, and a blue arrow points downwards from the bottom right of the tank.



Engine Models

Engine architectures consider:

- Insights from NASA's NTP Engine System/FMDP Conceptual TRD, of which BWXT and AR are providing support for engine, reactor and fuel design and analysis.
- Both expander and bleed cycles
- Engine transients
- Maximum fuel temperature of 2850 K [48,50]
- Thrust levels:
  - 25 klbf
  - 15 klbf
  - At $\dot{Q}_{max}$
- Line pressure losses

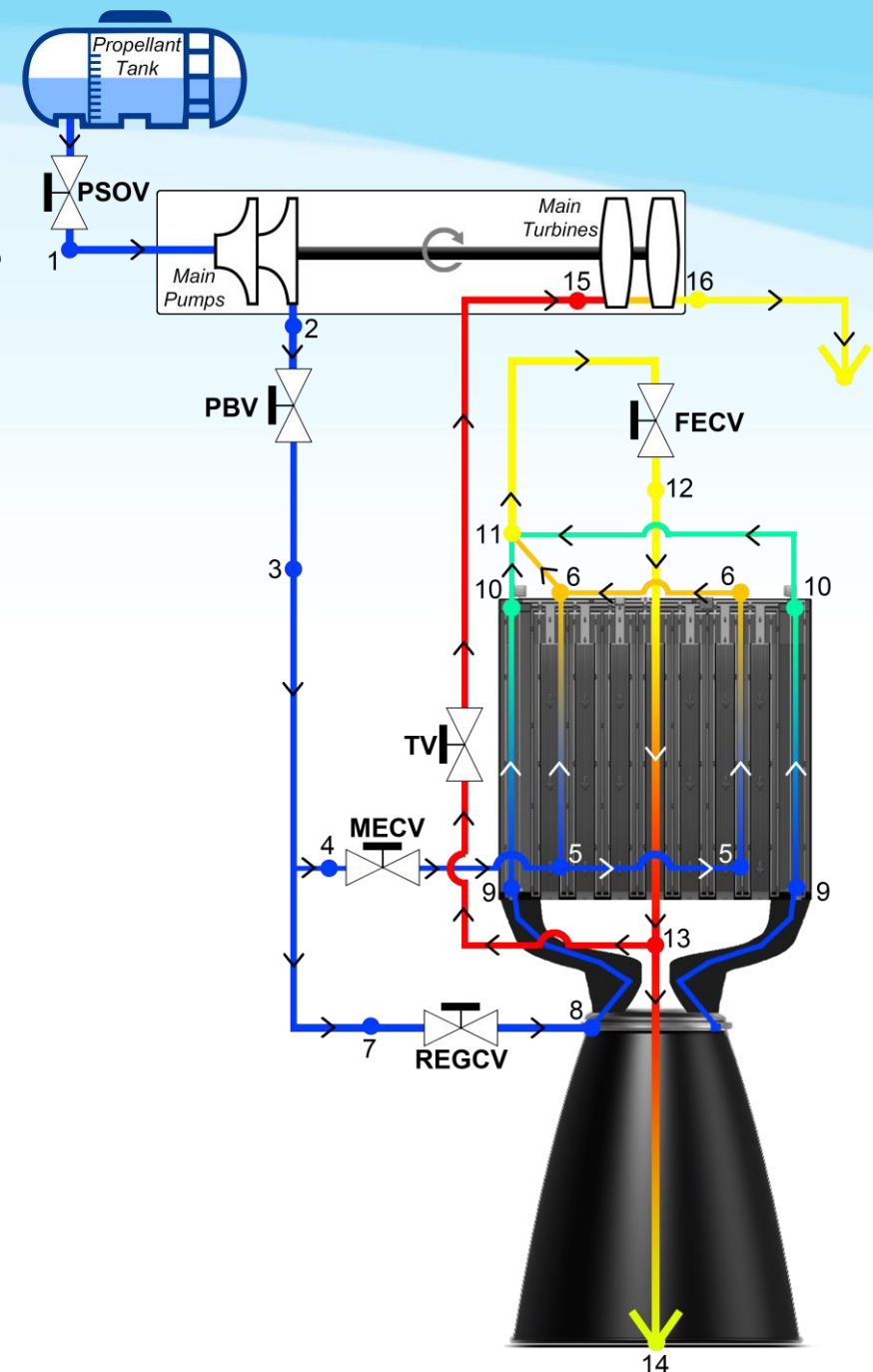


Figure 6: Bleed Cycle NTP Engine Model

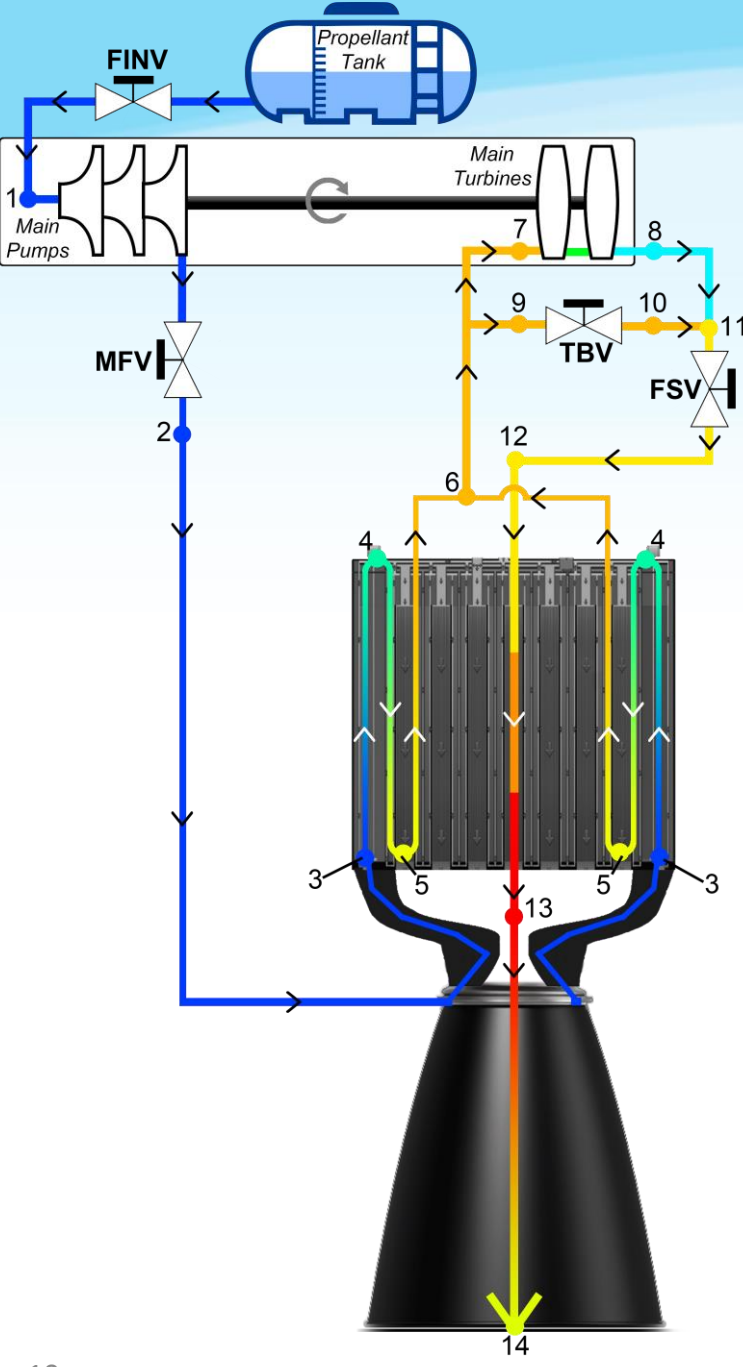


Figure 5: Expander Cycle NTP Engine Model

Engine Model (Ammonia)

MODEL SETUP

☒ Transient
 ☐ Steady State
 Save ☐ No Save
 # of Iterations per Step: 200

Thermal Profile: T0
  $\dot{T}$: 70 [K/s]
  $\dot{Q}$: 13.25 [MW/s]
  T_{max} : 2500 [K]

P0max: 68 [atm]
 Pressure Step: 1 [atm]
 Simulation Set Number: 1

GRAPH SETTINGS

Main	Preheat	Moderator	Control Drums	Nozzle
On	On	On	On	On
Off	Off	Off	Off	Off

Performance Parameters

Thrust: 42.7750 [klbf] 190.27 [kN] Isp: 355.49 [s]

$\dot{m}$: 54.577 [kg/s]
  T_0 : 2495.7 [K]
  P_0 : 68.012 [atm]

$\dot{Q}_{main}$: 399 [MW]
  T_{fmax} : 2807 [K]
  T_{smax} : 2622 [K]

$\dot{Q}_{pre}$: 103.0 [MW]
  T_{fmax} : 1038 [K]
  T_{smax} : 718 [K]

$\dot{Q}_{mod}$: 19.3 [MW]
  T_{smax} : 344 [K]
  $\dot{Q}_{tot}$: 527.3251 [MW]

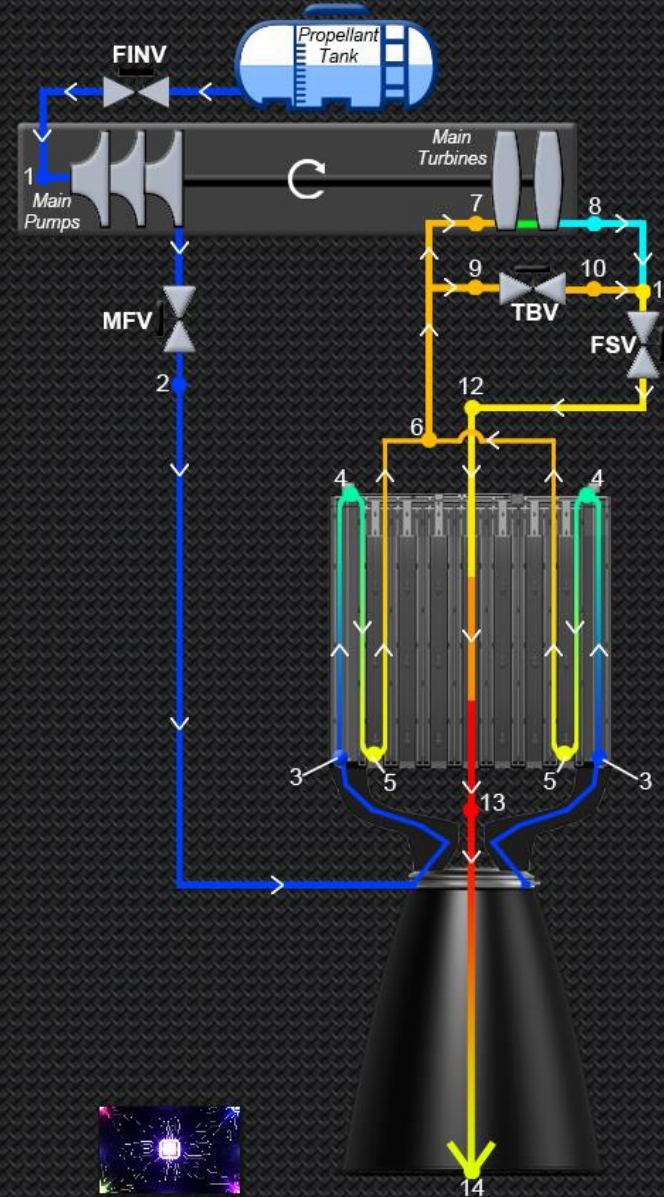
$\dot{Q}_{CD}$: 5.3 [MW]
  T_{smax} : 328.0 [K]

Wpump1: 504.83 [kW]
 Wpump2: 456.94 [kW]
 Wpump3: 456.68 [kW]
 Shaft RPM: 11363

η_{pump1} : 58.276 [%]
  η_{pump2} : 58.299 [%]
  η_{pump3} : 58.322 [%]

Wturb1: 3215.3 [kW]
 Wturb2: [kW]
 Turbine Bypass Flow: -- [%]

η_{turb1} : 68.733 [%]
  η_{turb2} : [%]



CALCULATE

ENGINE STATES			
S1	$\dot{m}$: 55 kg/s	T_0 : 200 K	P_0 : 1 atm
S2	$\dot{m}$: 55 kg/s	T_0 : 208 K	P_0 : 267 atm
S3	$\dot{m}$: 55 kg/s	T_0 : 244 K	P_0 : 257 atm
S4	$\dot{m}$: 55 kg/s	T_0 : 266 K	P_0 : 250 atm
S5	$\dot{m}$: 55 kg/s	T_0 : 344 K	P_0 : 227 atm
S6	$\dot{m}$: 55 kg/s	T_0 : 696 K	P_0 : 192 atm
S7	$\dot{m}$: 31 kg/s	T_0 : 696 K	P_0 : 192 atm
S8	$\dot{m}$: 31 kg/s	T_0 : 646 K	P_0 : 116 atm
S9	$\dot{m}$: 24 kg/s	T_0 : 696 K	P_0 : 192 atm
S10	$\dot{m}$: 24 kg/s	T_0 : 683 K	P_0 : 116 atm
S11	$\dot{m}$: 55 kg/s	T_0 : 662 K	P_0 : 116 atm
S12	$\dot{m}$: 55 kg/s	T_0 : 659 K	P_0 : 102 atm
S13	$\dot{m}$: 55 kg/s	T_0 : 2496 K	P_0 : 68 atm
S14	$\dot{m}$: 55 kg/s	T_0 : 903 K	P_0 : 0 atm

Figure 7: Engine Model Inputs

Ammonia Expander Cycle Model Graphs

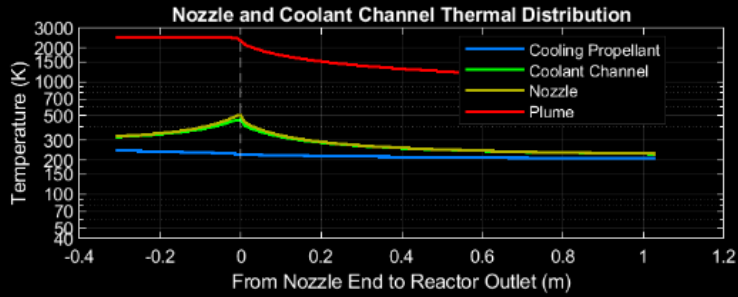
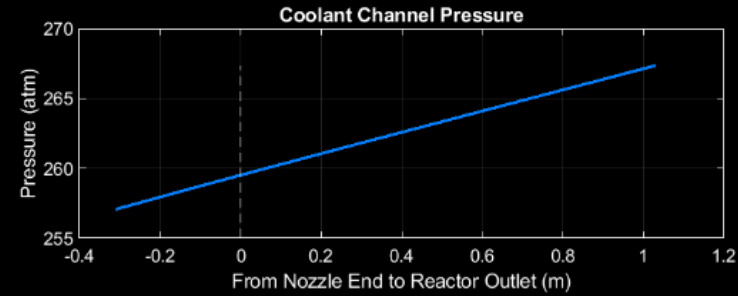
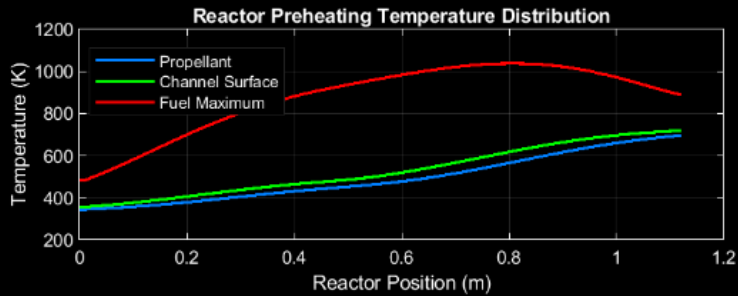
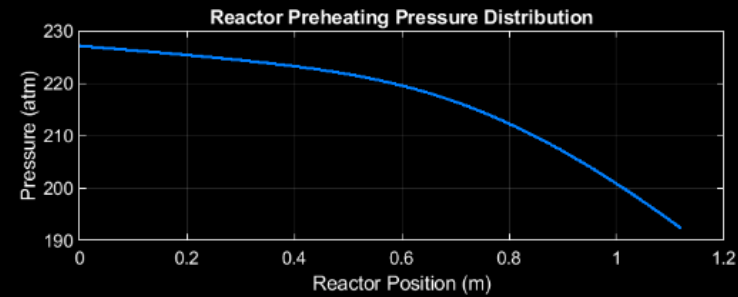
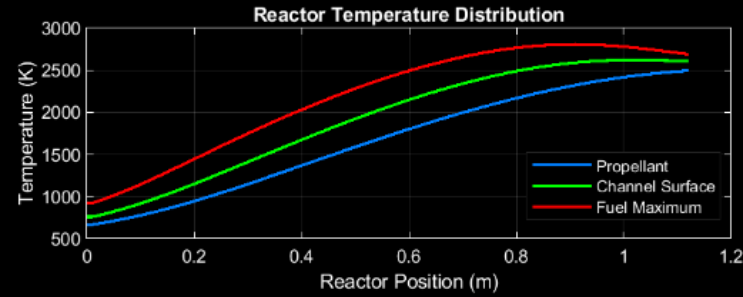
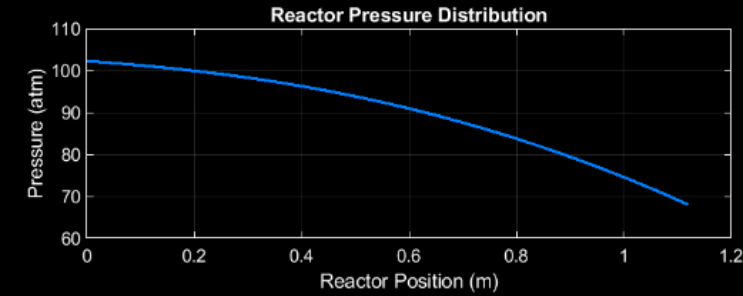
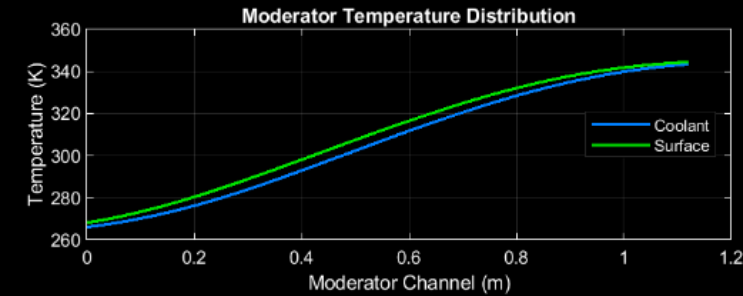
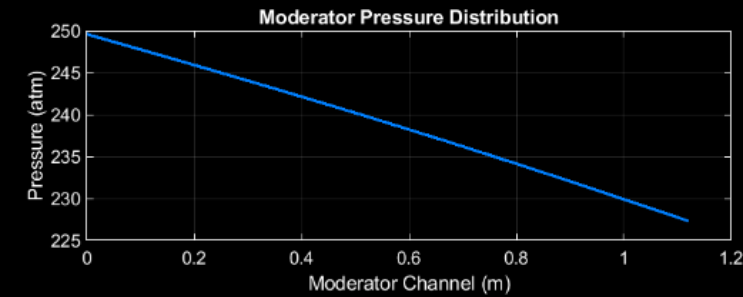
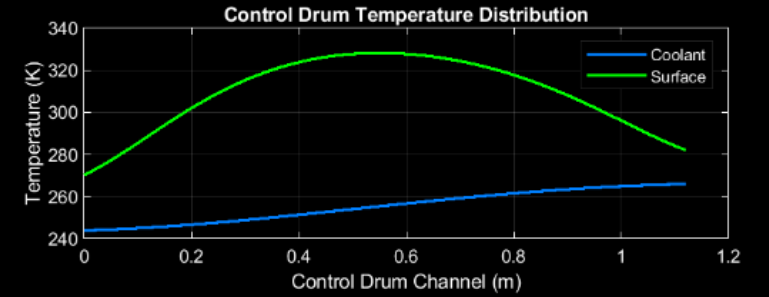
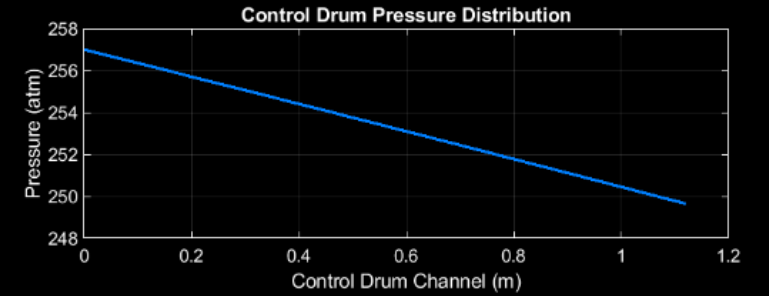


Figure 8: Expander Cycle Model Graphs

Water Bleed Cycle Model Graphs

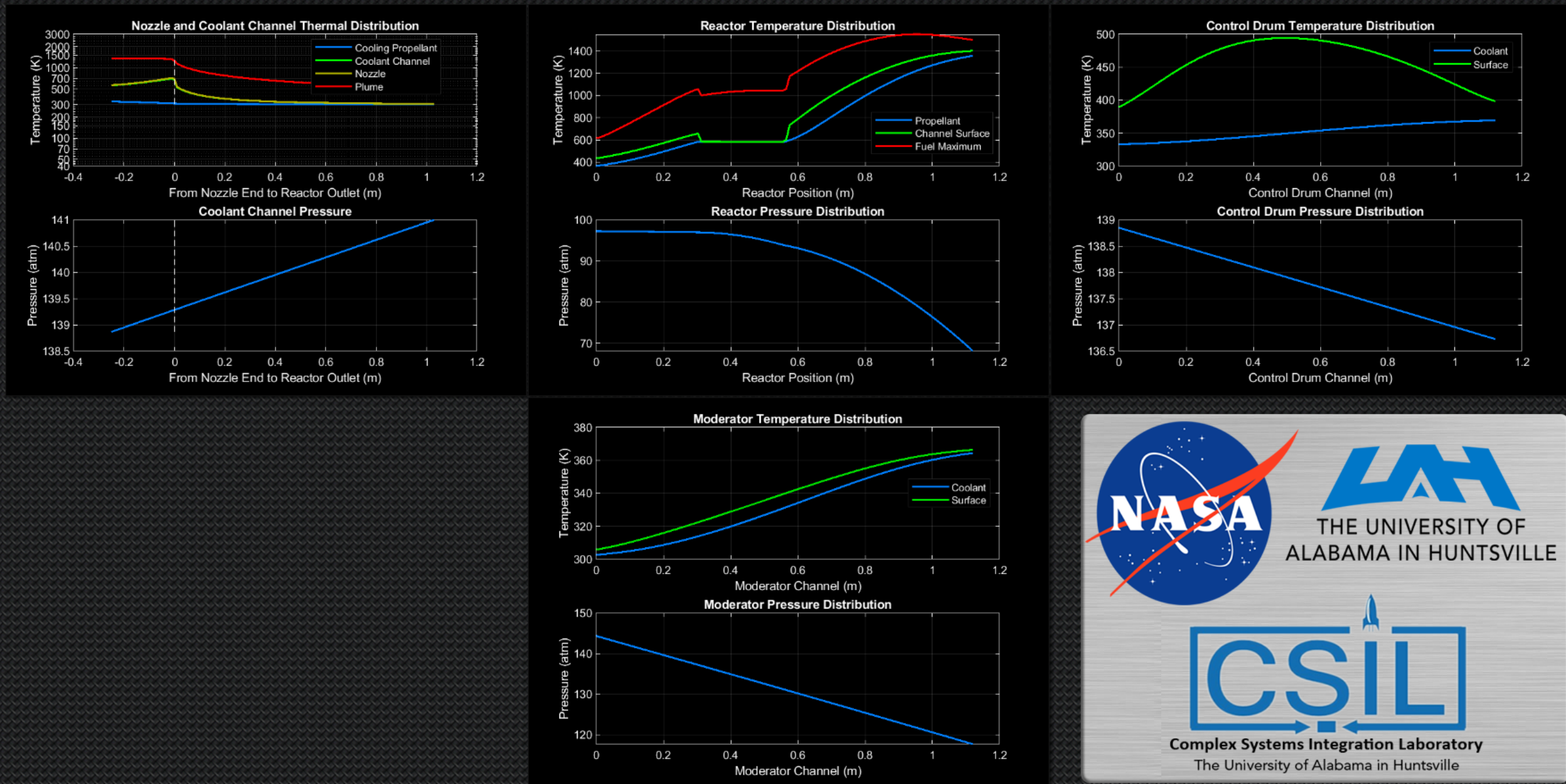


Figure 9: Bleed Cycle Model Graphs

Water NTP Results

- For a given reactor power level using **water**:
  - About **2X the thrust** of hydrogen-NTP can be achieved.
  - I_{sp} values range between:
    - 250 seconds** for sustainable cladding surface temperature (1400 K) and bleed cycle [51-54]
    - 315 seconds** for maximum cladding surface temperature (2400 K) and expander cycle [51-54]
- Multistage pump systems** (up to 7 stages to prevent cavitation) for expander cycles are required depending on thrust and surface temperature criteria. This results in pressures as high as 700 atm and a bleed cycle would be more feasible.
- Phase change **will occur** during engine transients and bleed cycle operation.

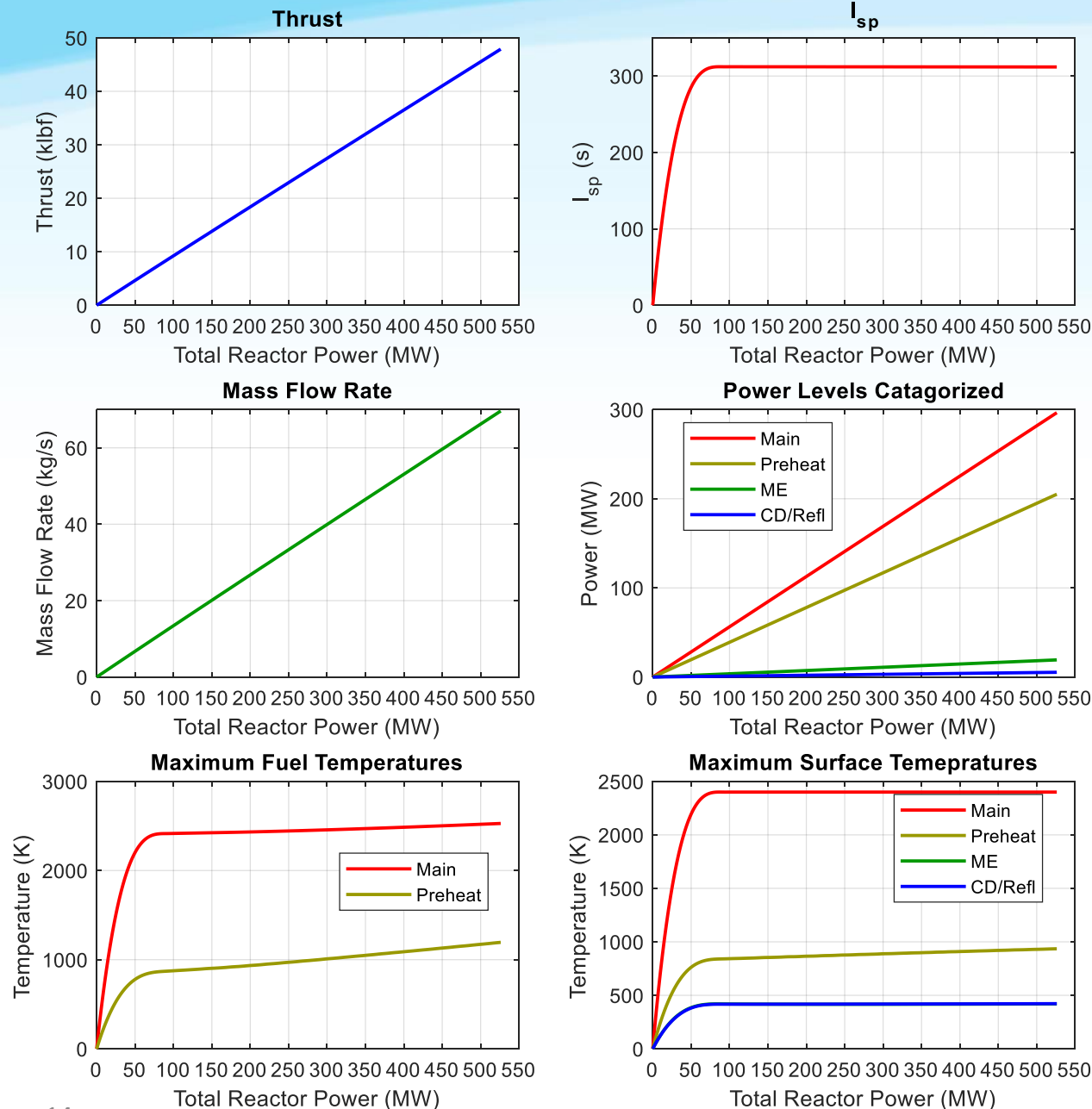
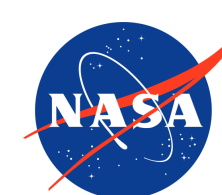


Figure 12: Water Expander Cycle Transient KPPs



Ammonia NTP Results

- For a given reactor power level using **ammonia**:
  - About **2X the thrust** of hydrogen-NTP can be achieved.
  - I_{sp} of
    - **345 seconds** for bleed cycle
    - **360 seconds** for expander cycle
  - **Multistage pump systems** (up to 4 stages to prevent cavitation) for expander cycles are required depending on thrust criteria. This results in pressures of 270 atm for expander cycles.
  - Phase change **will occur** during engine transients and bleed cycle operation.
  - Ammonia was found to yield a more feasible architecture with higher performing I_{sp} .
  - Detailed results are currently being extracted from the models.



Future Work

- Obtain data from ammonia engine models.
- Analyze vehicle performance in various mission architectures using extracted engine performance metrics.
- Determine the required Lunar infrastructure for mission architectures utilizing different propulsion systems.



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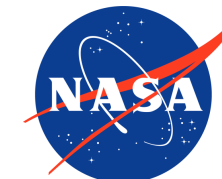
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QUESTIONS???

