



# Bimodal Nuclear Thermal Rocket Analysis Developments

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# Agenda

- Introduction
  - Nuclear Cryogenic Propulsion Stage (NCPS) Project
  - Nuclear Thermal Propulsion and Bimodal Reactors
  - Analysis Methodology
- NERVA Systems
  - Overview of NERVA fuel element/tie tube
  - Proposed system diagram
  - Tie tube exit temperatures issues
- ESCORT System
  - Power Mode Analysis
- Conclusions



# Introduction

- Nuclear Thermal Propulsion (NTP) preferred technology for manned mission to Mars [1]
- NCPS researching small 33.4 kN (7.5 klbf) engines for flight demo and robotic missions
- and 111.2 kN (25 klbf) engines for human missions

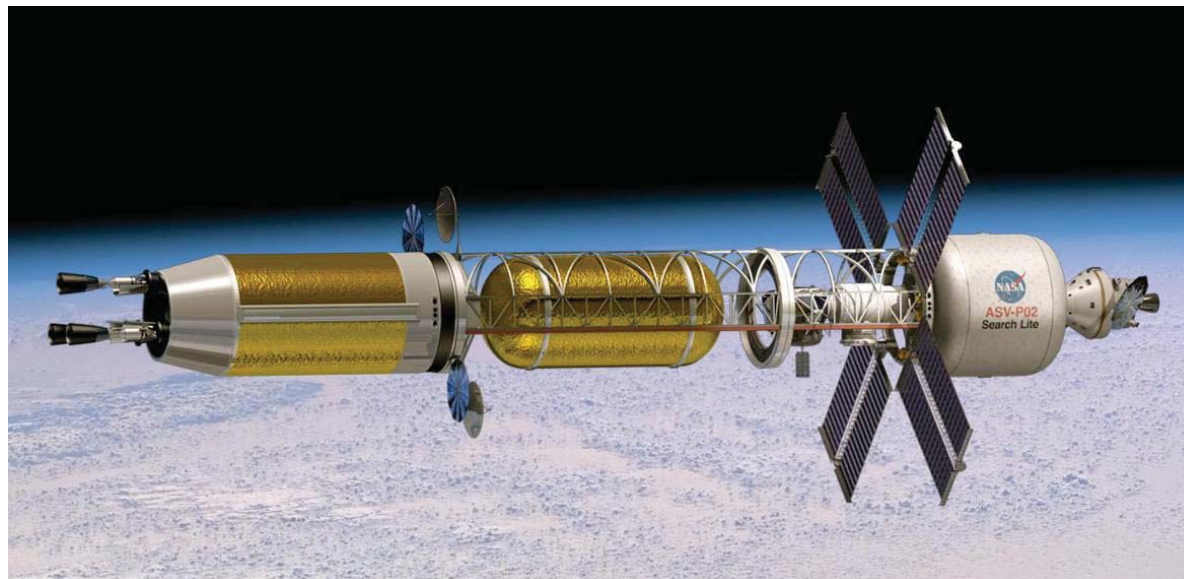


Image Reference [1]



# Nuclear Thermal Propulsion Basics

- Chemical propulsion performance limited by available energy stored in chemical bonds
- Nuclear propulsion performance limited by material temperature limitations

- Specific impulse

- Temperature (T)
- Molecular Weight (MW)

$$I_{SP} \propto \sqrt{\frac{T}{MW}}$$

- Example

- Hydrogen/Oxygen
  - MW ~ 13.8 g/mol, T ~ 3420 K, Isp ~ 480 seconds
- Nuclear Thermal Hydrogen Propellant
  - MW ~ 2 g/mol, T ~ 2700 K, Isp ~ 900 seconds



## Bimodal Basics

- Reactor core contains high amounts of unused  $^{235}\text{U}$
- Long coast periods of inactivity can be utilized
- Reactor operates at highly reduced power ( $\sim 1/1000^{\text{th}}$ )
- Tie tubes are used as heat source for closed Brayton power cycle with He-Xe working fluid
- Many Brayton cycle variations possible
- Chose most simple direct heat closed Brayton power cycle without a recuperator in order to reduce complexity and mass



# Analysis Methodology

- Propulsion Mode
  - Full system model in NPSS (Numerical Propulsion System Simulation)
  - Steady State Solution
  - Custom Reactor Elements
    - Fuel Element
    - Tie Tube Element
    - 1-D Thermo-Fluid Analysis axial temperature profile
- Power Mode
  - Isolated tie tube model in NPSS
  - Steady State Solution
  - Results from NPSS are fed to BRMAPS to compute Brayton cycle



# NERVA SYSTEMS



# NERVA Design

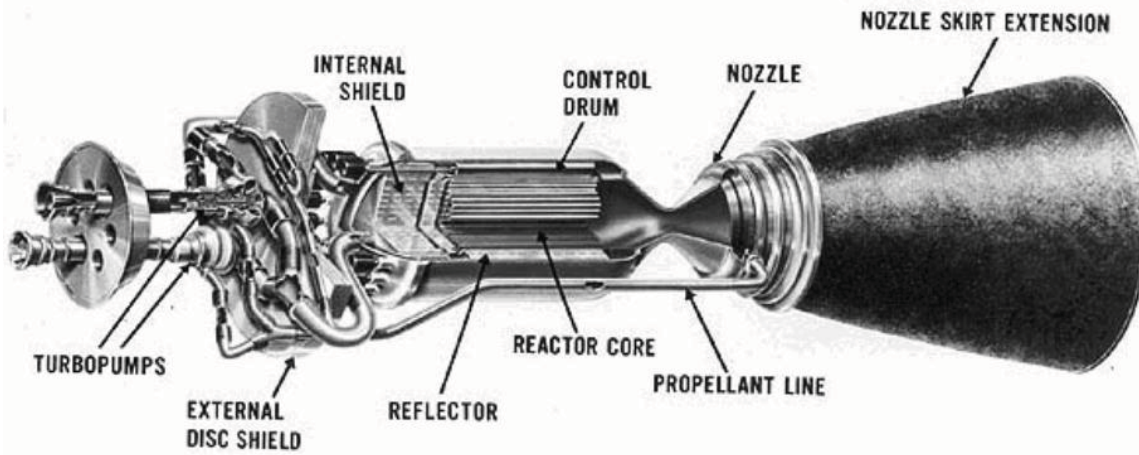
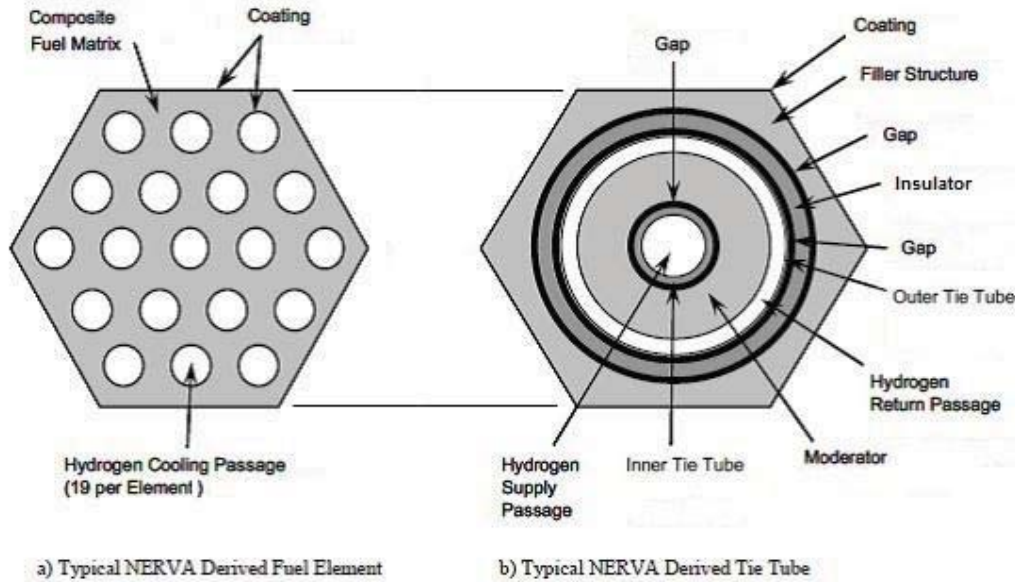


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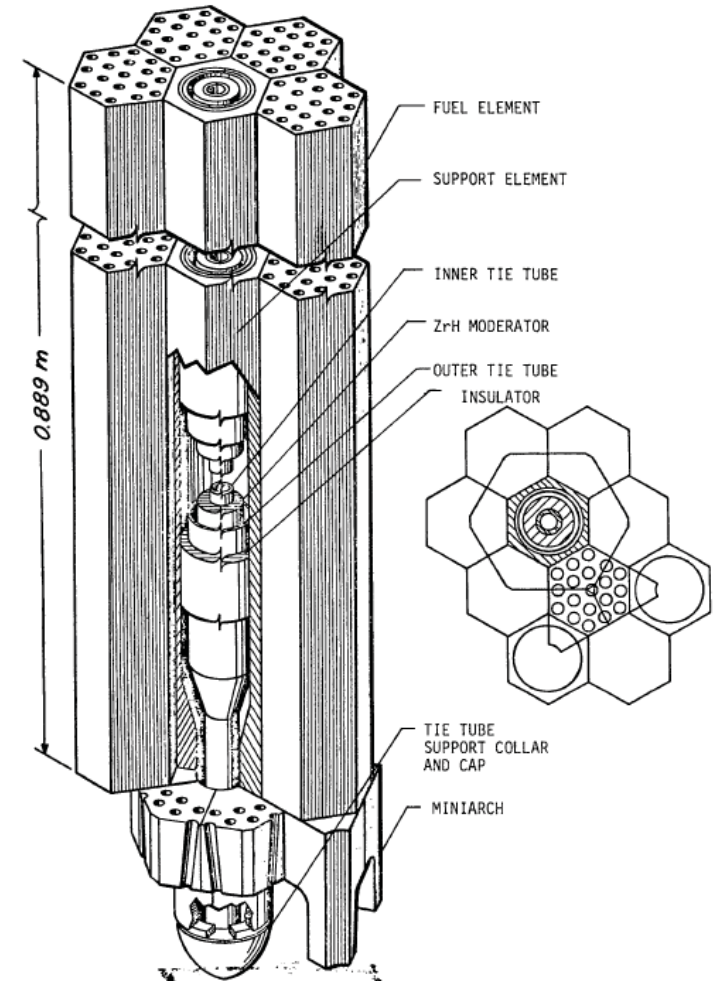


Fig. III-1. Schematic of fuel elements, support elements, and hot-end support hardware.

Image Reference: [4]

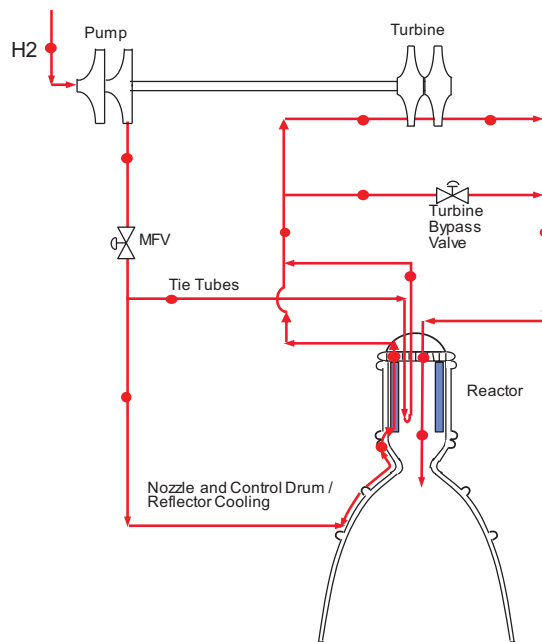




# NERVA: Propulsion vs. Power Mode

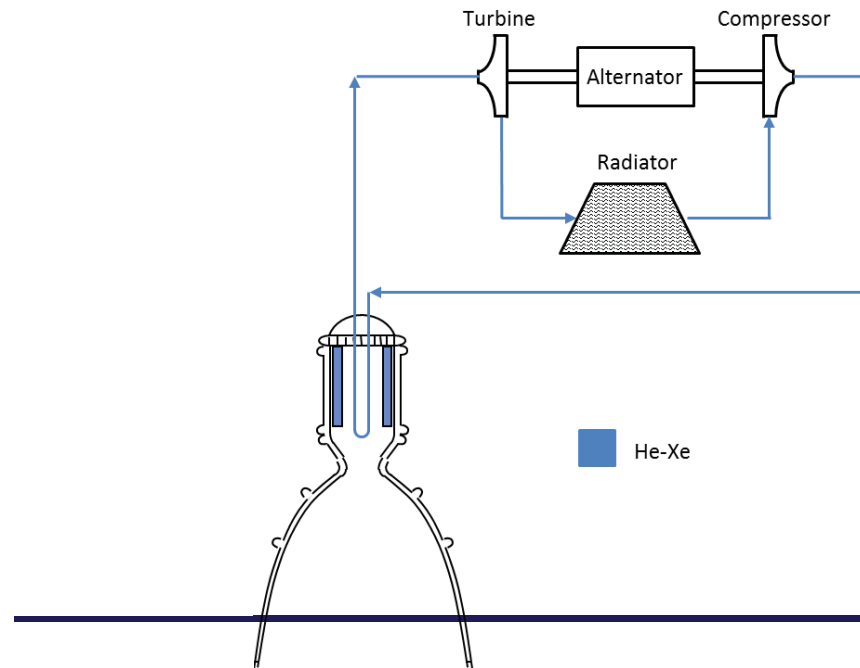
## Propulsion Mode

- High Power
- H<sub>2</sub> working fluid
- Tie tubes provide power for turbomachinery



## Power Mode

- Low Power
- He-Xe working fluid
- Tie tube flow only





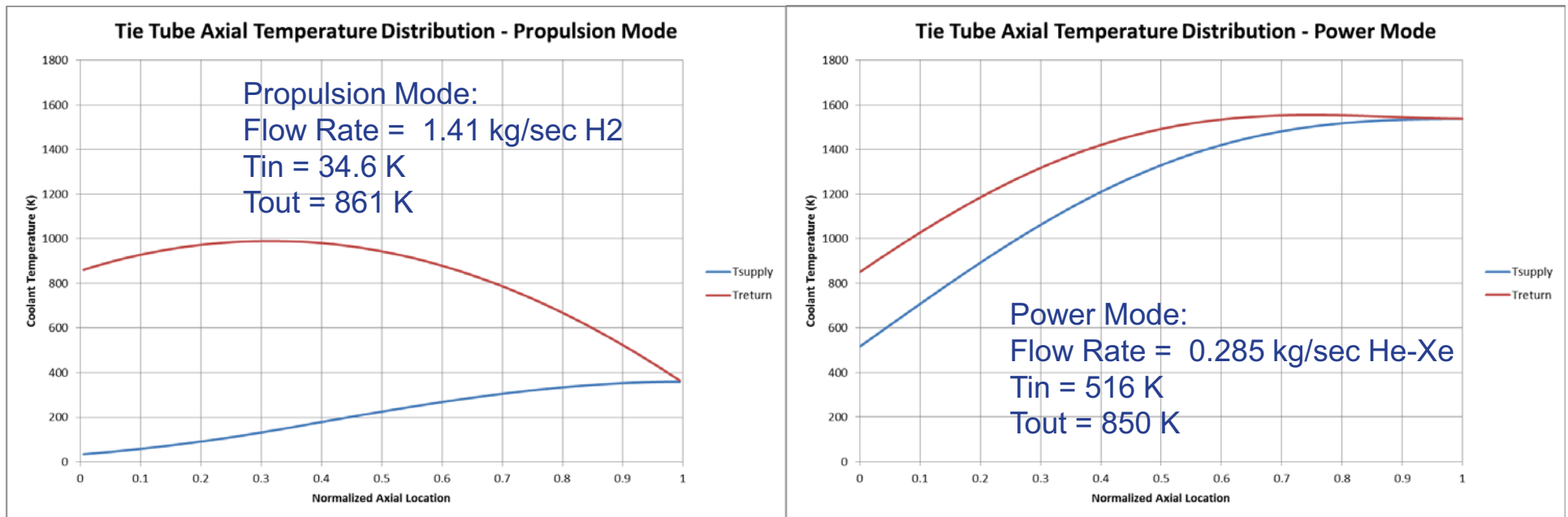
## NERVA Limitations During Power Mode

- ZrH moderator material
- Elevated temperatures cause H<sub>2</sub> to be released
- Moderator temperature limitation  $\sim < 1000$  K
- Potential long term effects on criticality
- Greater concern for power mode
  - Longer duration at elevated temperature
  - He-Xe working fluid
  - Higher temperature moderator



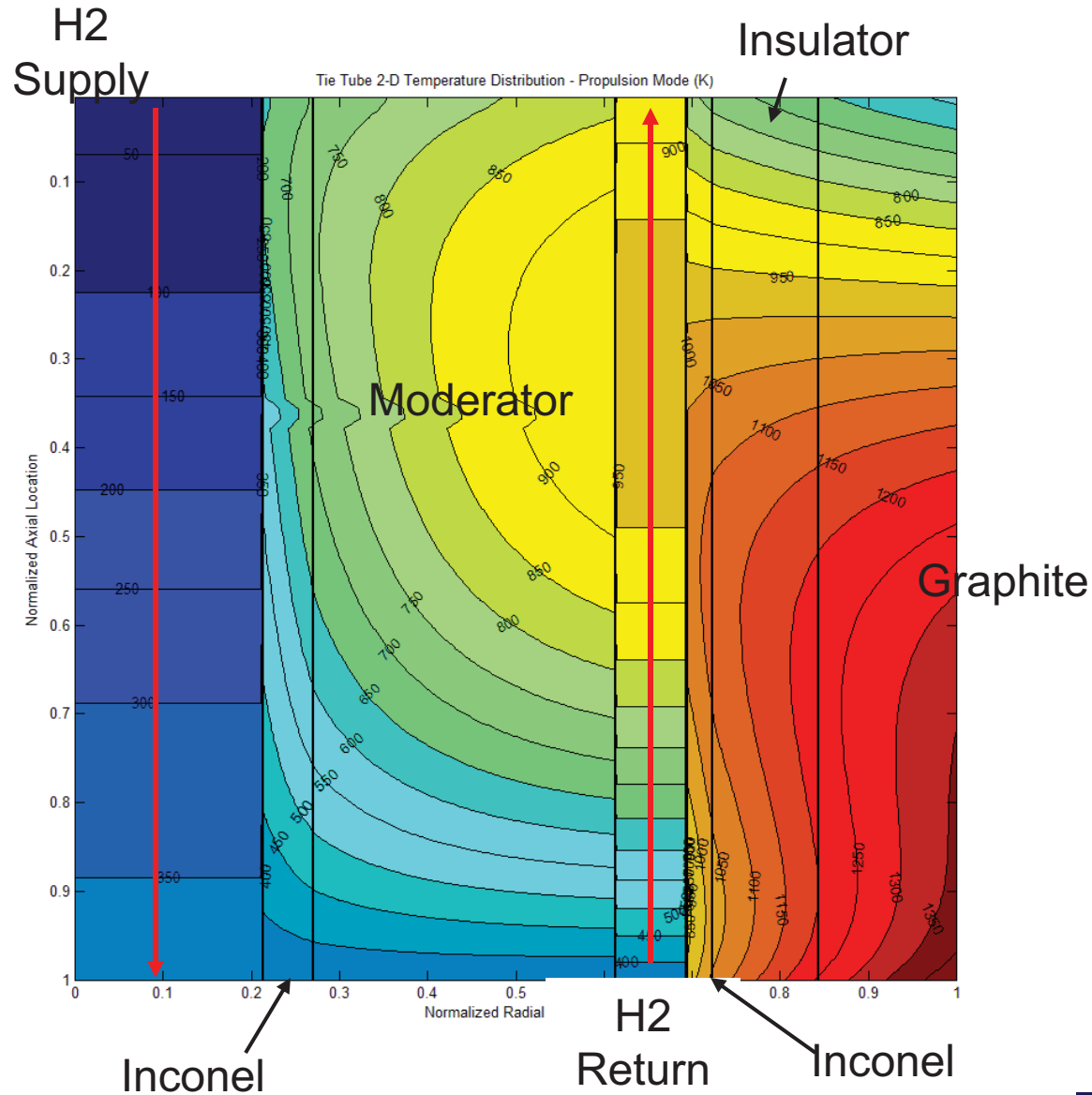
# Tie Tube Axial Temperature Profile

- Significant temperature profile difference between power and propulsion
- Results are consistent with previous analysis [5]
- Temperature profile is driven axially rather than radially



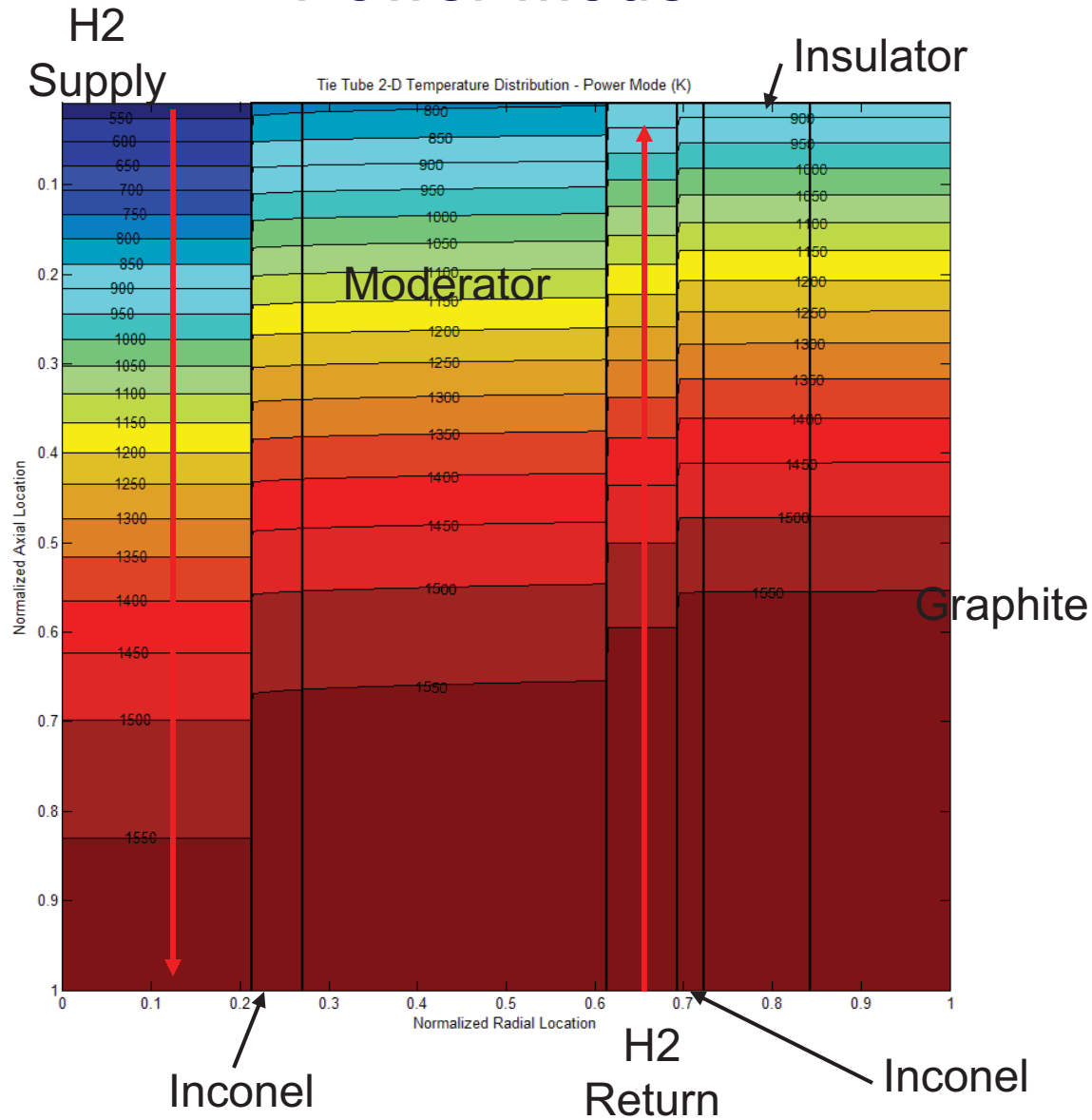


# Propulsion Mode





# Power Mode





## Discussion

- Lower mass flow rate → Lower heat transfer coefficient, Less Heat Flux
- Thermal gradient driven in axial direction rather than radial direction
- Model assumptions may be less accurate in power mode
  - No conduction axially assumed
  - Results show that axial conduction must be considered
  - Better assumption in propulsion mode due to higher heat fluxes
    - $Q_{\text{radial}} \gg Q_{\text{axial}}$



# ESCORT MANNED BIMODAL RESULTS



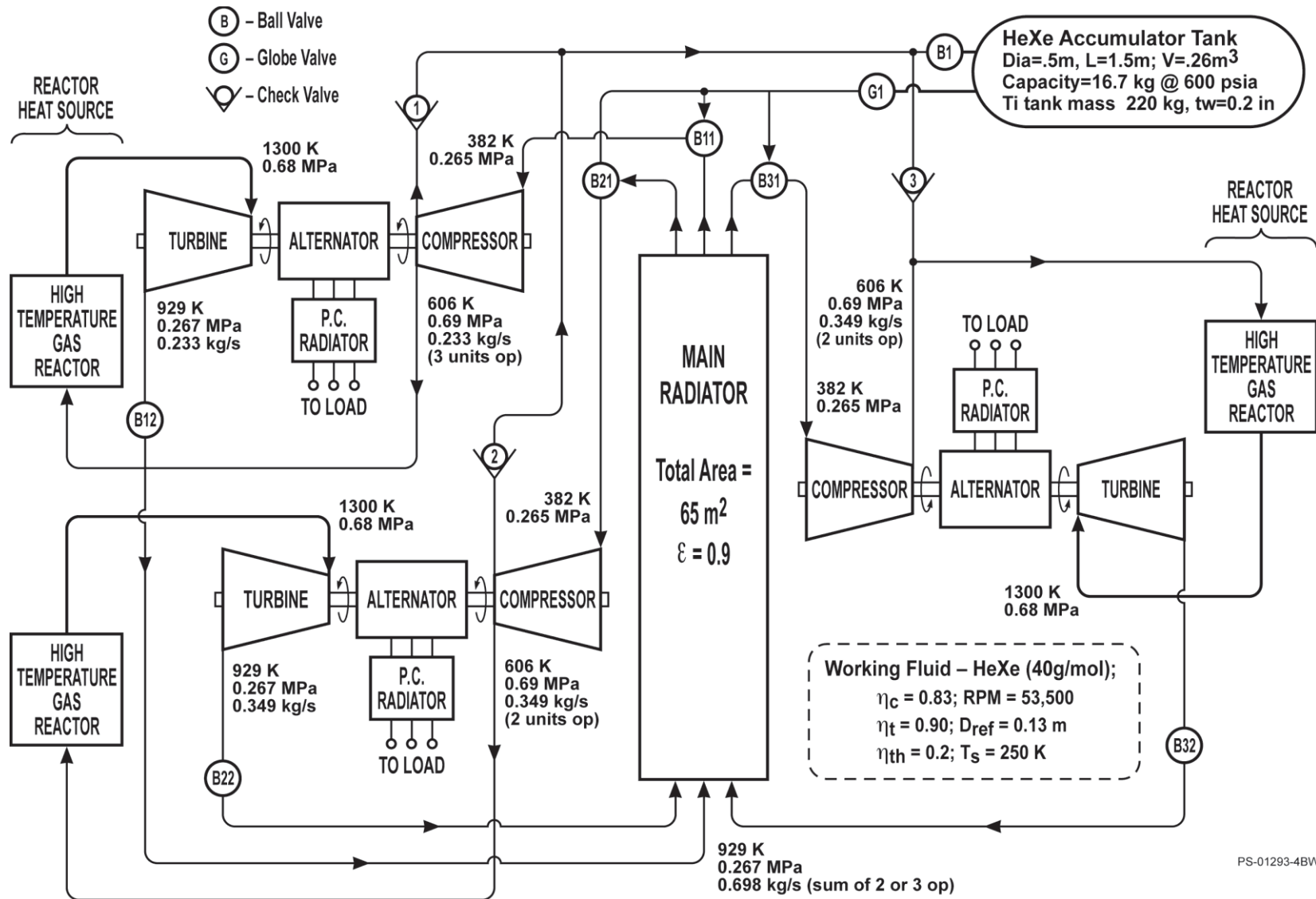
## Escort Manned Bimodal System

- Reactor core based on Escort/TRITON Design
  - 24 inch length
  - Central Energy Transfer Duct (ETD) for power mode
  - Ceramic Metallic (CERMET) fuel
- 3 x 25 klb engines clustered for propulsion mode
- 3 x 16.67 kWe Brayton rotating units in power mode
  - 25 kWe each, design, to provide 50 kWe in event of failure
  - Common radiator
- Temperature during power mode is not an issue due to materials and geometry





# 50 kWe System Results - Juhasz



PS-01293-4BW



# Conclusions

- NERVA Bimodal
  - Differences in operating characteristics between power and propulsion mode as well as the desire for maximum tie tube exit temperature results in temperatures above allowable for power operation in the NERVA reactor.
  - Improper modeling assumptions exaggerate the trend.
  - Look into new materials or design geometry to mitigate (NERVA not designed for bimodal)
- Escort Bimodal
  - Power mode operation seems feasible for a manned mission
  - Temperature during power mode is not an issue due to materials and geometry



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  - Charles Sarmiento
  - Albert Juhasz
  - Mark Stewart
- Colleagues
  - Stan Borowski
  - Jim Fittje
- Organizations
  - NCPS Project



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