# Thermal Fluid Analysis for Nuclear Thermal Propulsion Radiation Shield

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- Nuclear Thermal Rockets (NTR) are capable of producing high specific impulse by employing heat produced by a nuclear fission reactor to heat and therefore accelerate hydrogen through a rocket nozzle providing thrust.

Reactor Core

Cold Gas Hydrogen

Super Heated Hydrogen
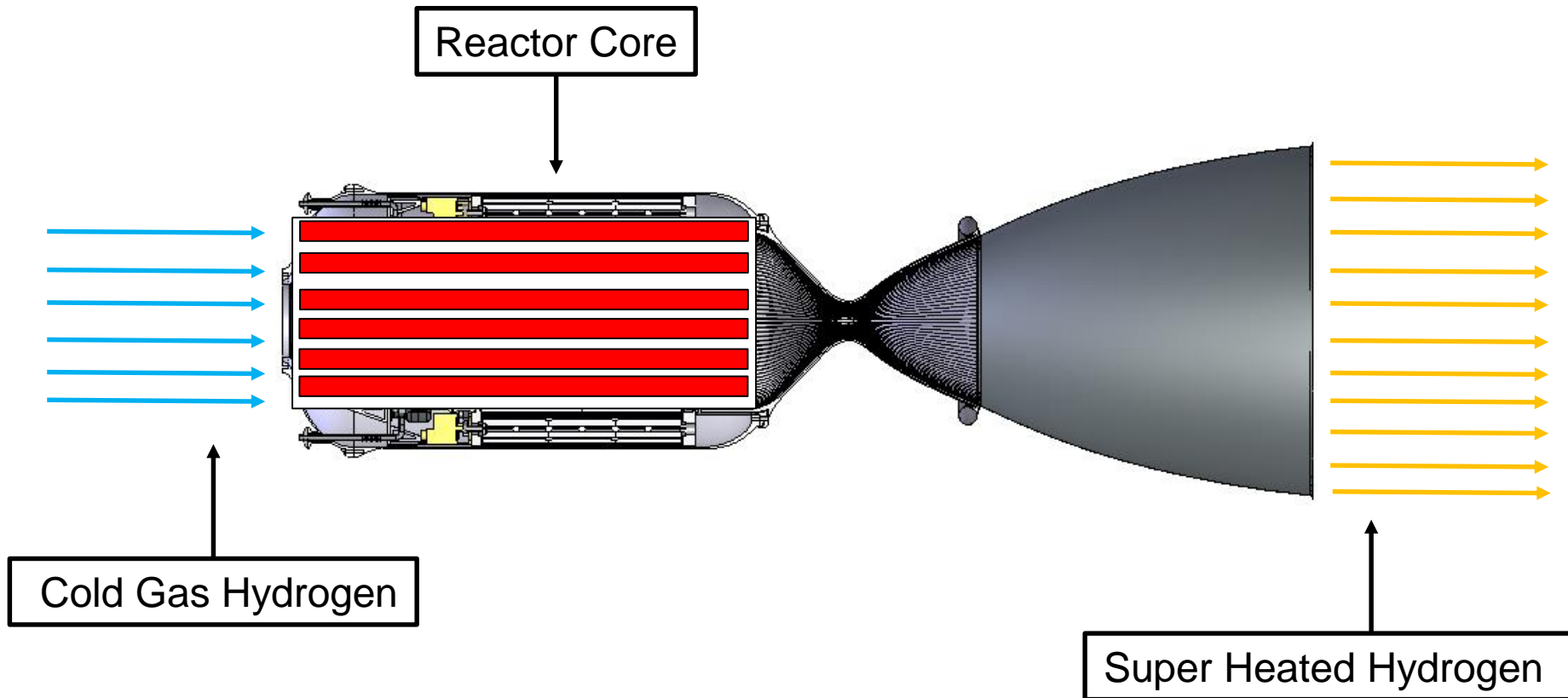
# Radiation

- Nuclear radiation ( Gamma rays and high energy Neutrons) is freely sprayed in all directions.

- Astronauts are exposed to nuclear and cosmic radiation

- Some components in the spacecraft are sensitive to radiation damage caused by radiation embrittlement, particularly electronic control circuits.

- Some materials are subjected to a substantial thermal load as radiation energy is converted to heat
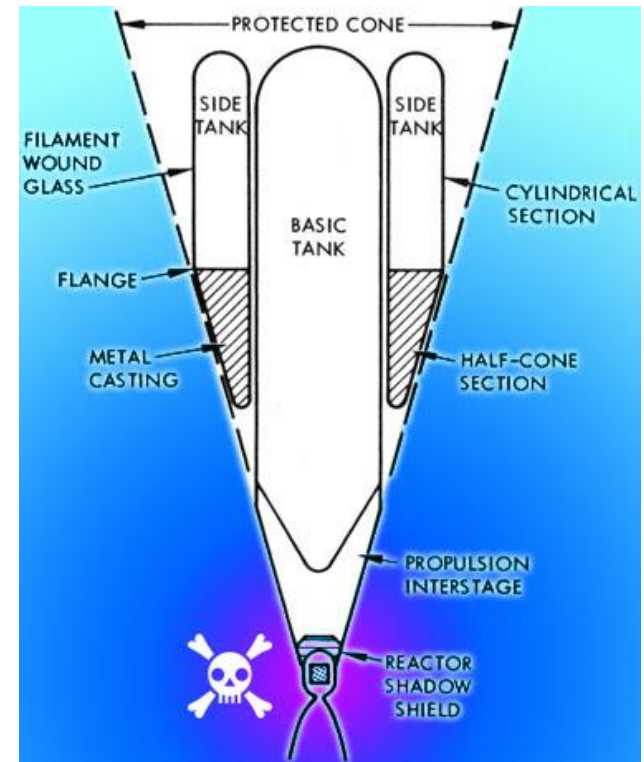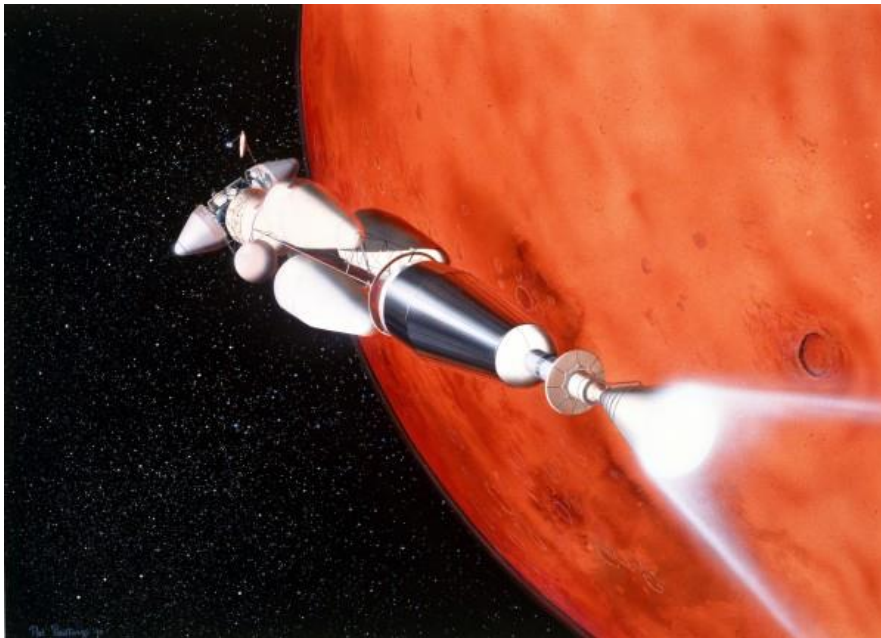
# Radiation Shields and Shadow

- Shadow shields are used specifically to protect the crew and spacecraft components from radiation emitted by the NTR. A safe design would be to encase the NTR in a shield, but that would reduce the ships payload since radiation shields weigh tons.
- Engineering challenge: protect crew and reduce mass

# Staging Radiation Shields

- Staging radiation shields help reduce weight but they have to be strategically placed
- Internal shields receive the majority of the high energy radiation but require active cooling due to the thermal loads.
- External shields provide the "shadow shielding" effect and are designed to be a thick solid mass. These shields take advantage of radiative cooling and loses heat by thermal radiation.
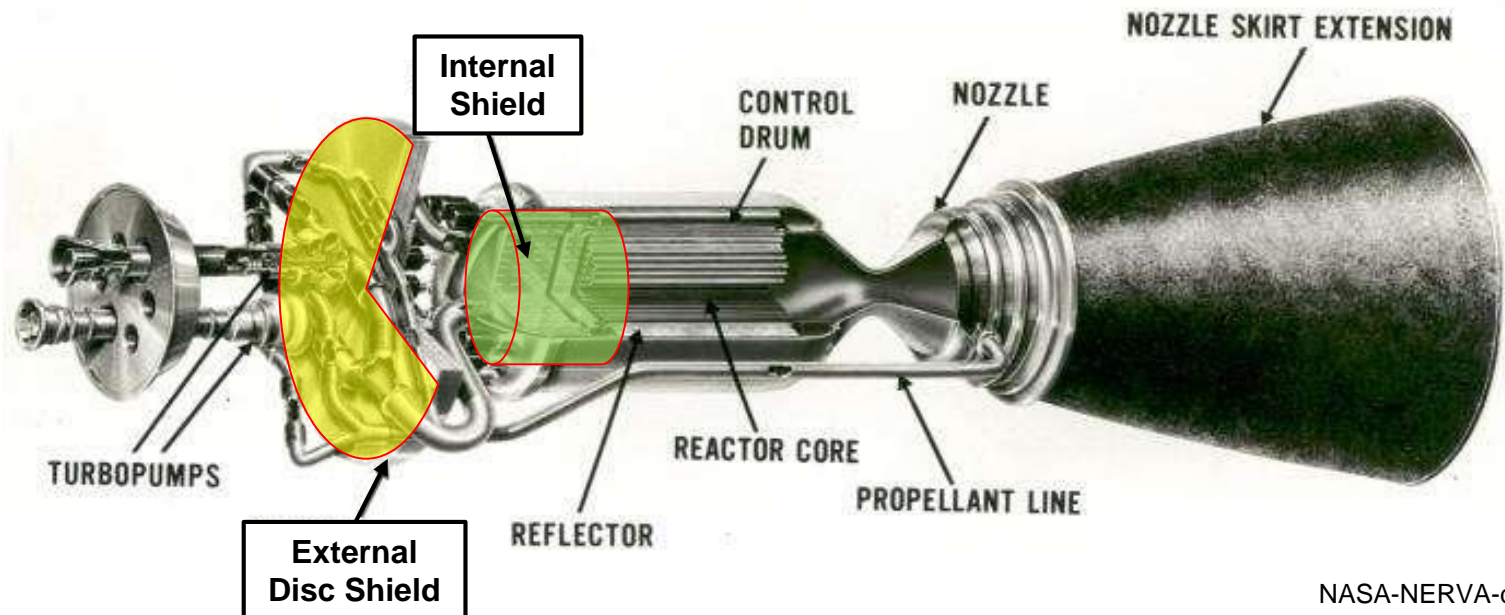


NASA-NERVA-diagram

# Radiation Shield
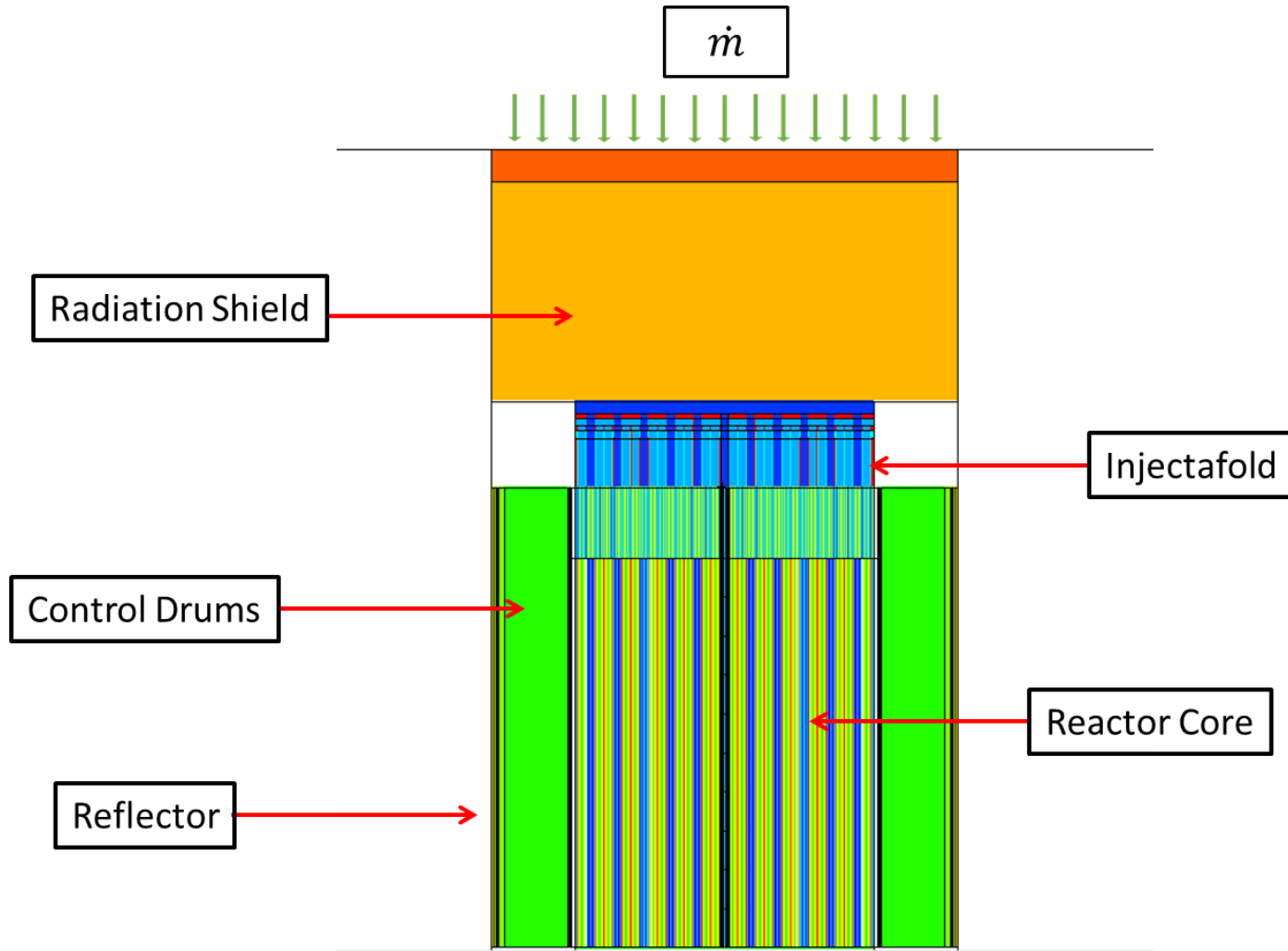
# Design Constraints and Materials

- The internal shield is subjected to a substantial thermal load as radiation energy is converted to heat.
- The active cooling system must be designed to absorb radiation and also reduce the amount of radiation leakage through cooling paths.
- Two designs were looked at:
  - Hex elements with helical flow path
  - Pelletized bed with tortuous flow path

## Material Selection

Lithium hydride (LiH)
- Pro- the most effective neutron absorber by per unite mass
- Con-poor thermal conductivity and narrow range of operating temperature. Material swells at high temperatures.
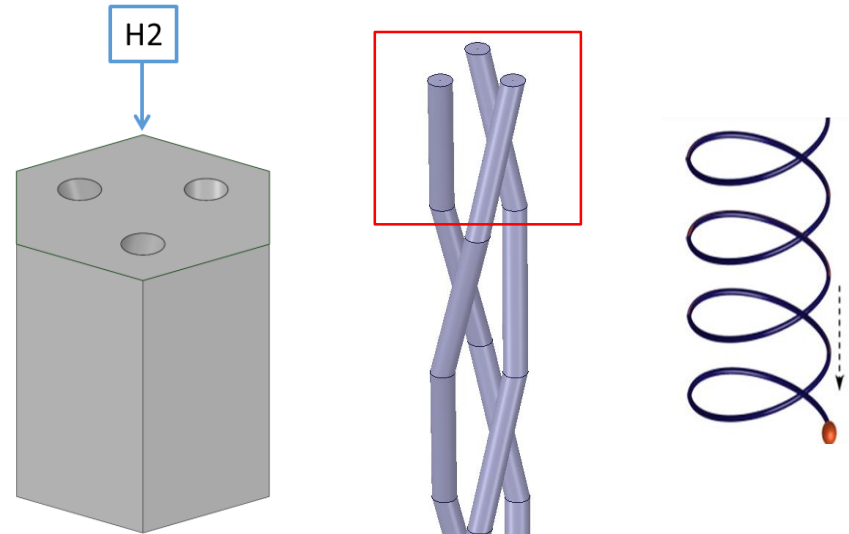
Boron carbide (B4C)
- Pro-effective neutron absorber
- Con- heavier than LiH by 20% . Has the best thermal conductivity for this application. Material is stable at high temperatures.
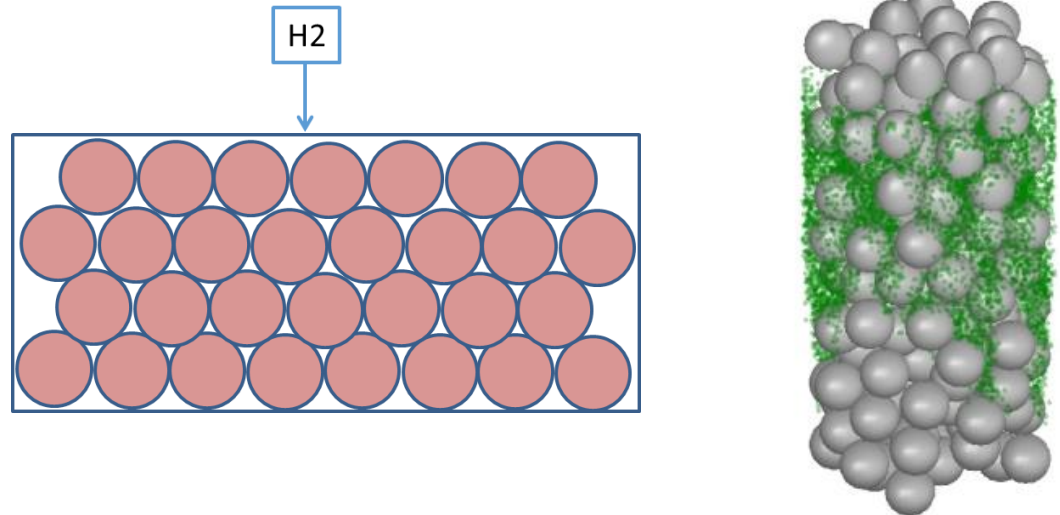
# Internal Radiation Shield Concepts

## Hex elements stacked

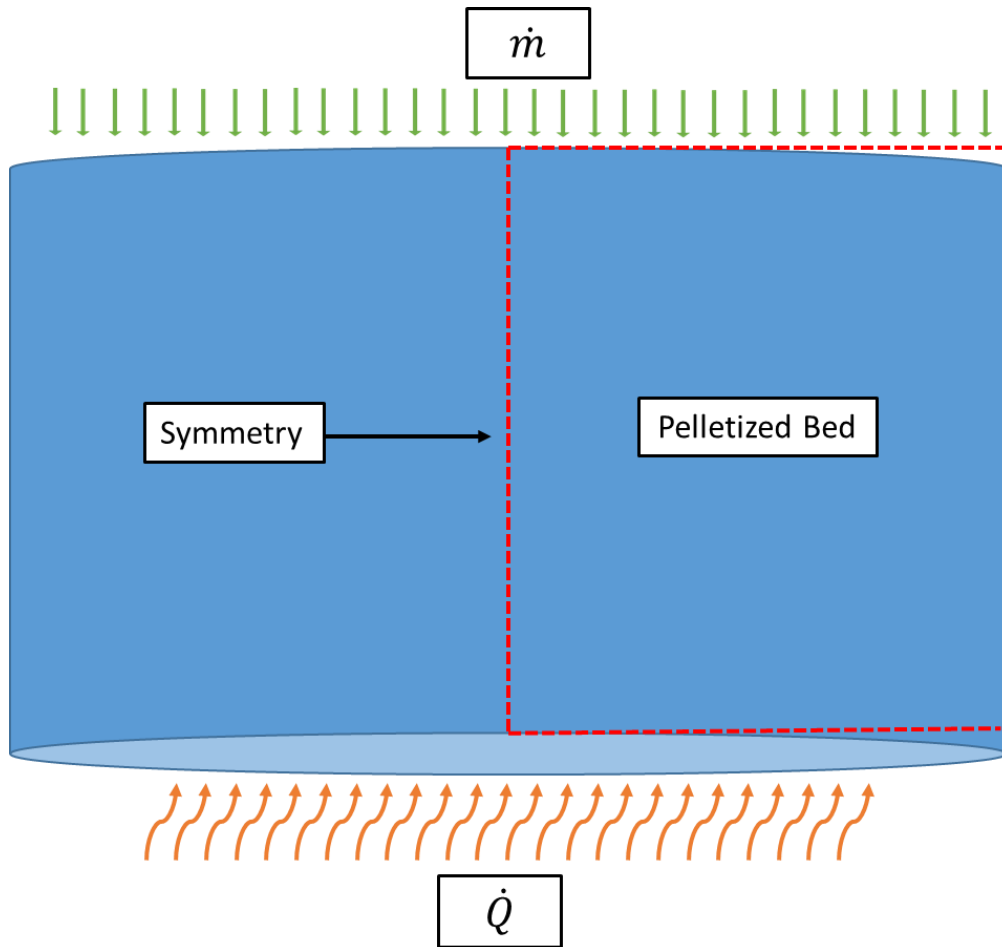- Cooling using flow channels through each hexagon element creating a helicoidal flow

H2

## Pelletized bed

- Randomly packed bed
- Tortuous flow distribution

H2

# COMSOL Assumptions for Pelletized Bed
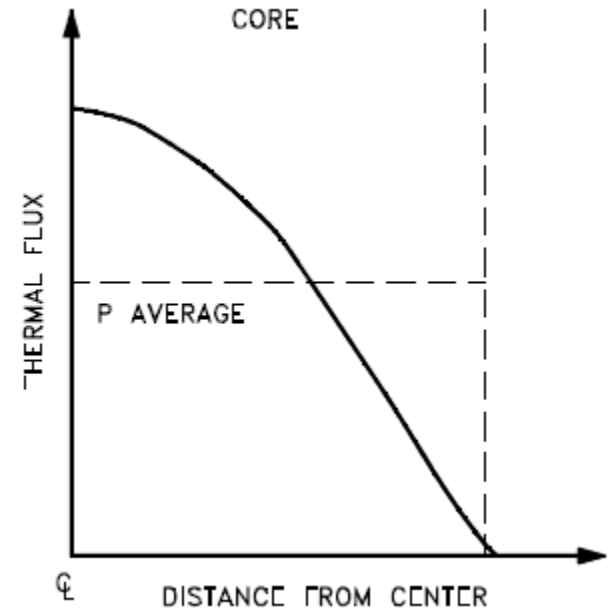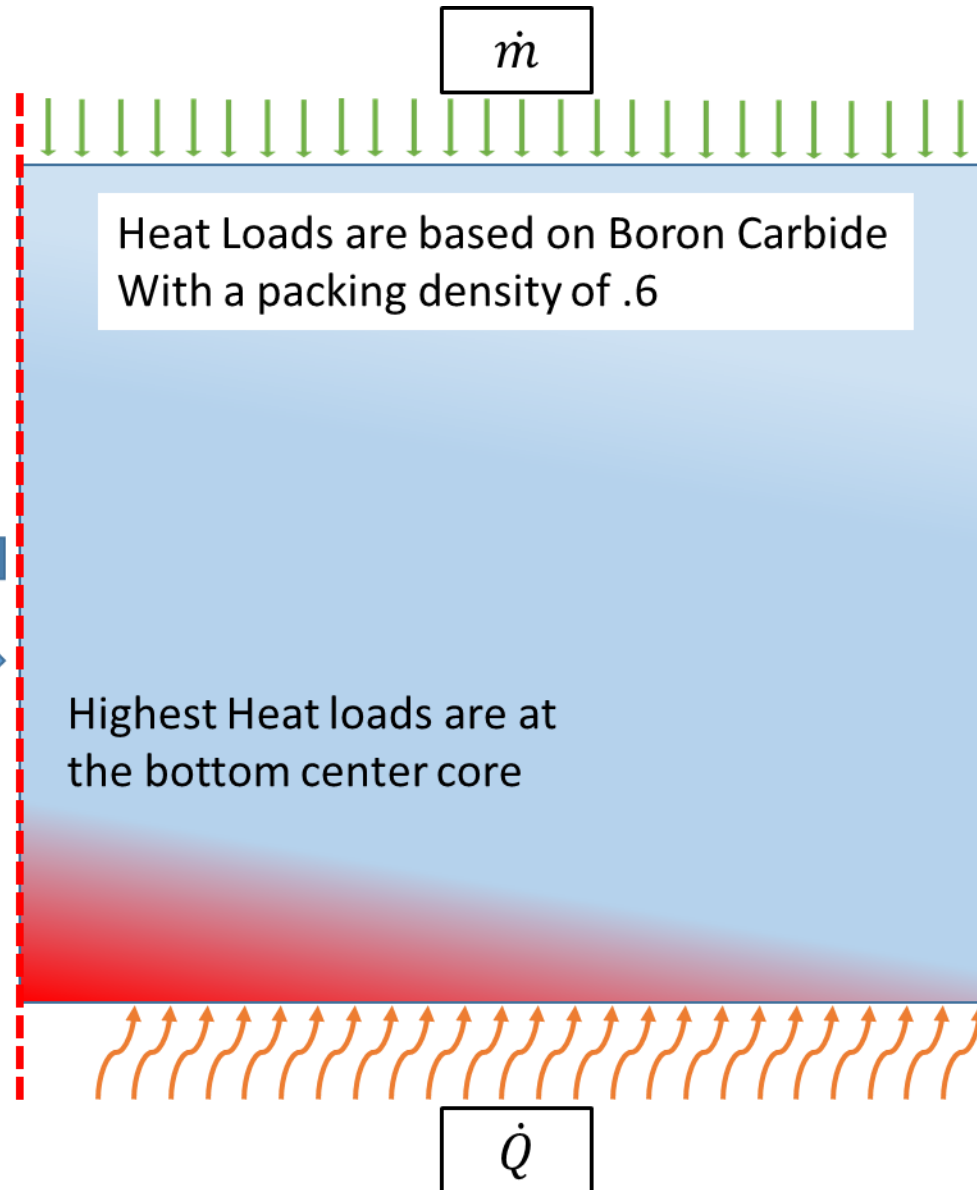


**Model Parameters**

- Mass flow= 13.2 [kg/s]
- Superficial Velocity= 5.4 [m/s]
- Outlet Pressure= 3757 [kPa]
- Inlet Temperature= 306.6 [K]
- Shield Diameter= 1 [m]
- Shield Length = 0.5 [m]
- Void Fraction= 0.4
- Mapped Heat Load
- Allowable DeltaP= 1379[kPa]≈ 200 [psi]

**Model Assumptions**

- Axisymmetric
- Pellet Diameter= 2 [cm]
- Density is based on ideal gas
- Gas and pellet surface temperature are the same

# Heat Load Distribution

$\dot{m}$

Heat Loads are based on Boron Carbide
With a packing density of .6

Highest Heat loads are at
the bottom center core

$\dot{Q}$

CORE
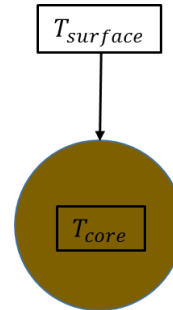
THERMAL FLUX

P AVERAGE

¢

DISTANCE FROM CENTER

Note
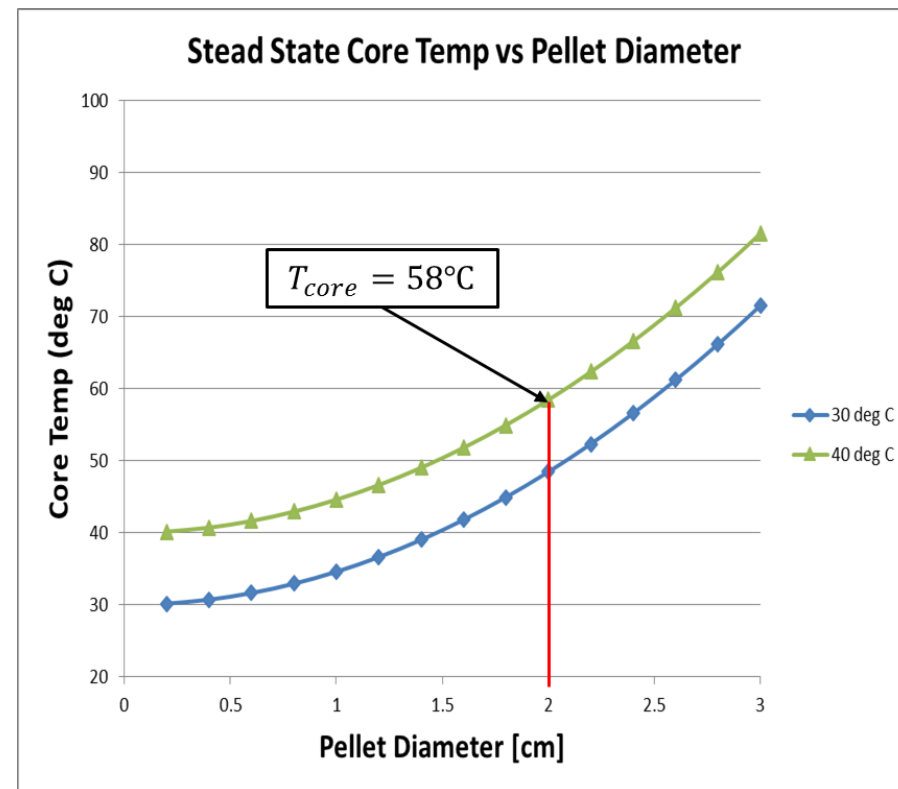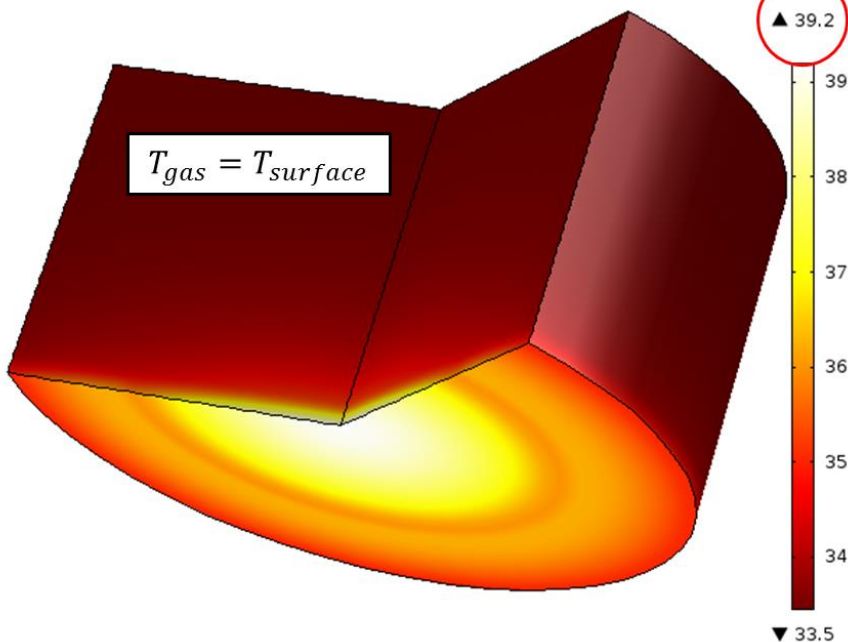• Heat loads were derived out of a Monte Carlo radiation transport code from Los Alamos National Laboratory (LANL)

# Temperature Distribution

Pellet Surface Temp Assuming:
- Mass flow= 13.2 [kg/s]
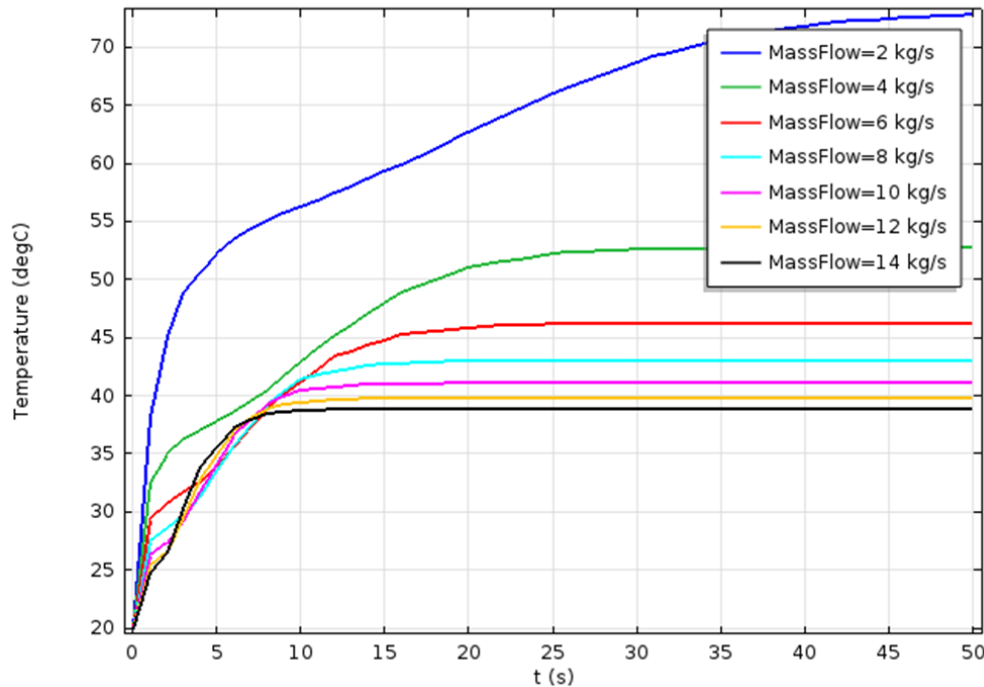- Superficial Velocity= 5.36 [m/s]
- Pellet Diameter= 2 [cm]

$T_{surface}$

$T_{core}$

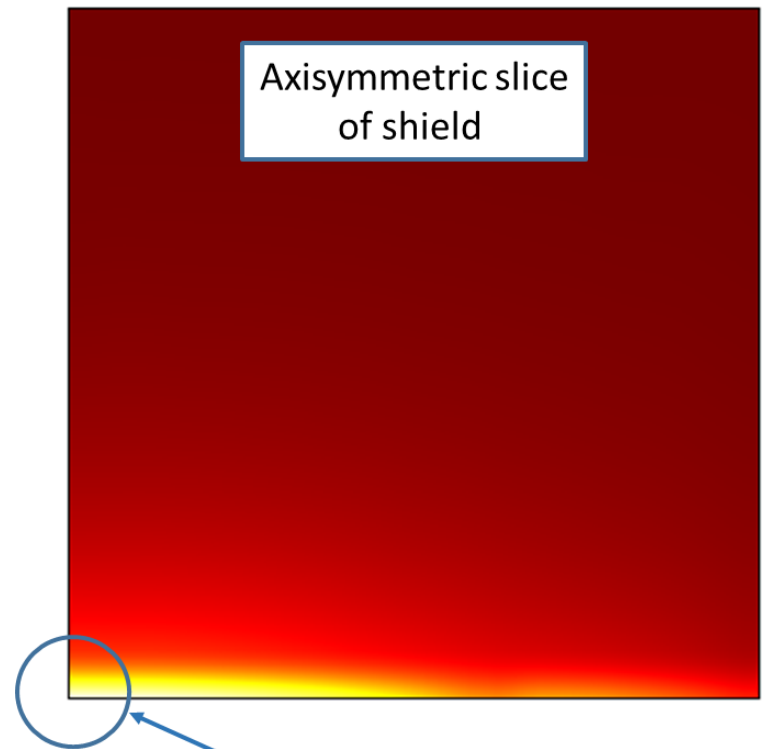Time=50 s   Surface: Temperature (degC)

▲ 39.2

$T_{gas} = T_{surface}$

**Stead State Core Temp vs Pellet Diameter**

$T_{core} = 58°C$

— 30 deg C
— 40 deg C

▼ 33.5

Point Graph: Temperature (degC)

Legend:
- MassFlow=2 kg/s
- MassFlow=4 kg/s
- MassFlow=6 kg/s
- MassFlow=8 kg/s
- MassFlow=10 kg/s
- MassFlow=12 kg/s
- MassFlow=14 kg/s

Axisymmetric slice of shield

Note: These temperature profiles are only for a pelletized bed

Mass Flow was varied and temperatures Profiles were taken from this point.

# Pelletized Bed Pressure Drop

The Ergun equation calculates the pressure drop along the length of a pelletized bed given the fluid superficial velocity, pellet size, void fraction, and fluid viscosity and density.

**Ergun**

$$\Delta P = \frac{150 \mu V_s L}{D^2} \frac{(1-\varepsilon)^2}{\varepsilon^2} + \frac{1.75 \rho V^2}{D} \frac{(1-\varepsilon)}{\varepsilon^3}$$

Permeability $\quad k = \frac{D^2 \varepsilon^2}{150(1-\varepsilon)^2}$

**Ergun with Forcheimer Drag term**

$$\Delta P = \frac{\mu V_s L}{k} + \frac{1.75 \rho V^2 L}{\sqrt{k}} \frac{\varepsilon}{\sqrt{150 \varepsilon^3}}$$

### Ergun vs Forchheimer Pressure Drop

Allowable $\Delta P = 1379[kPa] \approx 200\ [psi]$
Max $\Delta P = 375[kPa] \approx 54\ [psi]$