



Nuclear Thermal Propulsion Engine: Low-enriched Cermet-based Fuel

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Computational Reactor Engineering

Outline



- Motivation for nuclear propulsion systems
- Brief historical programs
- Description of operation
- Engine Requirements
- Neutronic Analysis
- T/H analysis
- Systematic approach to identify nearly optimum designs
- Summary

Why Nuclear Propulsion?

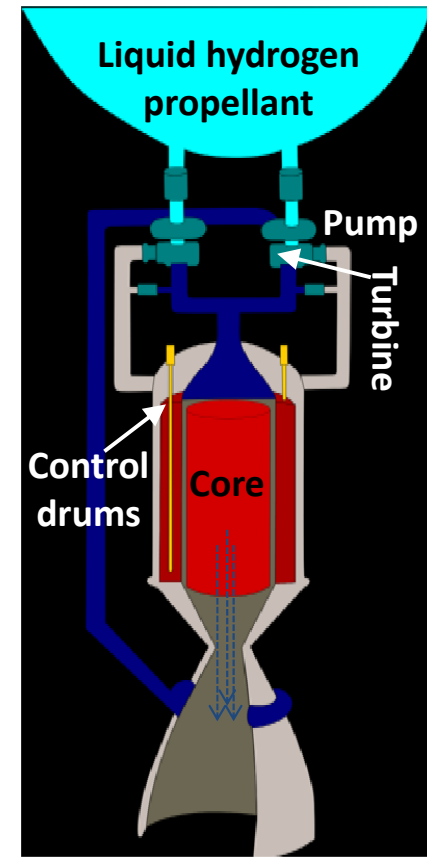
- Similar Thrust levels to chemical rockets
- Double efficiency over chemical rockets
- Faster travel times, reduced exposure/dose to the crew

	Chemical	Nuclear	Electrical
Thrust, klbf	100-500 klbf	10-100 klbf	10-100 mlbf
Thrust-to-weight,	30-200	3-5	<0.2
Specific impulse, Isp	<455 sec	800-1000 sec	1000-10,000 sec

- Over 20 engines tested under NASA's Rover Program (1955-1973)
- All designs used HEU based graphite matrix fuel elements
- Demonstrated feasibility of NTP systems
- Most current engine designs build on technology from Rover

Description of Operation

- Engine efficiency (I_{sp}) is dependent primarily on propellant exit temperature
 - $I_{sp} \nearrow M_{propellant} \searrow$
 - $I_{sp} \nearrow T_{propellant} \nearrow$
- **Hydrogen propellant** is used to cool a nuclear reactor core and its surrounding structural elements
- The hot hydrogen propellant is then **expelled through** a converging-diverging **nozzle**
- Radially distributed **control drums** are used to control reactivity, start, and shutdown the reactor

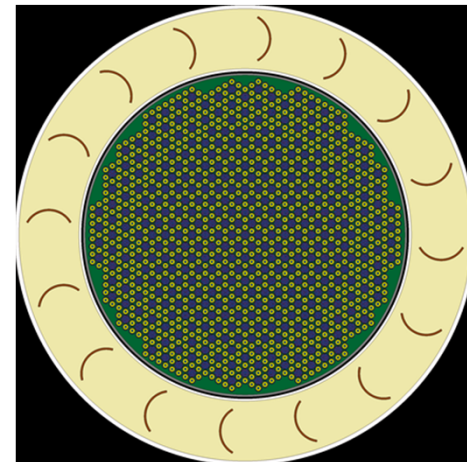


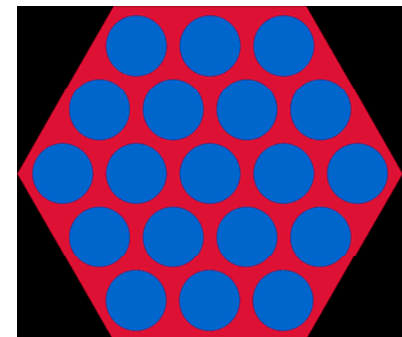
Engine Requirements

- Several baseline assumptions made by NASA about **NTR performance**:
 - Thrust: 25 klbf;
 - Isp: 900s;
 - Thrust-to-weight ratio: 3.5
- **Material Constraints**:
 - Fuel Material Melting Point: 3695 K
 - Moderator Material Melting Point: 1073 K
- **Objectives of our design**:
 - Previous tested NTPs have been all compact HEU (90% U^{235})
 - HEU is no longer acceptable, especially if the private sector is to become involved in the design, fabrication and testing of engines
 - Issues in previous graphite fuel designs caused by hot hydrogen corrosion

Neutronic Analysis

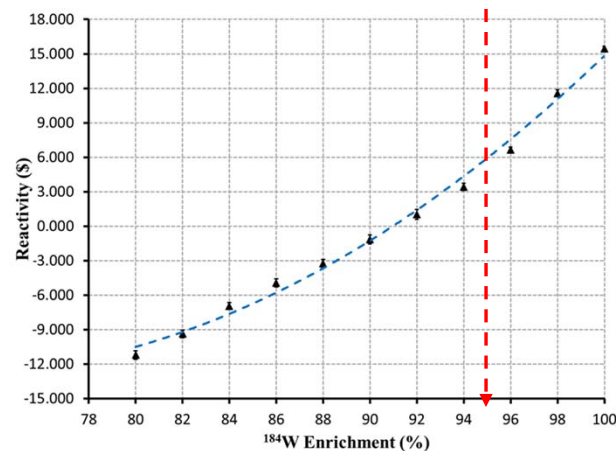
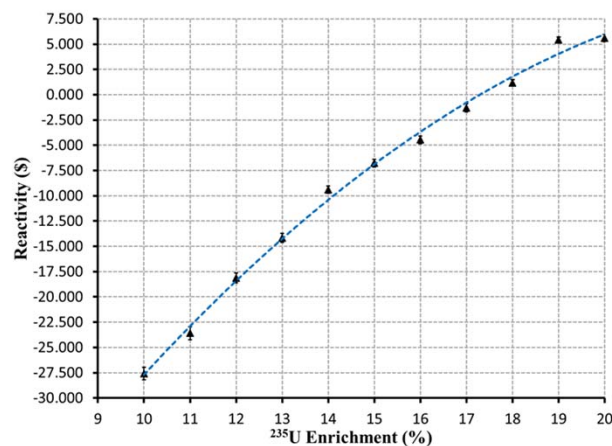
- Analysis performed using Serpent 2
- ENDF/B-VII.0 evaluated cross section library
- **Identified effects of:**
 - Active core height;
 - Axial reflector height;
 - Enrichment studies performed for fuel elements;
 - Investigation of different moderator materials;
 - Effects of moderator-to-fuel element ratio
- **Examined to ensure I_{sp} maximization while still maintaining $k_{eff} > 1$**





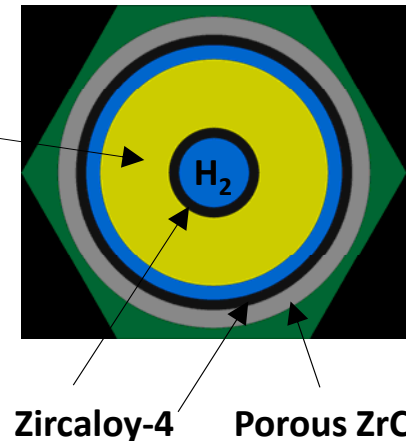
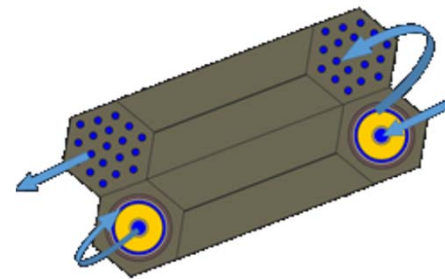
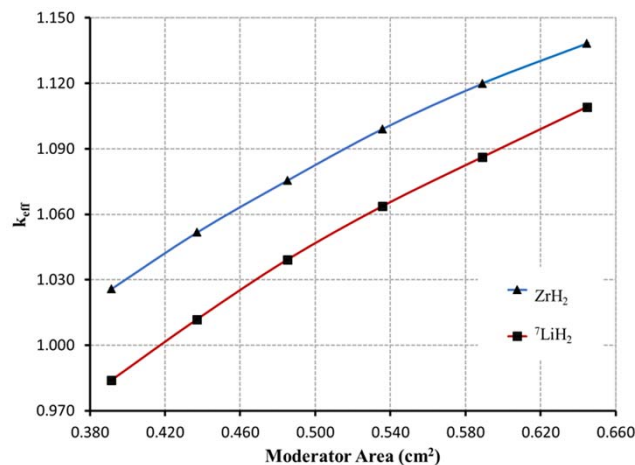
Fuel Element (FE)

- Ceramic metallic fuel composed of LEU (19.75%) enriched UO_2 particles
- Tungsten (IV refractory metal) is compatible with hot hydrogen
- Tungsten thermal conductivity >100 [W/mK] for all operating T [K]
- Melting point of tungsten and UO_2 in the cermet fuel = 3695 K
- Large parasitic absorption \Rightarrow Tungsten must be enriched with W^{184}



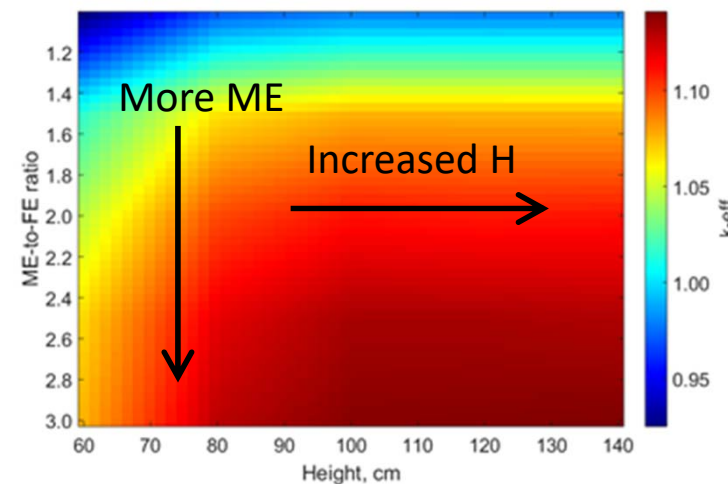
Moderating Element (ME)

- Create a thermal spectrum
- ${}^7\text{LiH}_2$ (0.82 g/cm^3) and ZrH_2 (5.56 g/cm^3) are the most formidable MEs
- Includes the H_2 supply/return channels
- Porous ZrC:
 - Large temperature drop and shields the graphite from any hydrogen contact



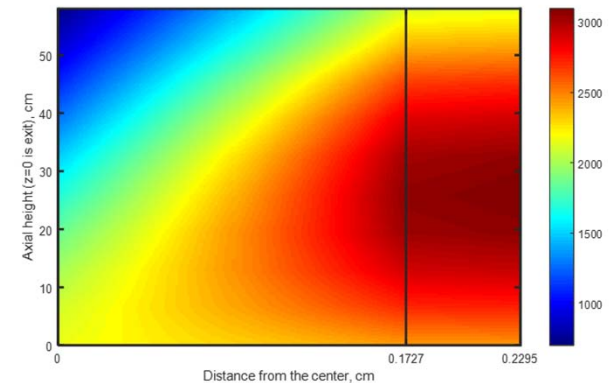
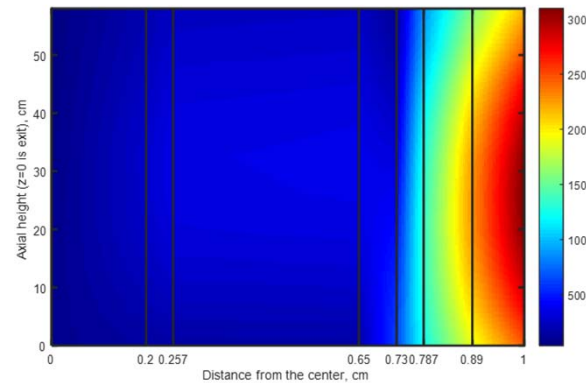
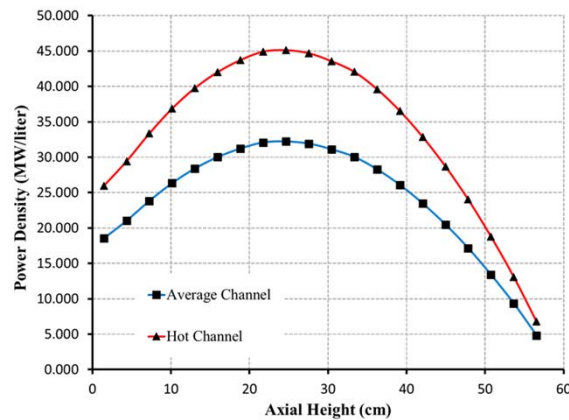
Neutronic Results

- Higher ME-to-FE ratio (greater moderation) yields higher reactivity
- Criticality peaks at 80cm height
- Short cores have lower criticality due to leakage
- Thicker axial reflectors reduce need for moderating elements



T/H Methods

- 1.5-dimensional T/H calculator
- Linearly discretized in axial direction
- Single channel radial conduction model



Specific Impulse and Thrust

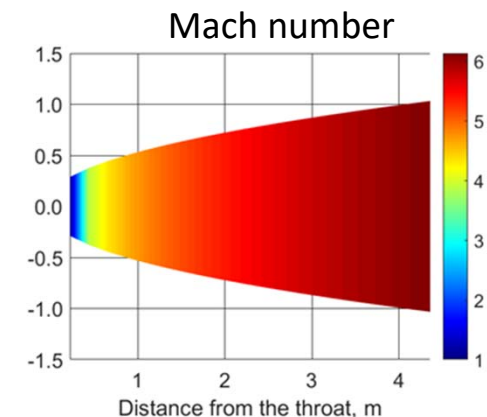
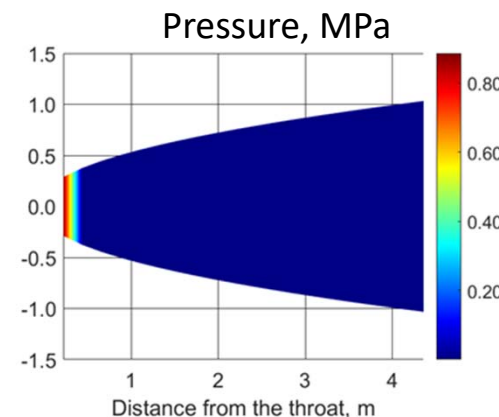
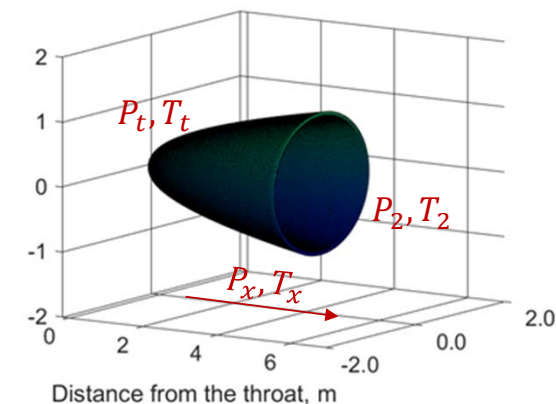
- T/H analysis \Rightarrow chamber T_1 and P_1 at the nozzle inlet
- The nozzle consists of convergent-divergent section
- Specific impulse and thrust, the velocity at the nozzle exit

$$\frac{v_x}{v_t} = \sqrt{\frac{k+1}{k-1} \left[1 - \left(\frac{P_x}{P_1} \right)^{\frac{k-1}{k}} \right]}$$

Solution:

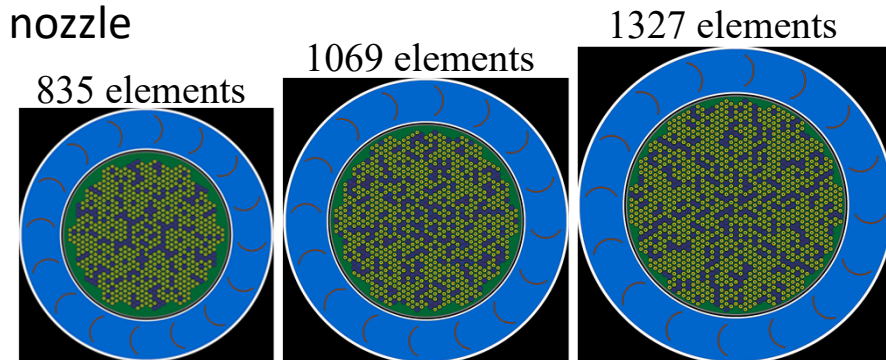
- Divide the nozzle into multiple 1D regions
- k is a function of P_x and temperature T_x
- An iterative process to update k in the nozzle

- $I_{sp} = \frac{v_2}{g_0} + \frac{P_2 A_2}{\dot{m} g_0}$
- $F = \dot{m} v_2 + P_2 A_2$



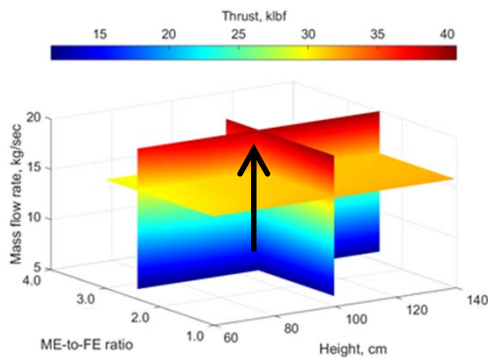
Systematic Approach: identify promising design

- **Automated tool:** generates Serpent input files with unique set of parameters:
 - H, the ME-to-FE, and total elements
 - Multi channel core with multiple axial layers \Rightarrow power distribution and T/H
- **Solution approach**
 - Iteration on power to achieve maximum fuel temperature
 - Radial power peaking of 1.3 assumed
 - Max. fuel temperature of 3100K
 - Specific impulse and thrust calculated via discretized nozzle

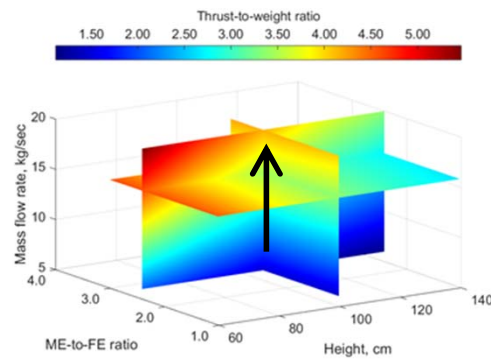


Results

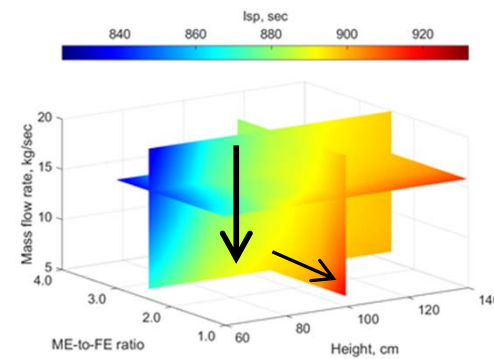
- Thrust
- Thrust-to-weight
- Specific Impulse
- Criticality



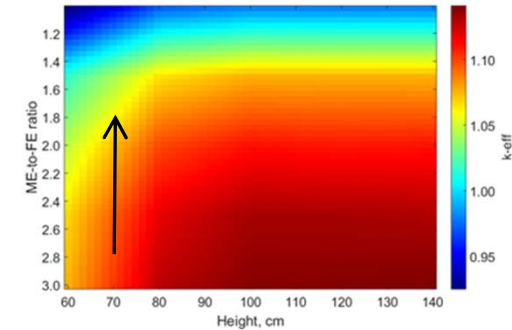
$$-\dot{m} \nearrow \Rightarrow F \nearrow$$



$$-\dot{m} \nearrow \Rightarrow \frac{F}{M} \nearrow$$



$$\begin{aligned} -\dot{m} \searrow &\Rightarrow I_{sp} \nearrow \\ -\frac{ME}{FE} \searrow &\Rightarrow I_{sp} \nearrow \end{aligned}$$

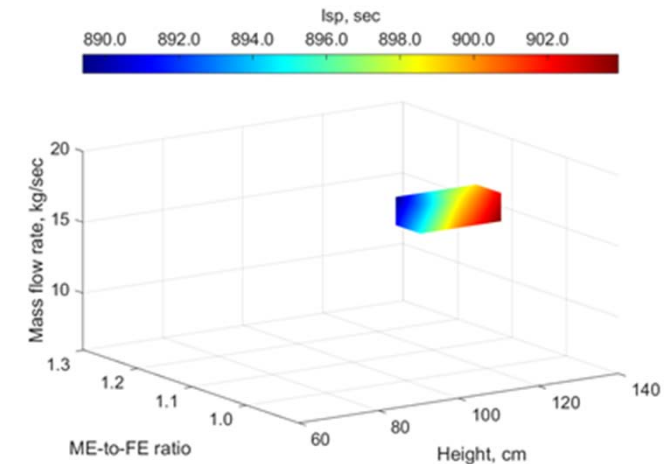


$$-\frac{ME}{FE} \searrow \Rightarrow k_{eff} \searrow$$

Near-Optimum Design

- NASA requirements \Rightarrow confined design space
 - 25,000 lbf of thrust, have a criticality greater or equal to 1, and a thrust-to-weight ratio greater than 4.0

Number of elements	835	1069	1327
ME-to-FE ratio	1.47	1.26	1.14
H, cm	102.86	99.2	101
Thrust, klbf	29.74	33.82	39.93
Thrust-to-weight ratio	4.023	4.016	4.032
Isp, sec	890.94	894.06	896.98

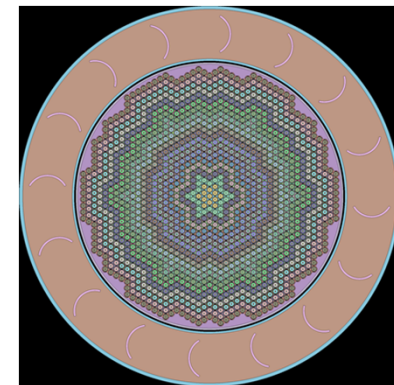


Summary

- Most past designs focus on HEU based fuels
- It is feasible to use LEU based fuels with little performance loss
- Near-optimum design meets or surpasses NASA requirements
- **Future work**
 - Further coupled analysis needs to be performed at all stages of engine operation

THANK YOU





Preliminary Coupled T/H Analysis

- Multi-channels (i.e. each radial ring)
- Converge on mass flow rate distribution (uniform pressure drop)

