VCU College of Engineering

Space Nuclear Thermal Propulsion (NTP) Conceptual Design Utilizing Modular High-Temperature Gas-Cooled Reactor (HTGR)

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Virginia Commonwealth University

Senior Design Capstone Team MNE 21-512, Dept. of Mech. and Nucl. Engr.

Today's Discussion

- Executive Summary
- Background
- Design Criteria
  - Goals
  - Objectives
  - Design Specs/Constraints
  - Codes and Standards
- Design Methodology
  - Design Philosophy
  - Hands Calculations
  - Detailed Calculations
- Preliminary Results
  - CONOPS
  - Preliminary Design
- Additional Design Considerations
- Project Timeline

This is nothing to do with the ANS meeting, I suggested to take this away. Keep in mind we are talking about an ANS conference paper, not a senior design preoject in this presentation

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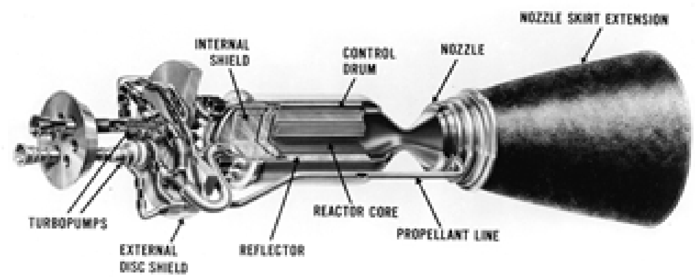
Executive Summary

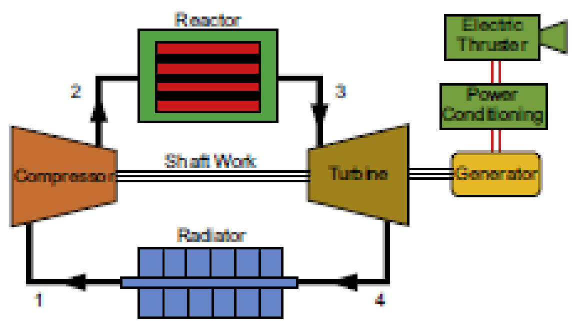
- Referencing NASA NERVA Project
- Specific Impulse is important for cost and objective
- HTGRs
- CAD/CFD
- Our Design

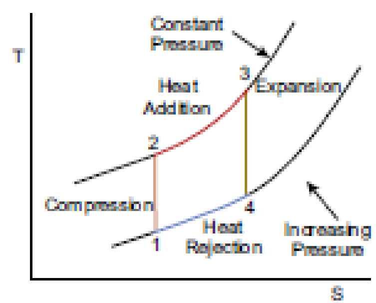
Background

- VCU Senior Design Capstone Team
- NASA NERVA Project Schematic
- HTGRs vs LWRs
- Moderator, Coolant
- Brayton Cycle

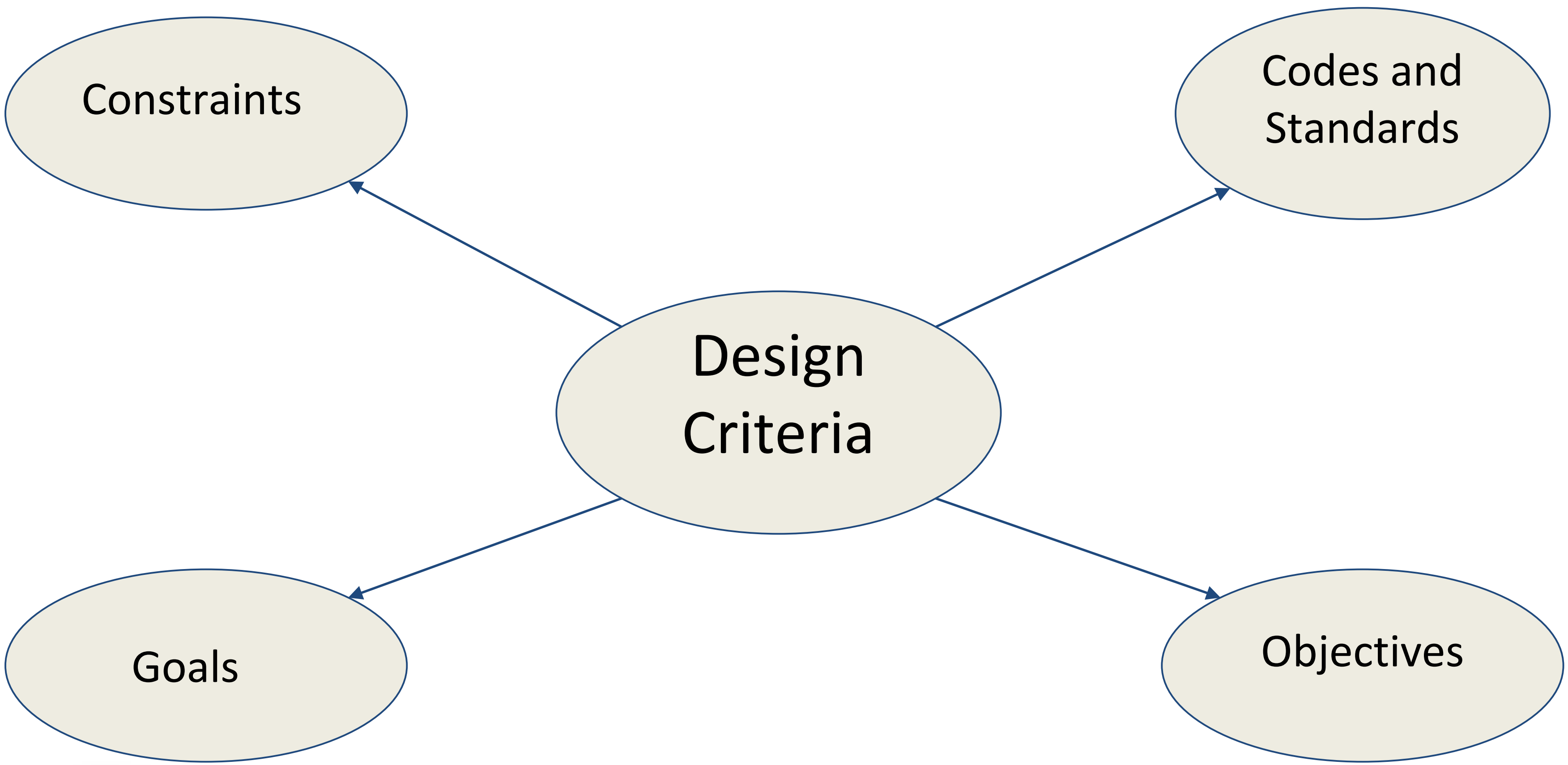


Dogdge, R. M. (1965). The NERVA Nuclear Rocket Reactor Program. Retrieved from https://www1.grc.nasa.gov/wp-content/uploads/NERVA-Nuclear-Rocket-Program-1965.pdf





Emrich, William. *Principles of Nuclear Rocket Propulsion*. Butterworth-Heinemann Ltd, 2016.

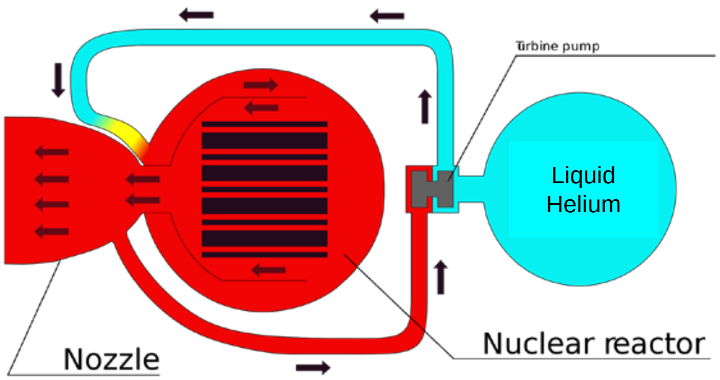

Constraints
Codes and Standards
Design Criteria
Goals
Objectives

Goals

Design an NTP System → Innovative Design → Lighter and Faster

Objectives

- Find time usage, estimated power, top flight speed, etc
- Design a theoretical NTP system
  - propellant tanks
  - pump
  - nozzle
  - reactor core
  - payload volume
  - structure



Design Specifications and Constraints

- Functional Constraints
  - operate w/o maintenance
  - high/low extreme temperatures
- Manufacturing Constraints
  - small/lightweight for commercial rocket fairing volume
  - shielding against radiation
  - small-scale CFD
- Codes/Standards Constraints

Codes and Standards

Design Methodology

- Design Philosophy
- Assumptions
- Hand Calculations
- Detailed Calculations

Design Philosophy

- Principles of Nuclear Rocket Propulsion
- Types of HTGRs
  - Prismatic Block Reactors (PMRs)
  - Pebble Bed Reactors (PBRs)
- Radiation Shielding
- Properties of Graphite
- NERVA

what would you plan to talk about this here? Do we have a preferred reactor with this discusssion?

Hand Calculations

- Conservation of Mass
- Specific Impulse (Isp)
- Velocity
- Max Attainable Velocity

$$m_{in} = m_{out}$$

$$I_{sp} = \sqrt{2Q/(m_{dot} * g_c^2)}$$

$$V = \frac{m_{dot}}{\rho A}$$

$$V_f = -g_c I_{sp} ln(m_f/m_0)$$

m_f is the vehicle dry system mass and m_0 is the fully fueled vehicle mass

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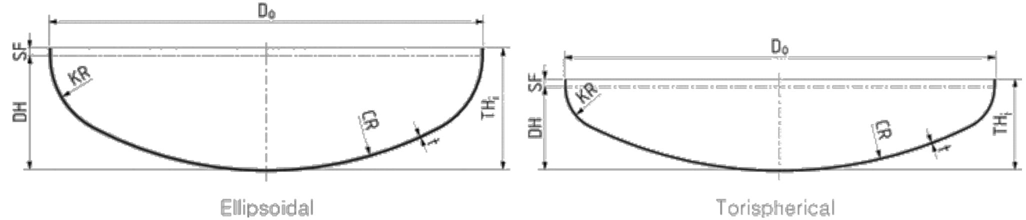
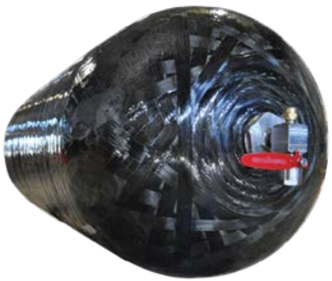
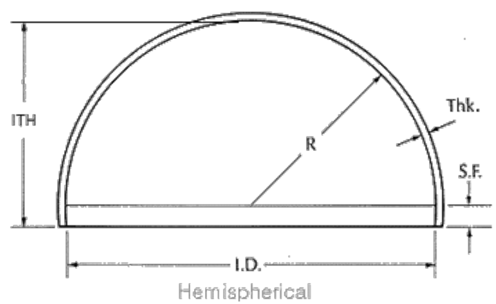
Hand Calculations

- Pressure Vessels - Composite Overwrapped Pressure Vessels (COPVs)







$$Volume_{total\ of\ tank\ material} = \pi R^2 h - \pi r^2 h + \tfrac{4}{3}\pi R^3 - \tfrac{4}{3}\pi r^3$$

$$mass_{total\ of\ tank\ material} = \rho_{tank\ material}(\pi R^2 h - \pi r^2 h + \tfrac{4}{3}\pi R^3 - \tfrac{4}{3}\pi r^3)$$

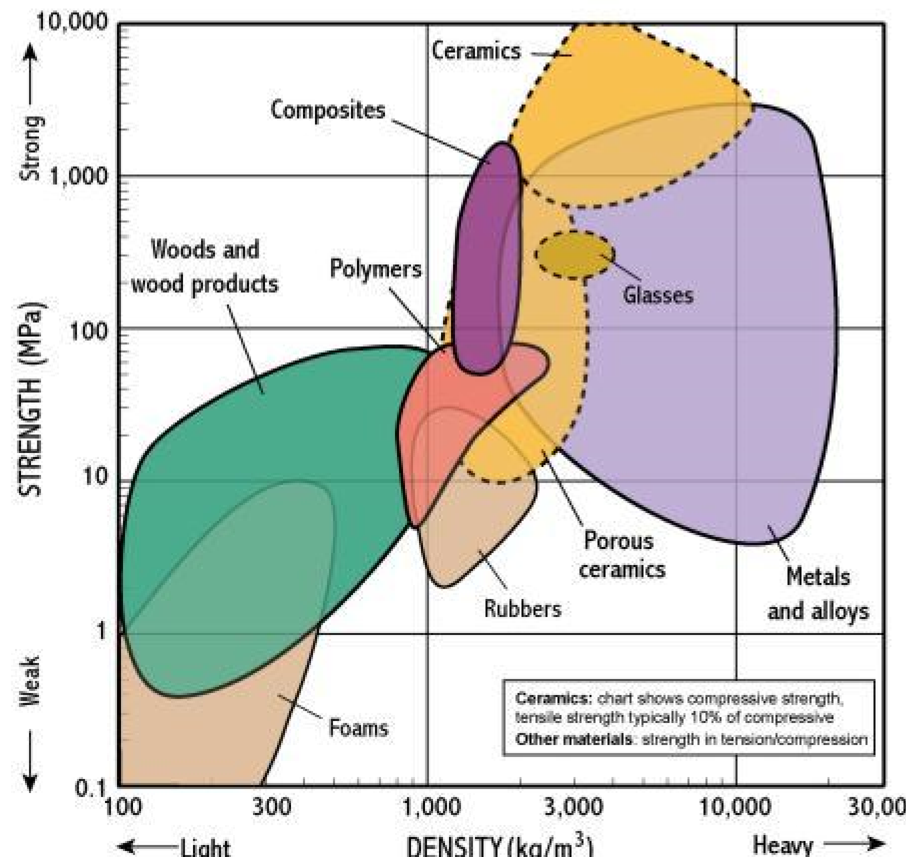
Hand Calculations

- Material Properties
- Heat Transfer (Q)
- Reynold's Number (Re)

$$Q = hA(T - T_\infty)$$

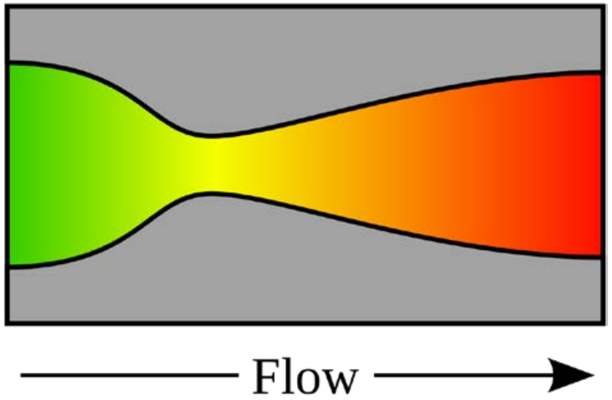
$$Q = k\frac{dT}{dx}$$

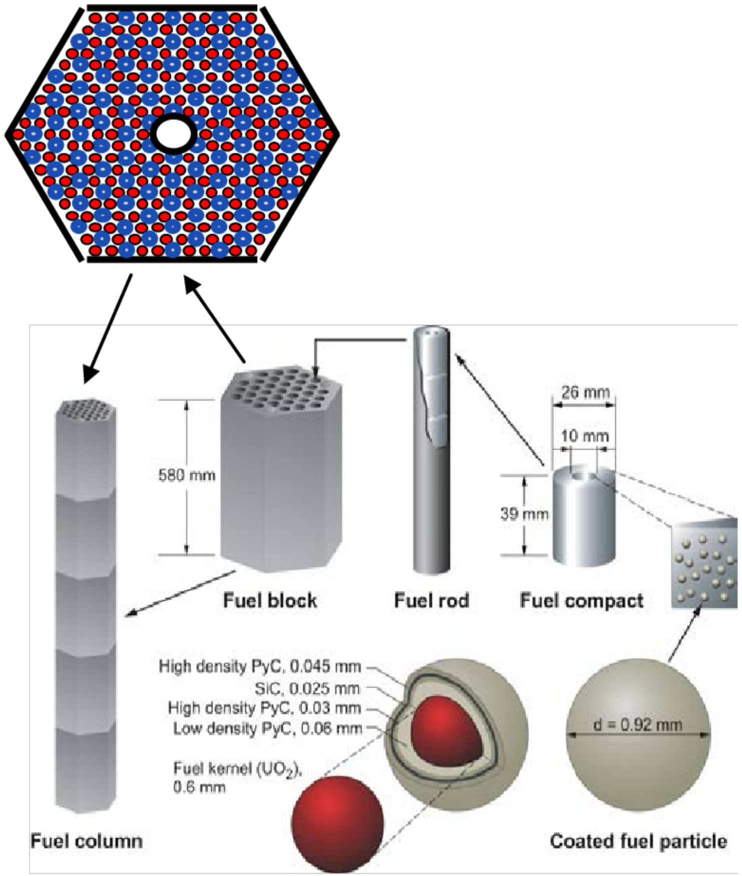
$$Re = \frac{4m'}{\pi D\mu}$$



Detailed Calculations

- CAD Design
- CFD Analysis
- Thermal Systems Design
- Reactor
- Nozzle





Detailed Calculations

what exactly this calculations for?

```
%%writefile seniordesigncalcs.m
%%INPUTS%%
Q = 350;  %power of reactor (MWth)
m = 25; %mass flow rate (kg/sec)
T_in = -268.95; %C (4.2K)
r = .0001;  %outer radius of fuel compact (m) Calculate the amount of triso particles, and size dependent on power
c_p = 1.8154; %J/gK assume P1 in 6.39 MPa
rho_in = 193.3; %(kg/m^3) of He @4.2K
height_fuel_compact =1; %? %full length of pipe (m) assume a certain length I guess
f = 0.2; %pipe friction factor for graphite  (temperature dependent)
D = r*2; %
P1 =6.39; %pressure rating (MPa) (assumption from danny's paper)
k =  0.034760 %thermal conductivity (NIST) (W/(m*K))
P=r*2*pi %wetted perimeter (m) (also circumference)
mu = 0.001; %(Pa*s) %dynamic viscosity find dynamic visc

volume_fuel_compact=pi*r^2*height_fuel_compact; %volume of a single fuel compact

%Control Rod Inputs% We basically have nothing for this so far
Number_of_triso_particles = 100000
Power_per_pellet = Q/Number_of_triso_particles; %(MWth)
%Number_of_absorbed_neutrons =
%Number_of_fuel_pellets =
%Power_of_each_fuel_pellet =
```

Inputs:				Outputs:		
Variable/Parameter (units):	Value:	Reasoning:	Link/Source:	Variable/Parameter (units):	Value:	Reasoning:
total pressure, Pt (kPa)	10000	arbitrary value	NASA slide	mass flow rate (kg/s)	25	assumption
temp of He after leaving core = total temperature, Tt (K)	2773.15	arbitrary value, average nozzle temp of a NTP				
			NASA slide	exit temperature (K)	1273	design objective
free stream pressure = static pressure of the free stream P0 (kPa)	0	property of space	NASA slide	exit pressure (kPa)	37.59679049	calculation
specific heat ratio, gamma	1.667	property of helium	~~NASA slide~~	~~exit velocity (m/s)~~	~~331.9561423~~	~~calculation~~
gas constant, R (kJ/kgK)	2.0771	property of helium	NASA slide	thrust (N)	9050.839367	calculation
exit area, Ae (m^2)	20	arbitrary value	~~principle of NTR book (~~	~~specific impulse (sec)~~	~~6.35880964~~	~~calculation~~
exit mach, Mach, Me, M (dimensionless)	5	arbitrary value	~~https://inis.iaea.org/colle~~	~~ideal impulse (sec)~~	~~26.32180001~~	
molecular weight of He (u)	4.0026	property of helium				
temp of liquid He in the tank (K)	4.2	property of helium		specific power kW/kg(U)		
coolant/propellant volume (m^3)	500	arbitrary value	https://ai-solutions.com/	Time it will take to get to Mars using Hohmann transfer orbit (days):	259	definition. Lower limit. Aim to go faster
tank mass (kg)	10000	arbitrary value	https://www.jpl.nasa.gov			
payload mass (kg)	1000	arbitrary value		Dry Mass of Vehicle = Initial Mass (kg)	31646	calculation
reactor core mass (kg)	500	arbitrary value		Wet Mass of Vehicle (kg)	51646	calculation
nozzle mass (kg)	100	arbitrary value		Change of Mass of Vehicle:		
turbopump mass (kg)	40	arbitrary value		Specific Impulse using Danny's formula (sec)	576.64	Q=1/2mdotgc2Isp2
			https://www.physicsclas	Speed of Vehicle Orbiting Mars (m/s)		
propellant mass (kg)	20000	arbitrary value	https://www.physicsclas	Acceleration of Vehicle Orbiting Mars (m/s^2)		
			https://www.physicsclas	Orbital Period of Vehicle Orbiting Mars (sec)		
Pressure at nozzle (Mpa)	6					
				Maximum velocity attainable (m/s)	2770.73	
NASA Slide explanation!						
v/WWW/K-12/airplane/isentrop.html						
lu/full/2005ESASP.563..373Z						
v/WWW/K-12/rocket/thrsteq.html						
y of He at Temp_tank = 4.2 K (m^3/kg)	191.45	arbitrary				
He at Temp_nozzle = 1273 K (m^3/kg)	2.2574	arbitrary				
f nozzle (smallest cross-section) (m^2)	0.10	arbitrary		velocity of propellant out of turbopump (m/s)	1.283	calculated
ea of pipe right out of turbopump (m^2)	0.10	arbitrary		Volume of tank (m^3)	3829000	calculated
Area of pipe around core (m^2)	12.57	arbitrary		velocity of propellant out of nozzle (m/s)	108.80	calculated

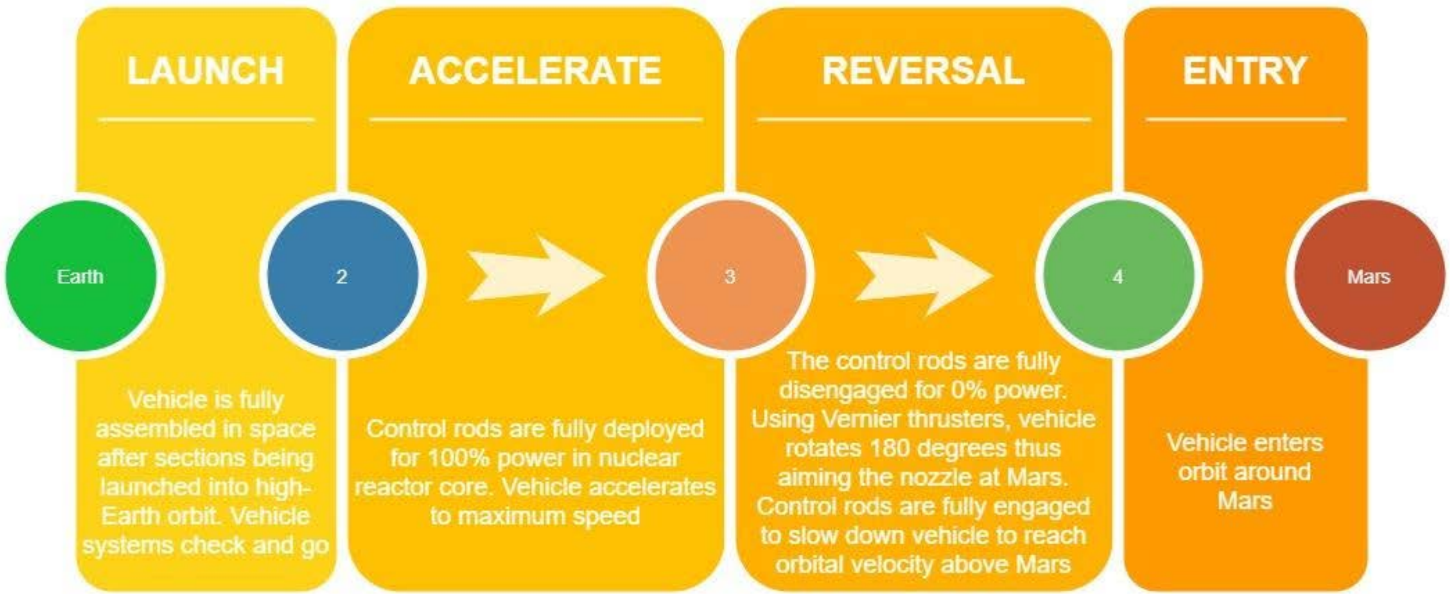
Propulsion Calcs | Stability and Burnup

Preliminary Results

- CONOPs
- Preliminary Design

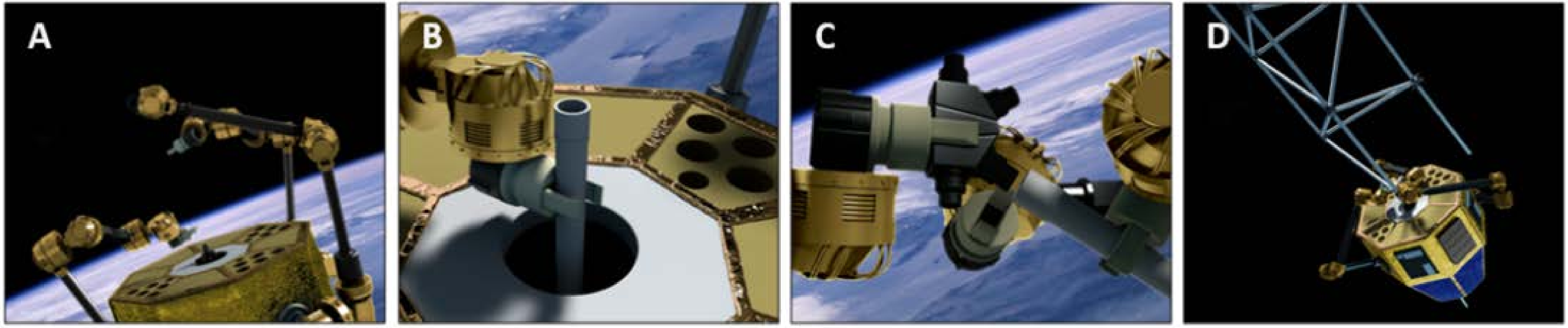
CONOPS (Concept of Operations)

- Earth to Mars
- In-Space Manufacturing Assembly



CONOPS (Concept of Operations)

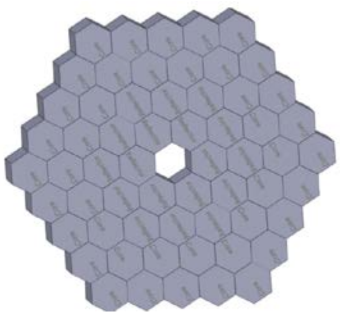
- Earth to Mars
- In-Space Manufacturing Assembly

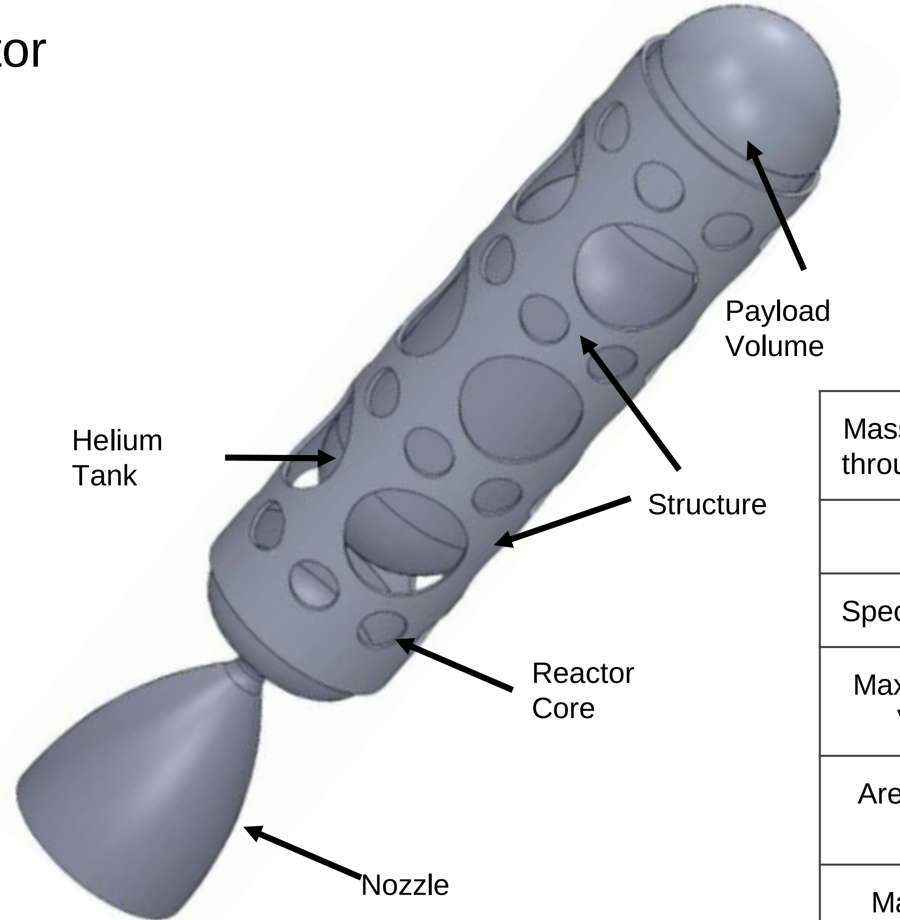


Preliminary Design

Innovations in Reactor

TRISO Particle Fuel
Hexagonal Prism core configuration w/ Cylindrical Coolant Channels
Use of Newly Created Ceramic Matrix Composites (CMCs)

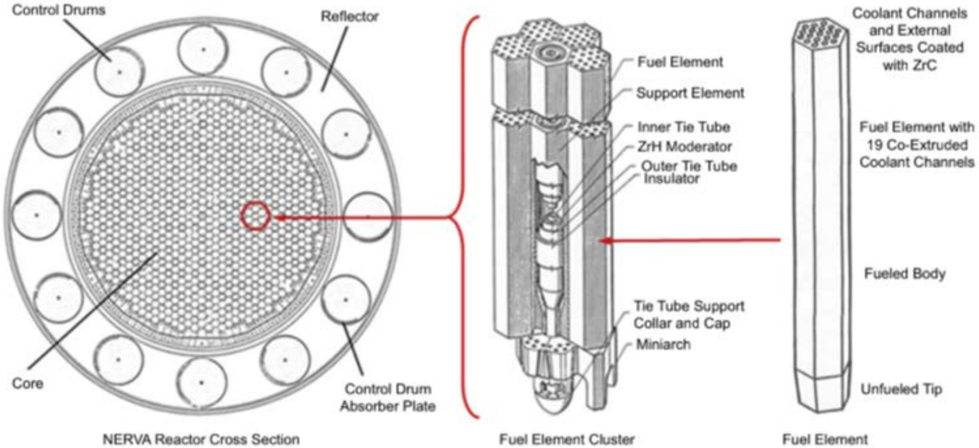


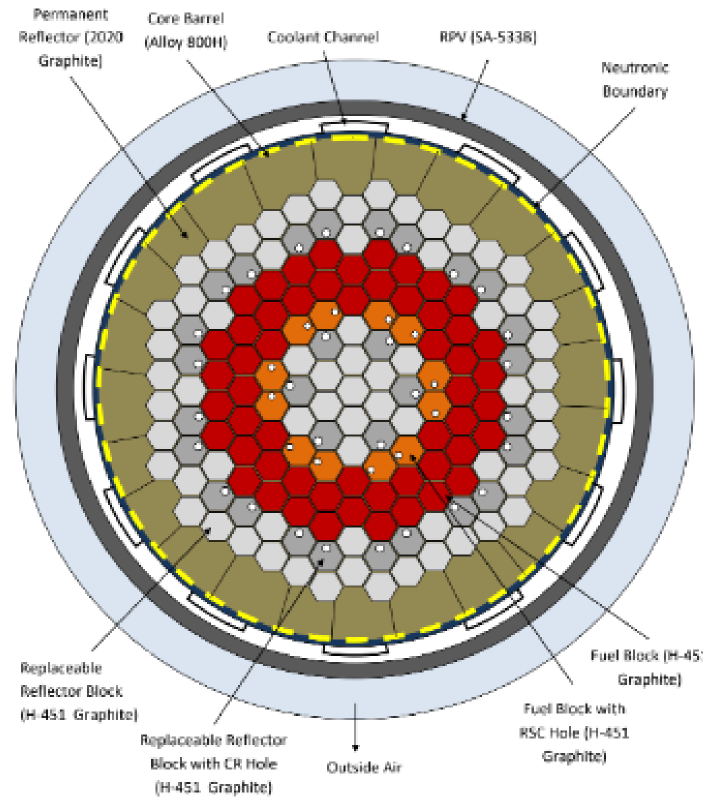


Mass Flow Rate through the core	8.3 kg/s
Thrust	1050 N
Specific Impulse	1000 sec
Max attainable Velocity	8000.46 m/s
Area Ratio for Nozzle:	5.637
Max Power:	400 MWth

Preliminary Design

Reactor Core References

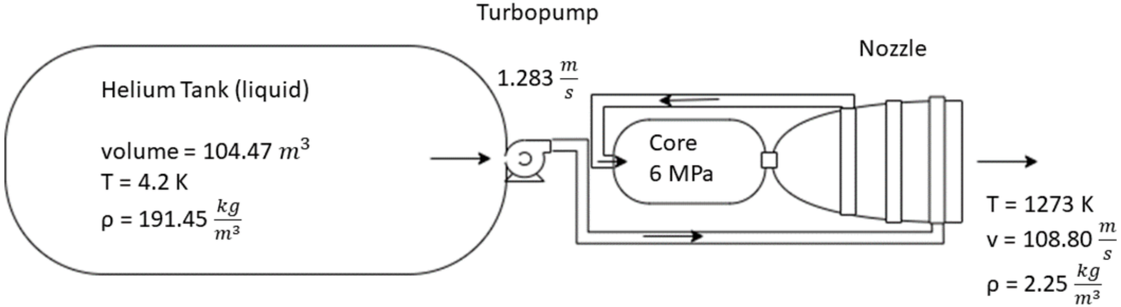




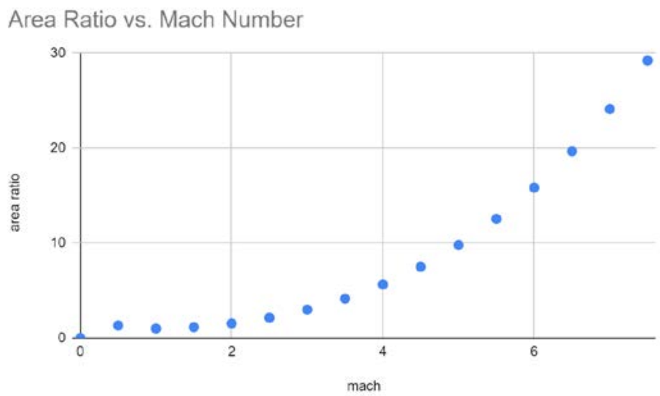
Preliminary Design

- Additional Preliminary Design Values
- Estimated Mass

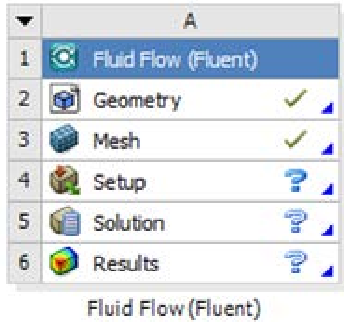
Parameter	Value (kg)
Dry Mass	53670
Wet Mass	73670
Propellant Mass	20000
Core Mass	50000
Turbopump Mass	70
Nozzle Mass	100
Tank Mass	3500

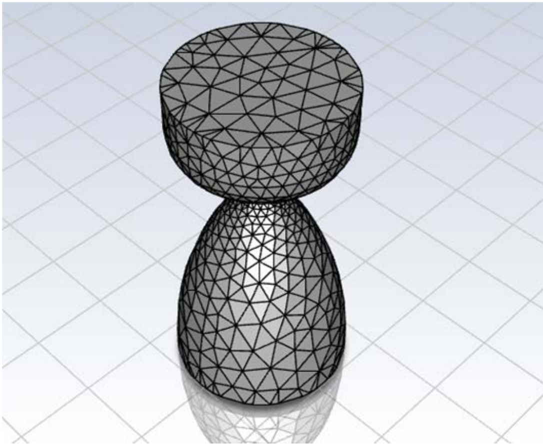


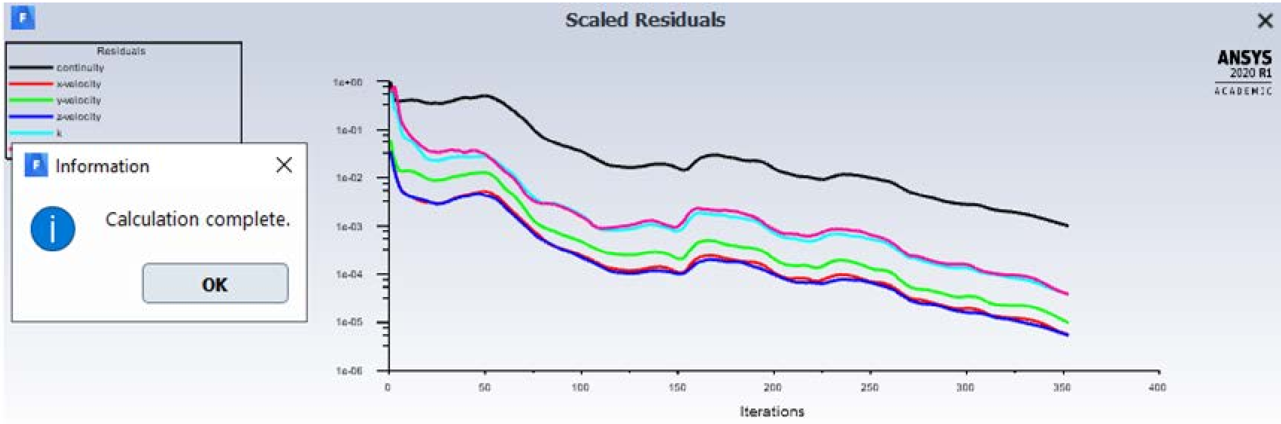
Parameter	Value (K)
Average Fuel Temp	2244.38
Average Moderator Temp	2040.76
Average Propellant Temp	2023.08
Re, at steady state, coolant through the core	162,399.85



Preliminary Design - Nozzle Analysis







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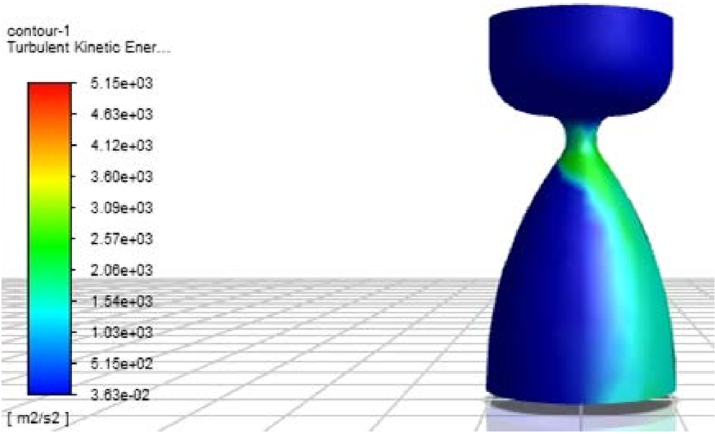

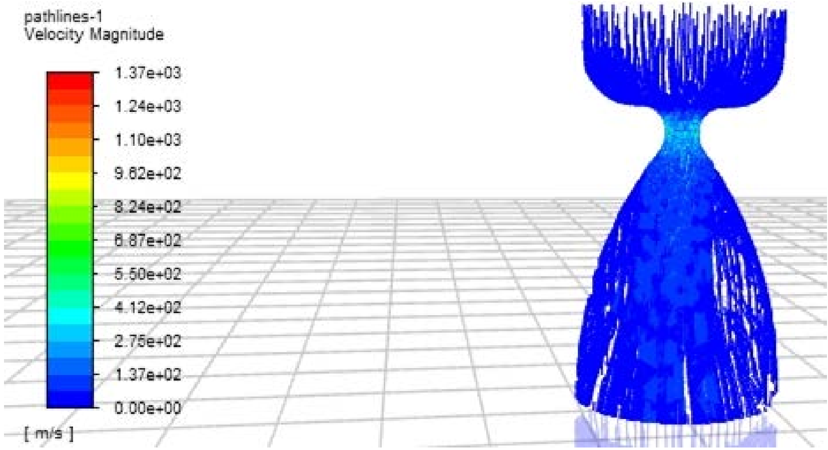

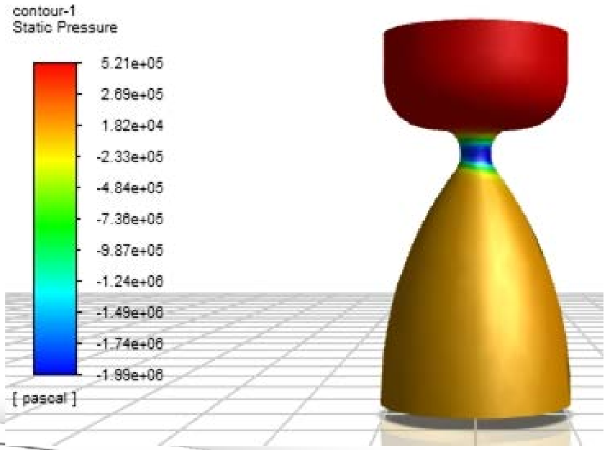

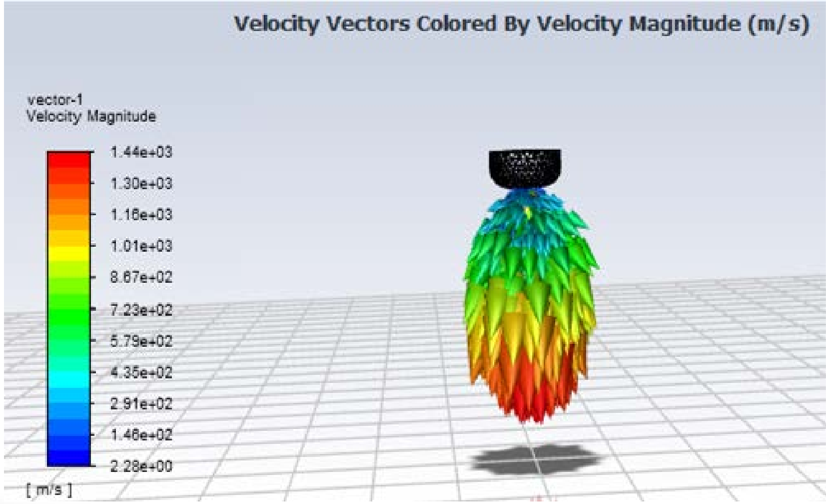

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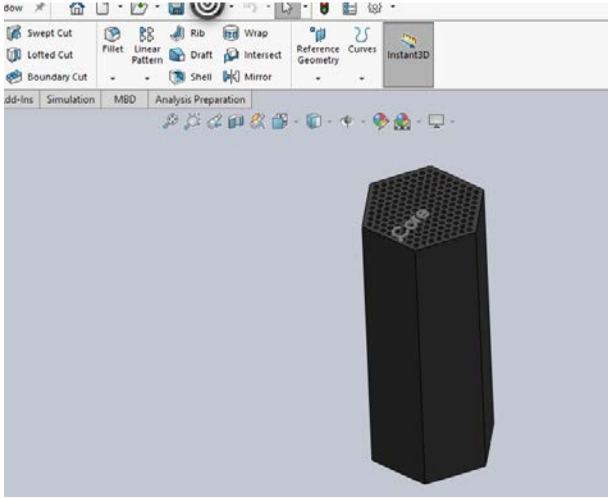
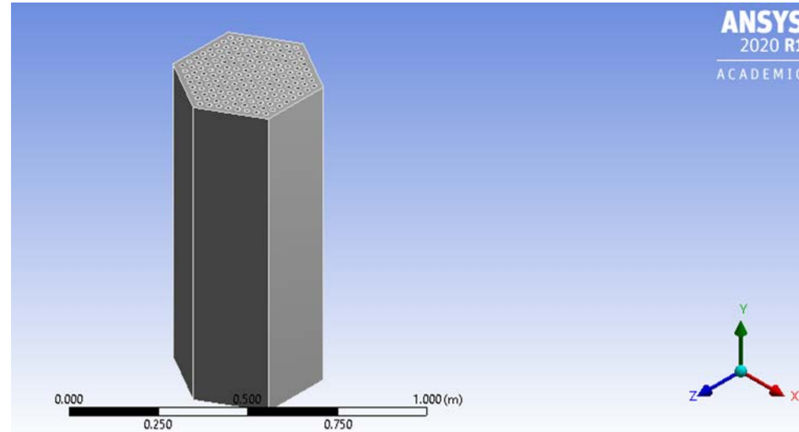
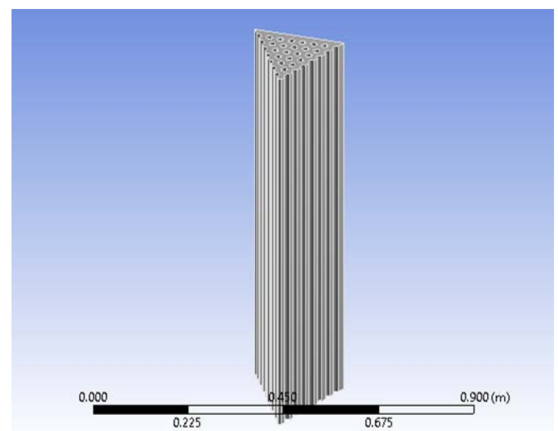
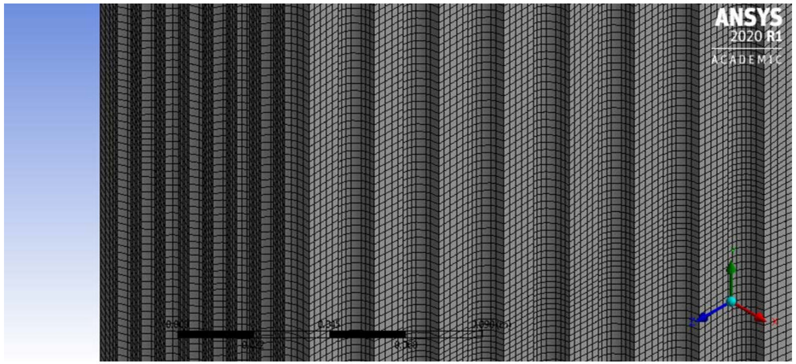
Preliminary Design - Core Analysis

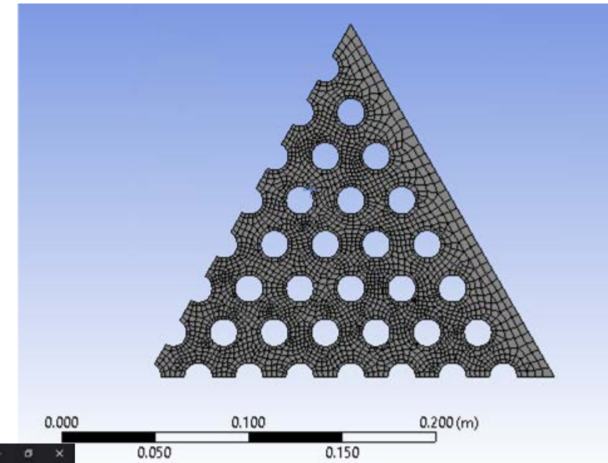


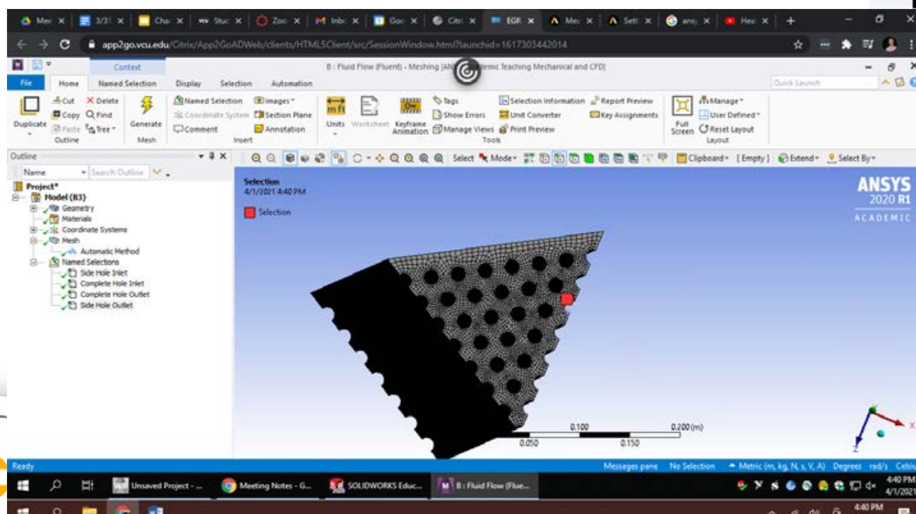




Preliminary Design - Core Analysis







Additional Design Considerations

- Political Environment
- Fear
- Economics
- Global Impact
- Environmental Impact

UNITED NATIONS

Project Timeline

No needed for this talk

Activity/Task	Start	Due	Days	Sept				Oct					Nov					Dec				Jan				Feb				Mar				Apr				May	
Project Proposal				1	2	3	4	1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
Executive Summary	1-Sept	1-Oct	30	X	X	X	X																																
Introduction	1-Sept	1-Oct	30	X	X	X	X																																
Project Definition	1-Sept	1-Oct	30	X	X	X	X																																
Scope	1-Sept	1-Oct	30	X	X	X	X																																
Deliverables	1-Sept	1-Oct	30	X	X	X	X																																
Organization	1-Sept	1-Oct	30	X	X	X	X																																
Timeline	1-Sept	1-Oct	30	X	X	X	X																																
Project Proposal Submission	1-Oct	1-Oct	1				M																																
Preliminary Design Report																																							
Initial Design	14-Oct	30-Oct	17					X	X	X	X	X	X	X	X	X	X																				
Hand Calculations for Preliminary Design	21-Oct	13-Nov	24							X	X	X	X	X	X	X	X																				
Prelim. Design Report Submission	4-Nov	4-Dec	31										X	X	X	X	M																				
Final Design																																							
CFD Analysis and CAD Model of Iteration 1	1-Sept	14-Apr	133																						X	X	X	X	X	X	X	X	X						
Optimization	1-Sept	14-Apr	133																																				
Final CAD Model	14-Apr	14-Apr	1																																M				
EXPO Abstract/EXPO Poster																																							
Abstract	4-Dec	16-Apr	133																						X	X	X	X	X	X	X	X	X						
Poster	4-Dec	16-Apr	133																						X	X	X	X	X	X	X	X	X						
Presentation	16-Apr	16-Apr	1																																M				
Final Design Report / Prototype (if applicable)																																							
Completion of FDR & Analysis	16-Apr	3-May	17																																				
Final Design Report Submission	3-May	3-May	1																																		M		

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Questions

Thanks to members of the MNE 21-512 Senior Design Team

D. Monge
M. Murphy
R. Blackwell
Z. Wu
A. Chadwick

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