Revised Point of Departure Design Options for Nuclear Thermal Propulsion

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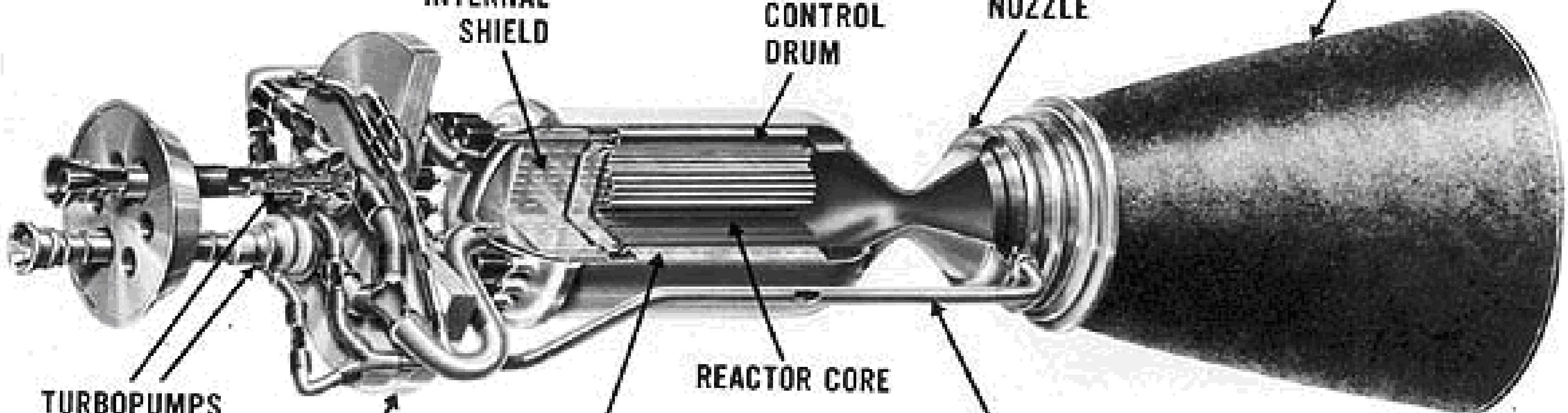
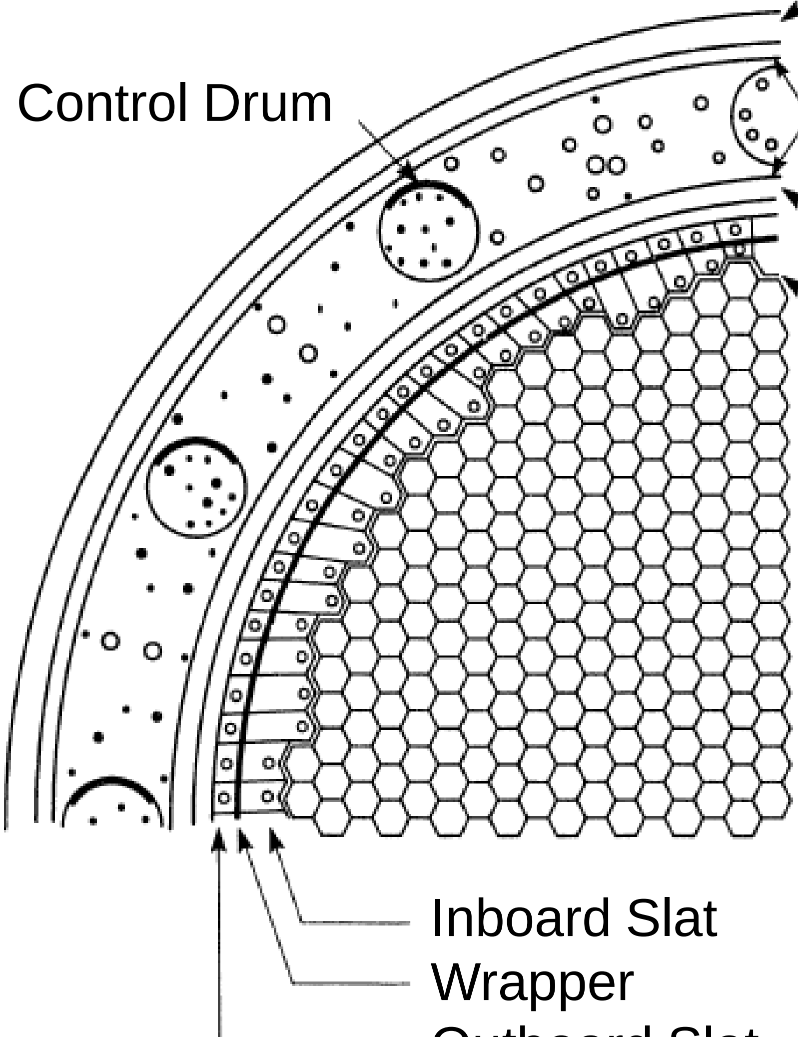
Introduction

- Brief NTR Systems Background
- Fuel Element Geometries
- MCNP/NESS Model
- NERVA Derived Designs
  - Criticality Limited
  - 111 kN (25 klb_f) Thrust Class
- Cermet Based Designs
  - Criticality Limited
  - 111 kN (25 klb_f) Thrust Class
- Analysis Results
- Questions

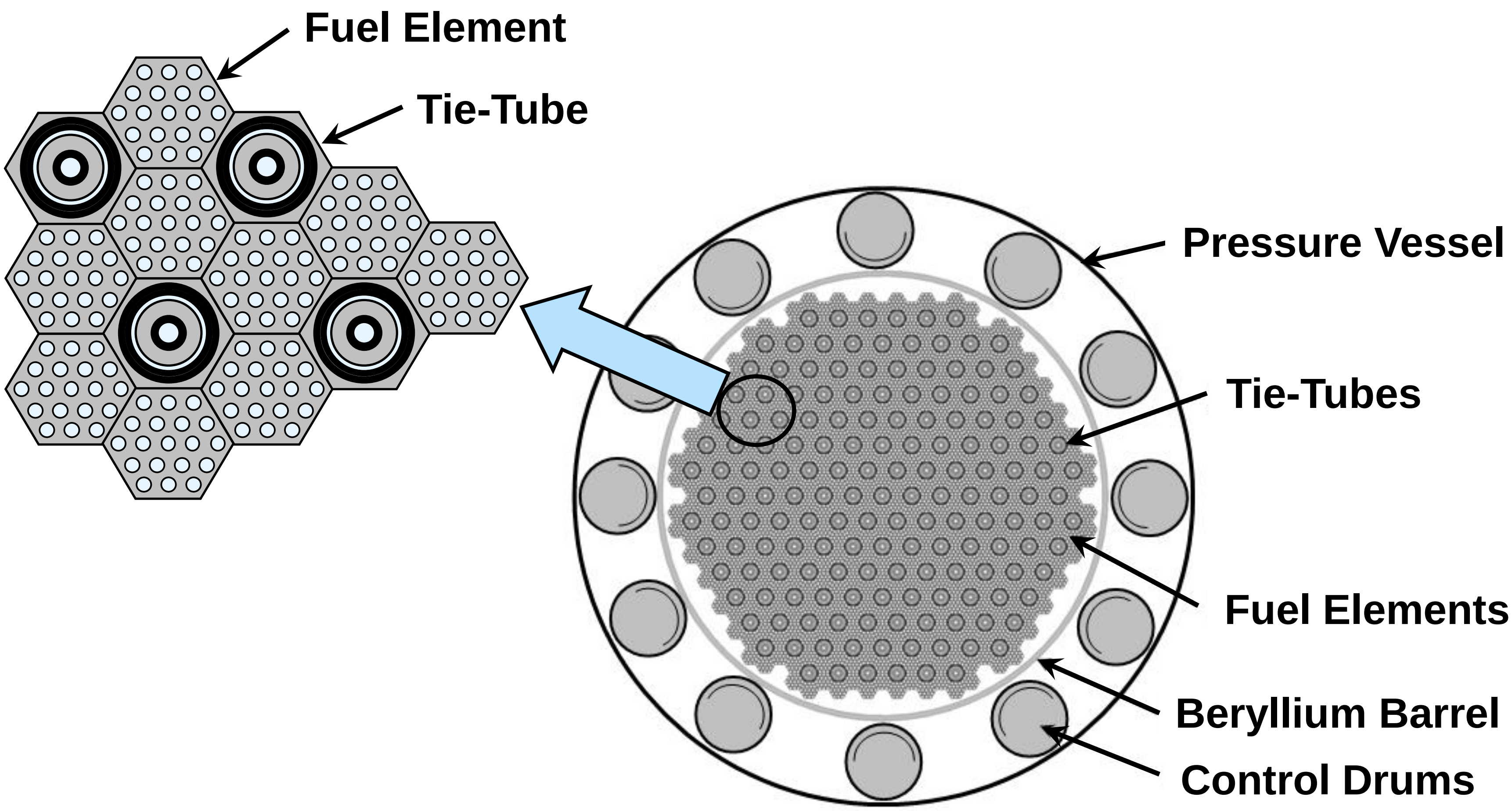
Typical NTR System



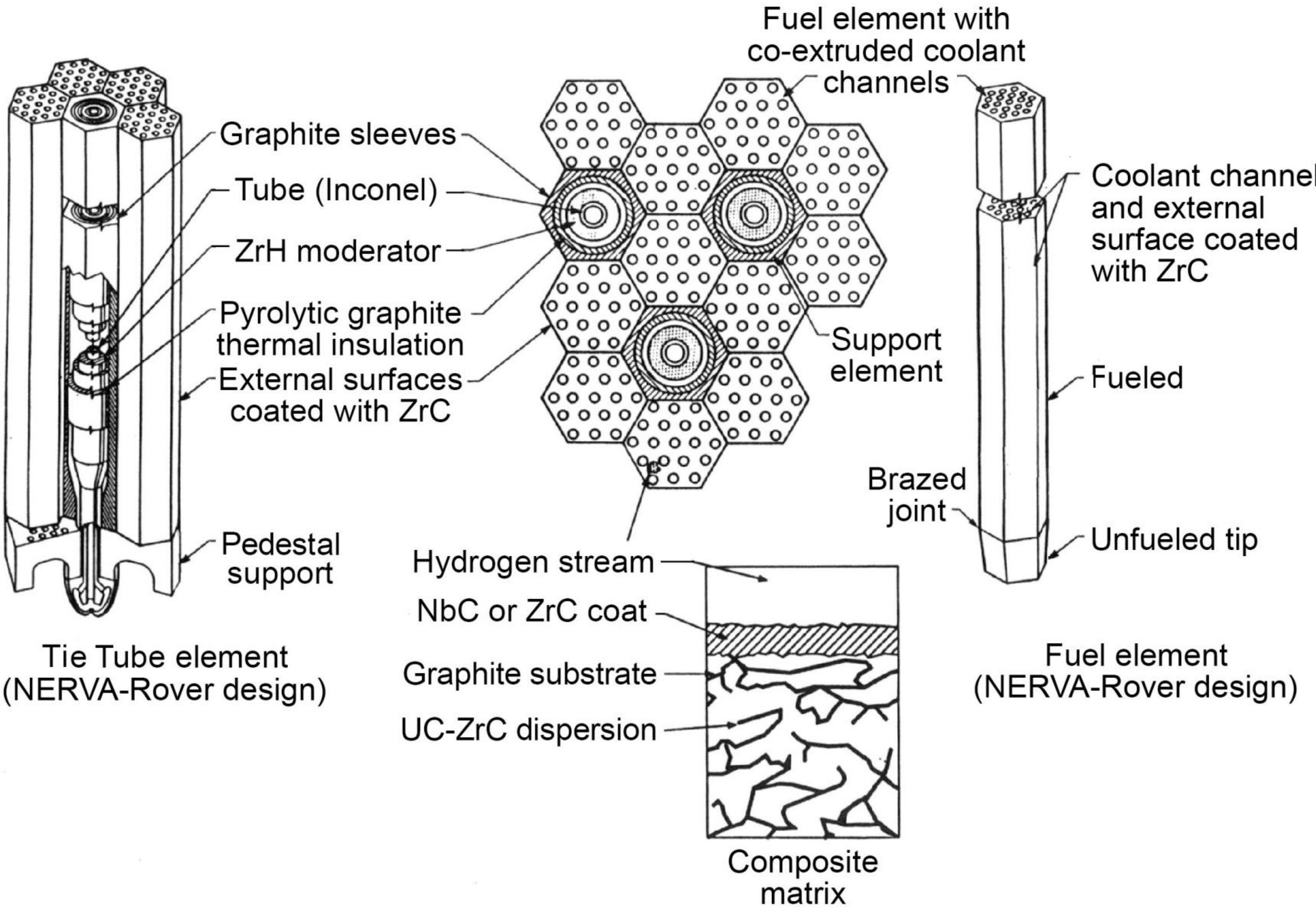
Typical NTR Core Cross Section



NERVA Derived Reactor Cross Section



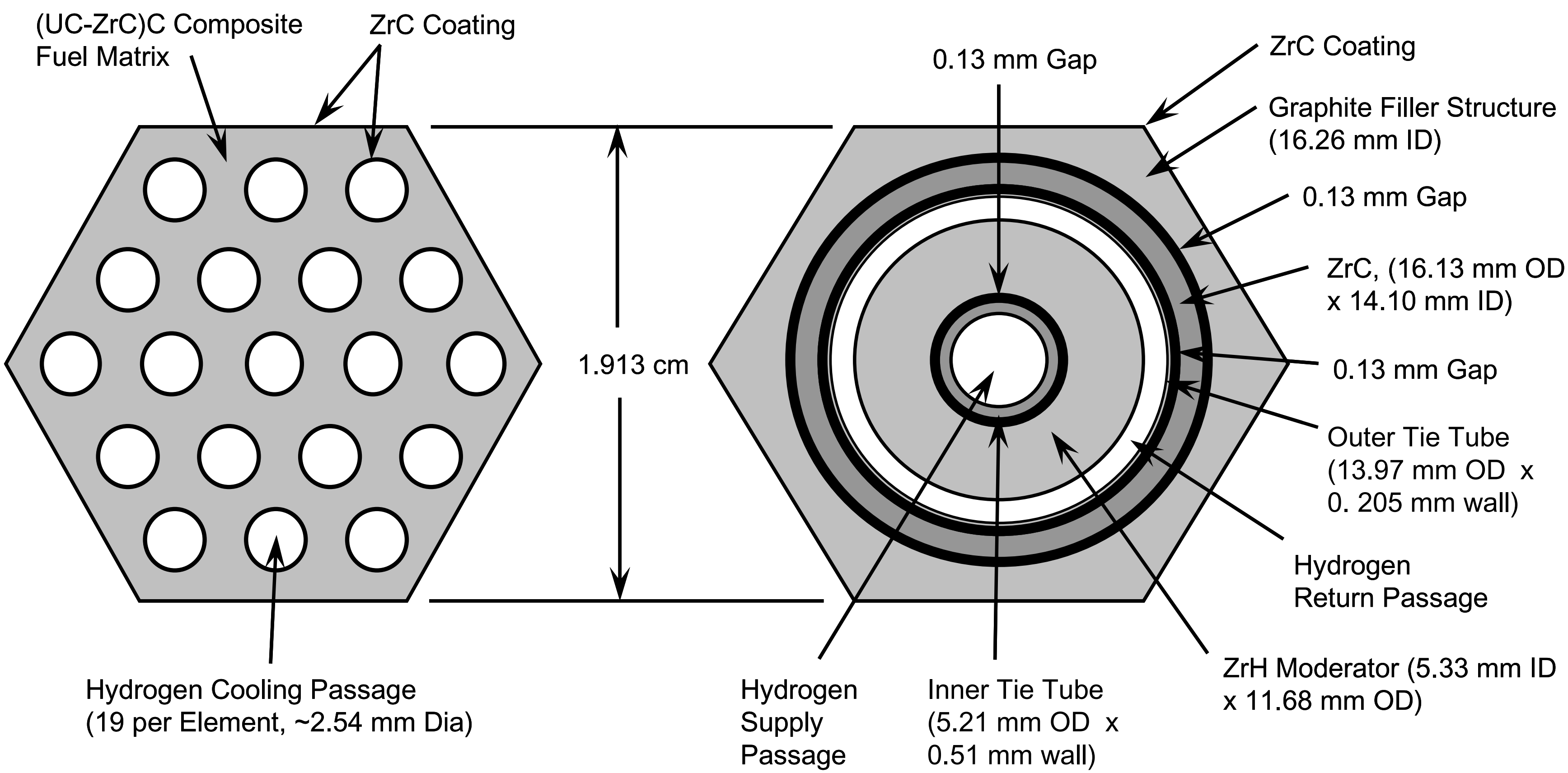
Fuel Element and Tie Tube Arrangement



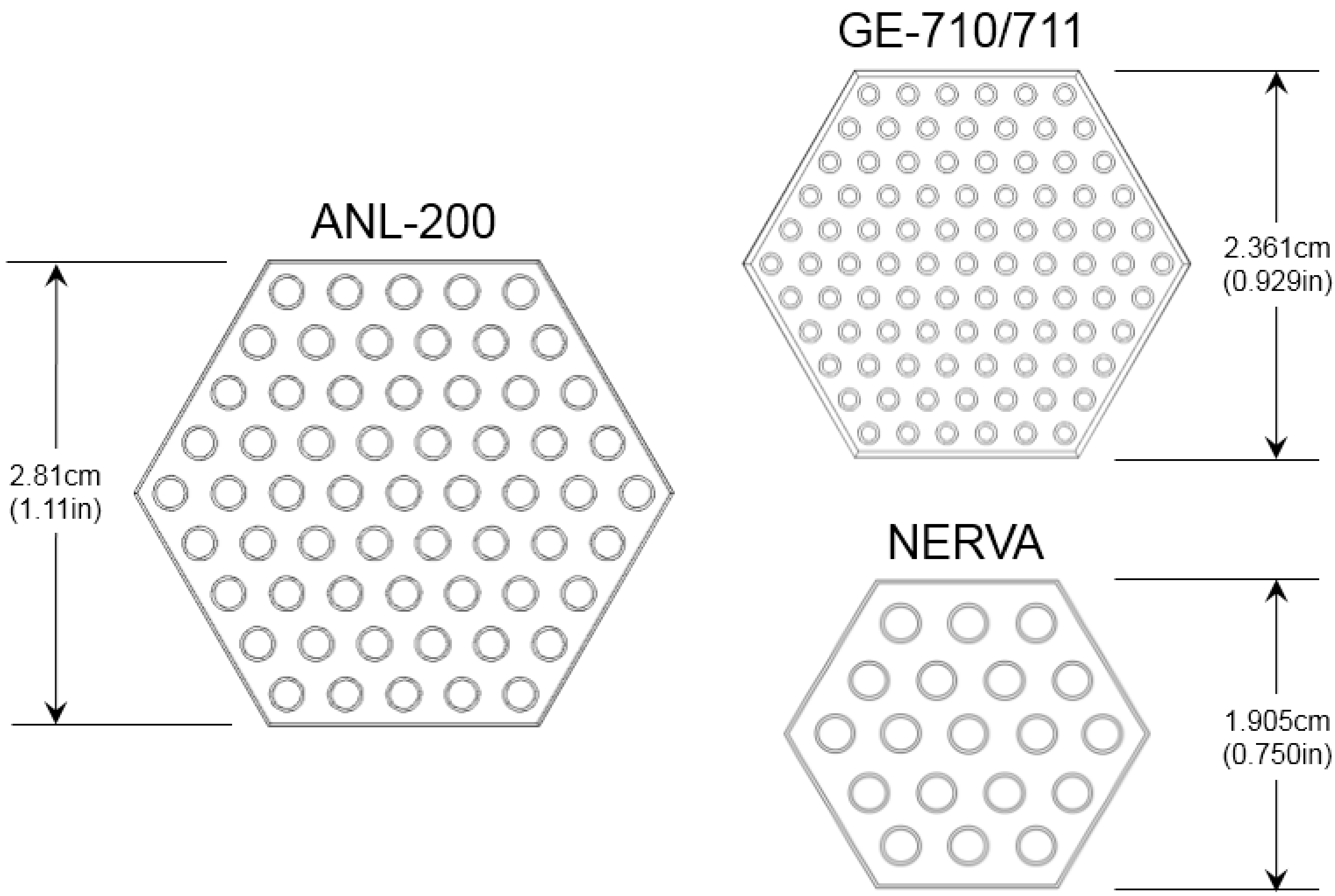
Tie Tube element (NERVA-Rover design)

Fuel element (NERVA-Rover design)

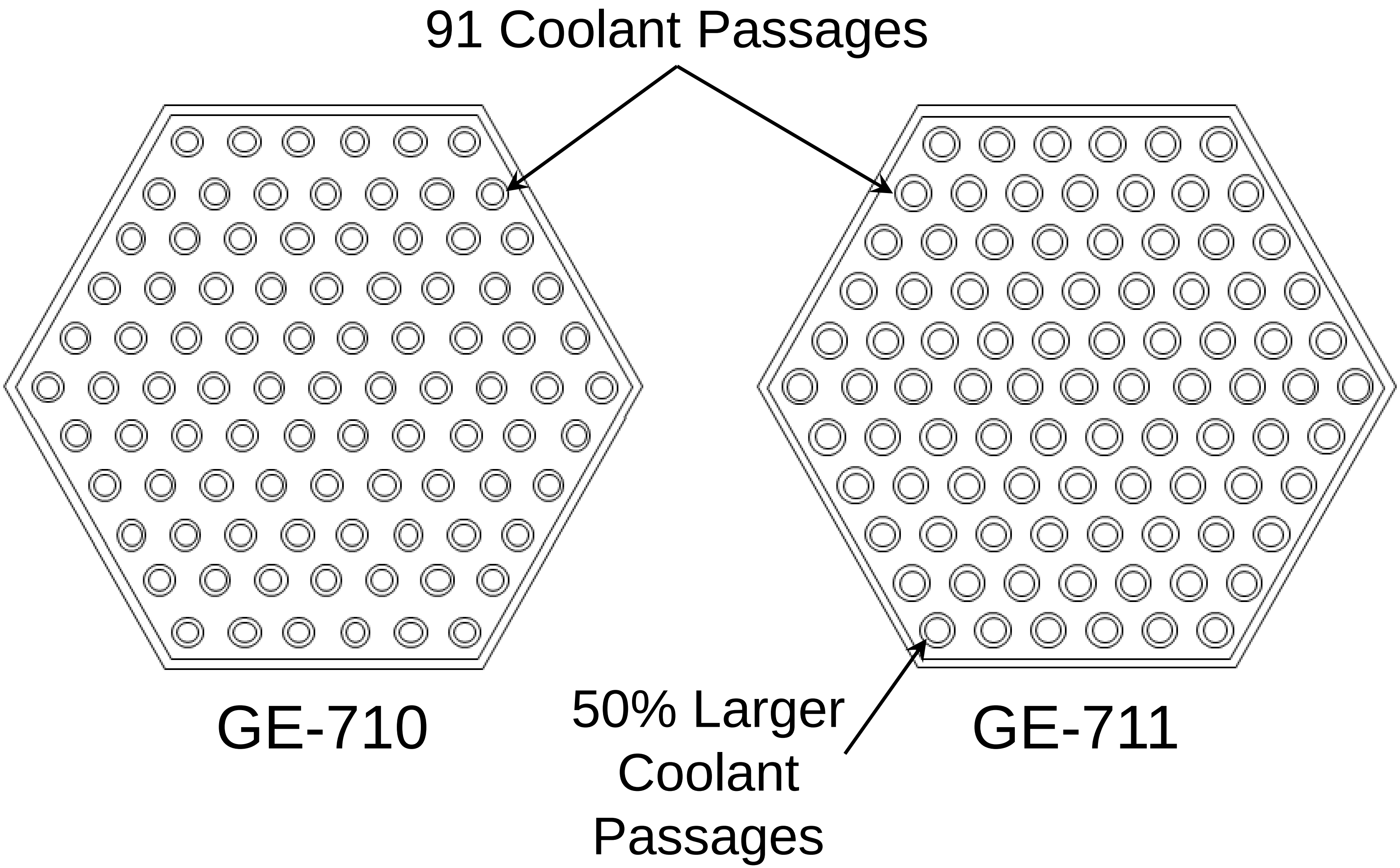
Fuel Element And Tie Tube Cross Sections



NTR Fuel Element Comparison
(Relative Scale)



GE-710 and GE-711 Comparison



GE-710 and GE-711 Comparison, cont.

Parameter	GE-710		GE-711	
Fuel Element Width w/o Cladding	2.278 cm	0.8976 in	2.278 cm	0.8976 in
Fuel Element Width with Cladding	2.361 cm	0.9296 in	2.361 cm	0.9296 in
Outer Cladding Thickness	0.381 mm	0.015 in	0.381 mm	0.015 in
Fuel Element Length	60.96 cm	24.00 in	60.96 cm	24.00 in
Fuel Composition	W -60% UO_2 -6% Gd_2O_3		W -60% UO_2 -6% Gd_2O_3	
Cladding Composition	W / 25% Re		W / 25% Re	
Coolant Channels per Element	91		91	
Coolant Channel Diameter without Cladding	1.321 mm	0.052 in	1.524 mm	0.060 in
Coolant Channel Diameter with Cladding	0.914 mm	0.036 in	1.118 mm	0.044 in
Coolant Channel Pitch	2.353 mm	0.0938 in	2.353 mm	0.0938 in

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NESS (Nuclear Engine System Simulation) Code Features and Capabilities

- Developed by NASA, SAIC, and Westinghouse in early 1990’s
- NESS is used for Conceptual Level Analysis of both the Reactor and Key Engine Subsystems
- NESS can Model Expander, Gas Generator, and Bleed Cycles
- GASPLUS for Liquid Hydrogen Properties
- Accept MCNP Analysis Results as Input
- Propellant Flow Rate Determined by Reactor Thermal Performance
- Able to Optimize Engine System Performance Based on Peak Allowable Fuel Temperature

NESS System Model

- Reactor Component Mass and Thermal Energy Deposition Data from MCNP
  - Fuel Elements and Tie-Tubes (NERVA Derived Systems Only)
  - Control Drums, Radial Reflector, and Filler Elements
  - Numerous Other Non-Nuclear Components
- Expander Cycle with Two Different Chamber Pressures
  - 3.89 MPa (565 psia) for Criticality Limited Designs
  - 6.89 MPa (1000 psia) for 111 kN (25 klb_f) Class Engines
- Fixed Pump and Turbine Efficiency Values
  - Pump Efficiency of 65%
  - Turbine Efficiency of 80%
- Regeneratively Cooled Thrust Chamber and Nozzle to a Nozzle AR of 25:1
- Individually Orificed Fuel Elements
- Peak Allowable Fuel Temperature of 2860 K (5148 R)
- Total Nozzle Area Ratio 300:1
- RL10-B2 Style Retractable Nozzle Extension

NESS System Model (Cermet Only)

- No Tie-Tubes, Periphery Fuel Elements Used to Provide Supplemental TPA Drive Energy as Required
  - Added to TPA Drive Flow Path in Opposing Pairs
  - No Longer Used to Heat Propellant to Produce Thrust
  - Corresponding Fuel Element Pressure Drop Added to Cycle Flow Path
  - Thermal Energy Added in Parallel Path to Control Drums and Radial Reflector
- Axial BeO Axial Reflector Treated Computationally as Fuel Element Extension

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NERVA Derived Engine Design Results

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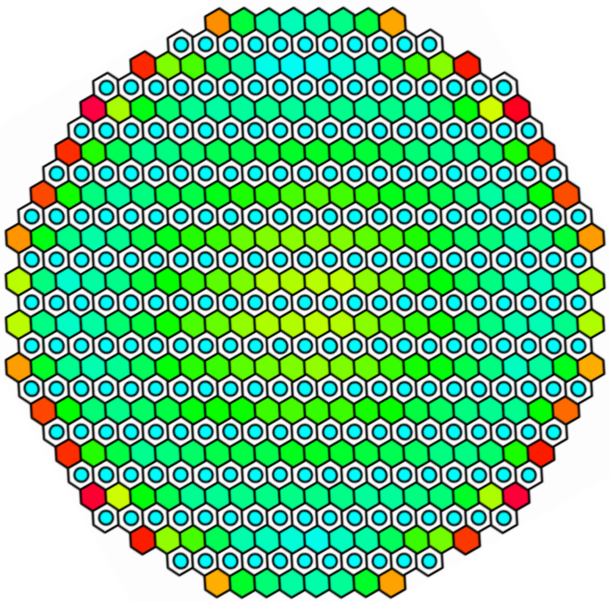
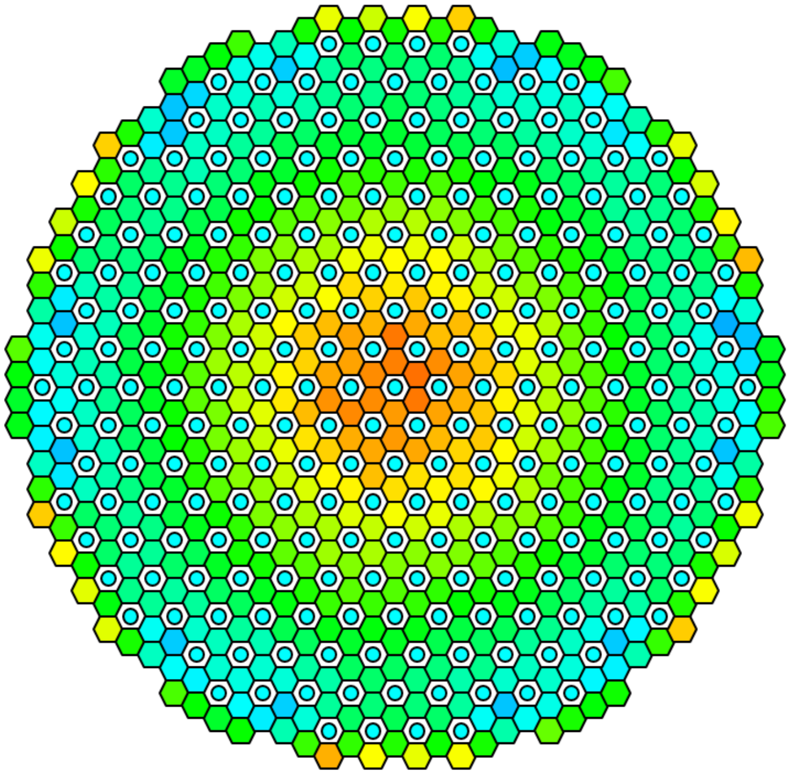
Normalized Thermal Energy Deposition Rate Profiles

NERVA Derived Engine Designs – Composite Fuel

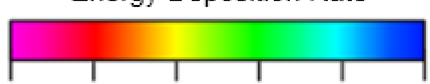


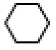
Criticality Limited
NERVA Derived Option

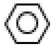


111 kN (25 klb_f) Thrust
NERVA Derived Design

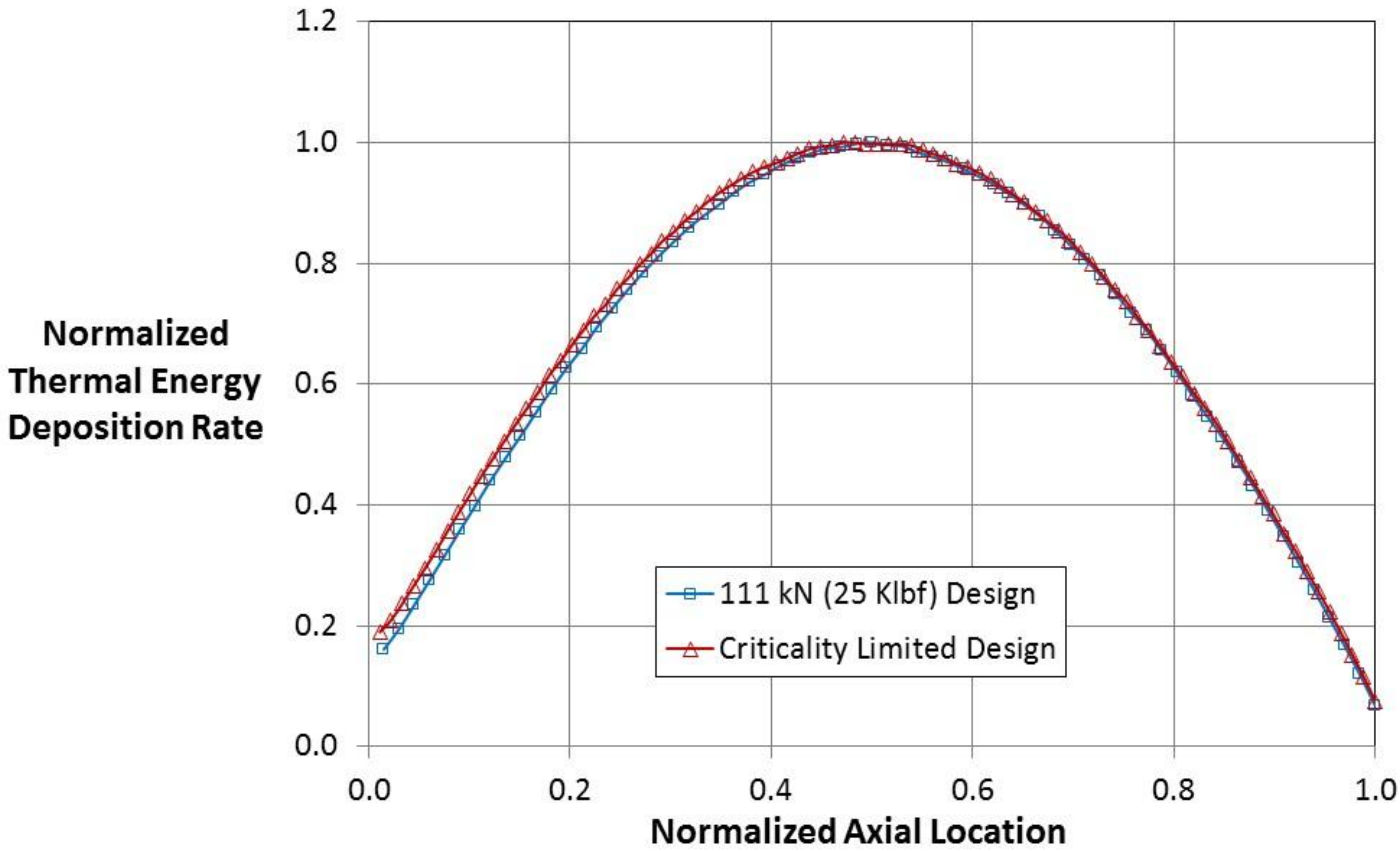
Normalized Thermal
Energy Deposition Rate



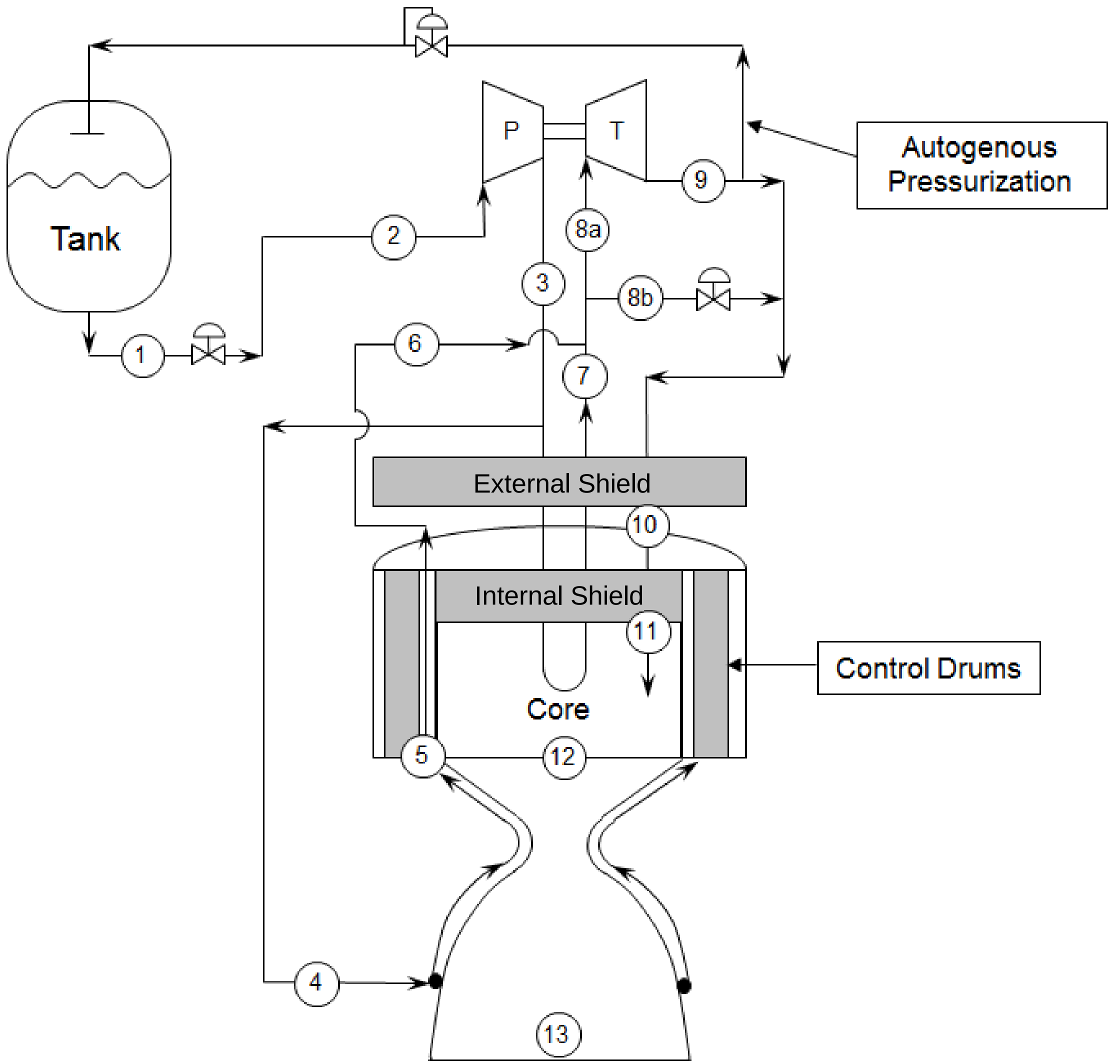
 Fuel Element

 Tie-Tube

Normalized Axial Thermal Energy Deposition Rate Profiles
(NERVA Derived Designs)



NERVA Derived Expander Cycle Flow Path (Single TPA)



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Oak Ridge National Laboratory

NERVA Derived Engine Summary

Peak Fuel Temperature of ~2860 K and Nozzle Area Ratio (NAR) of ~300:1

	NERVA-Derived (Composite)	
Masses (kg)	**Criticality-Limited**	**25 klb$_f$ Class**
Fuel Elements (FE)	207.7	612.84
Tie Tubes (TT)	231.0	313.70
Heater Elements (HE)	-	-
Reflector Assembly	717.71	1141.57
Pressure Vessel	87.93	284.72
TPA	9.07	41.43
TVC, Lines, and Valves	38.2	85.82
Nozzle	81.03	149.78
Assorted Hardware	416.36	708.14
Engine Mass	1789	3338
Dimensions (cm)		
Core / FE Length	89	132
TPA / TVC System Length	178.1	228.3
Pressure Vessel Length	207.1	320.9
Nozzle Length	233.7	320.2
Nozzle Exit Diameter	137.9	189.0
Approx. Total Engine Length	618.9	869.4
Engine Parameters		
No. Elements (FE/TT/HE)	260 / 251 / 0	564 / 241 / 0
Core Power Level (MW$_t$)	157	563
Chamber Pressure (MPa)	3.89	6.89
U-235 Mass (kg)	27.5	36.8
Thrust (klb$_f$)	7.52	25.18
Thrust-to-Weight Ratio	1.91	3.42
Delivered Isp (s)	894	909

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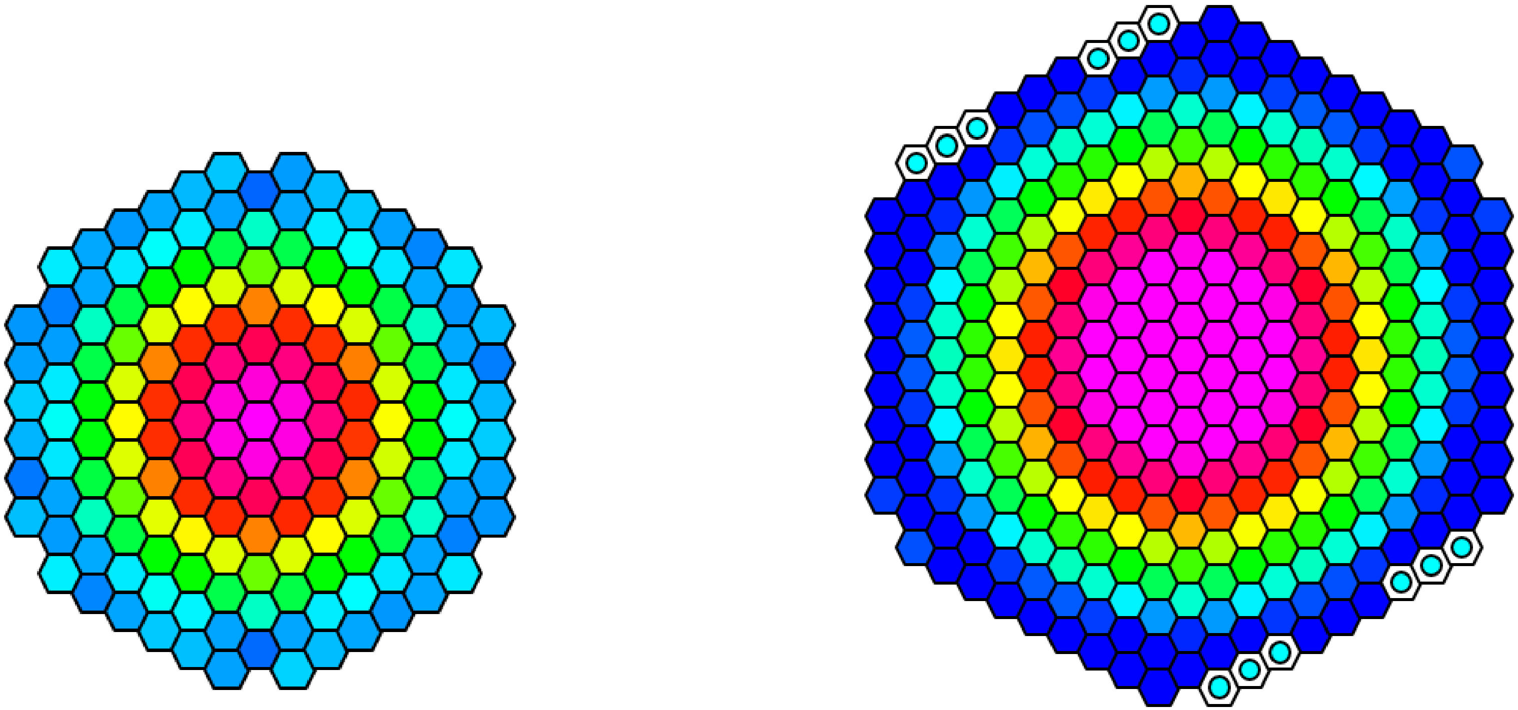
Cermet Engine Design Results

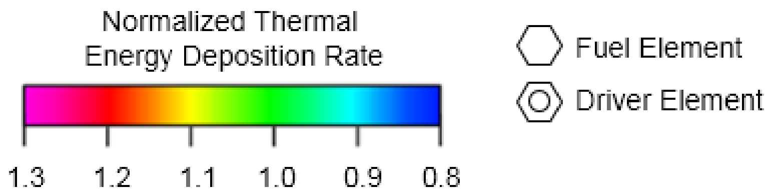
Normalized Thermal Energy Deposition Rate Profiles

Cermet Fuel Based Engine Designs



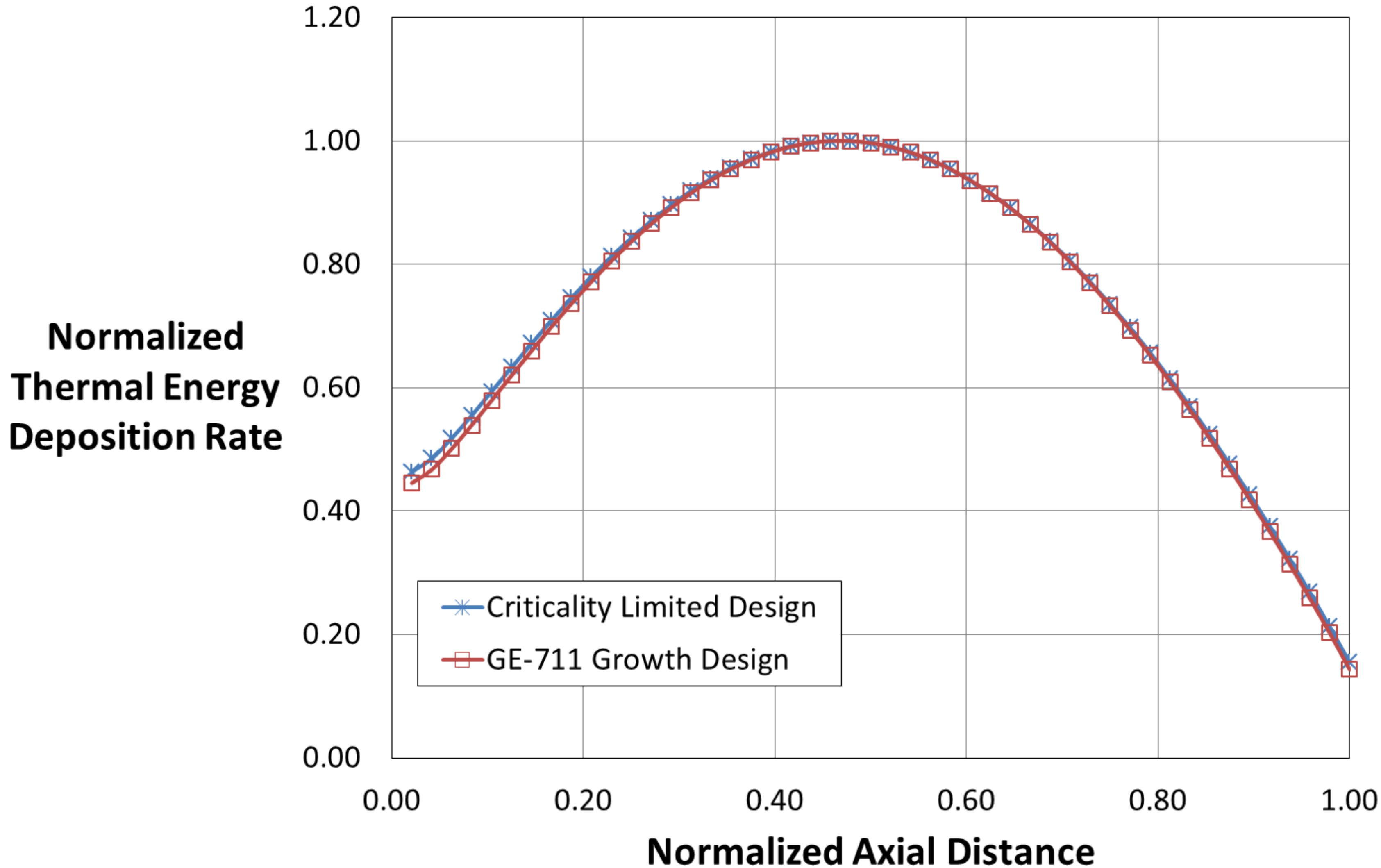
Criticality Limited
ANL-200 Based Design

111 kN (25 klb_f) Thrust
GE-711 Based Design



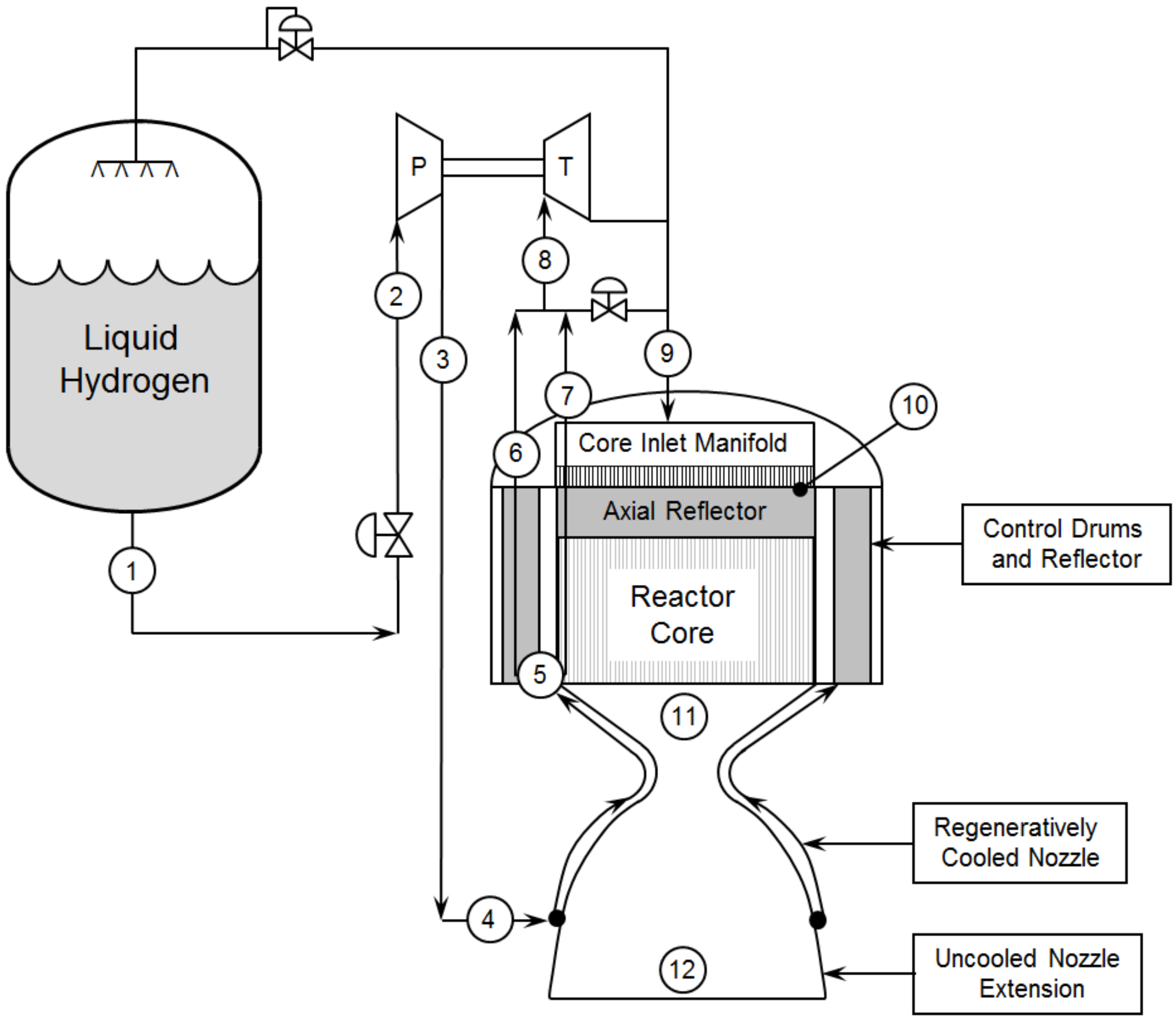
Normalized Axial Thermal Energy Deposition Rate Profiles

(Cermet Designs)



Cermet Based NTR Flow Diagram

(Expander Cycle with Single TPA)



Point of Departure Engine Summary

Peak Fuel Temperature of ~2860 K and Nozzle Area Ratio (NAR) of ~300:1

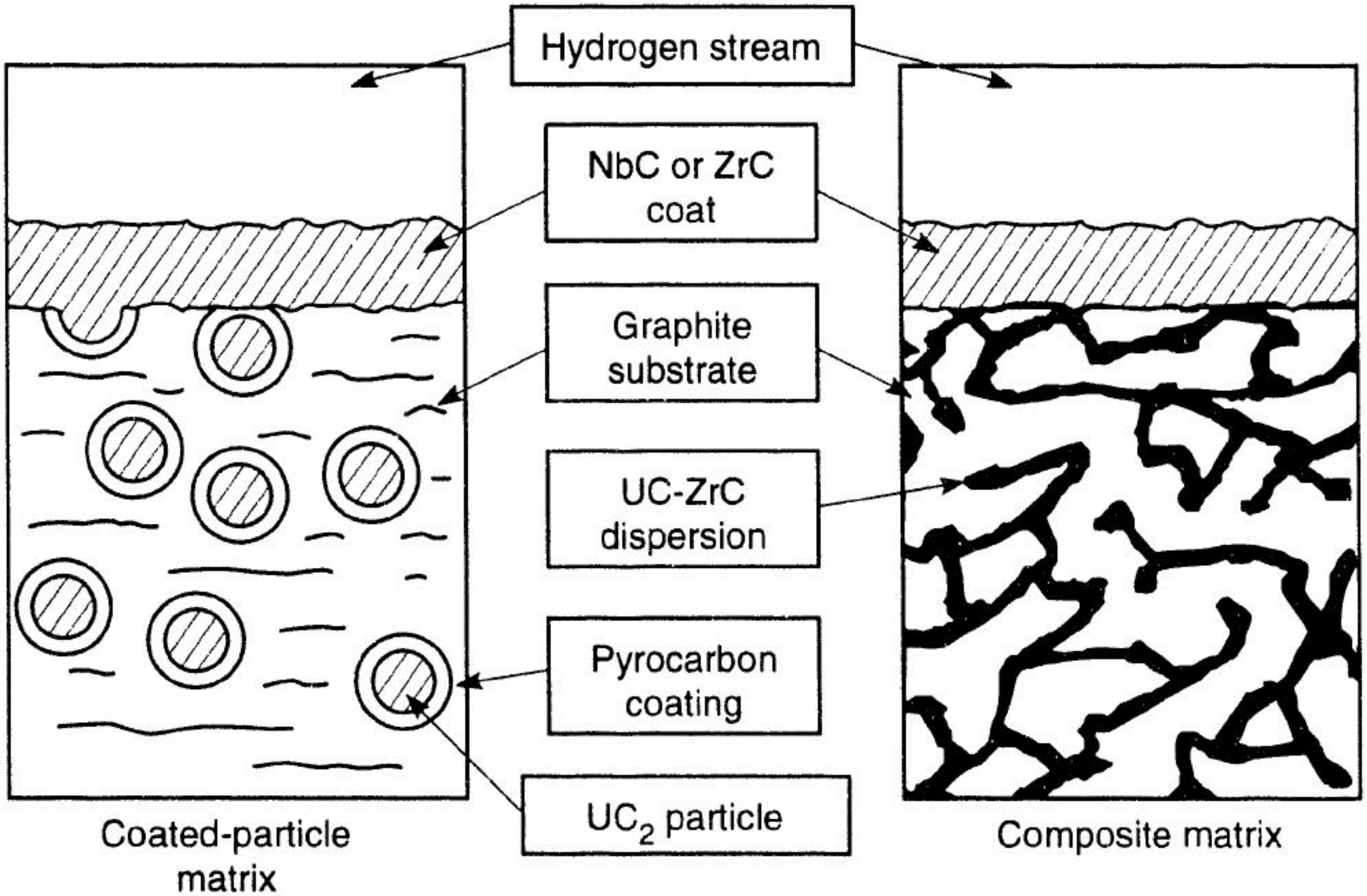
	NERVA-Derived (Composite)		ANL-200	GE-711 Variant
Masses (kg)	**Criticality-Limited**	**25 klb_f Class**	**Criticality-Limited**	**25 klb_f Class**
Fuel Elements (FE)	207.7	612.84	950.50	1226.63
Tie Tubes (TT)	231.0	313.70	-	-
Heater Elements (HE)	-	-	-	48.90
Reflector Assembly	717.71	1141.57	414.74	437.51
Pressure Vessel	87.93	284.72	74.98	205.28
TPA	9.07	41.43	13.28	53.04
TVC, Lines, and Valves	38.2	85.82	42.68	73.39
Nozzle	81.03	149.78	106.95	149.49
Assorted Hardware	416.36	708.14	208.87	480.76
Engine Mass	1789	3338	1812	2675
Dimensions (cm)				
Core / FE Length	89	132	71	61
TPA / TVC System Length	178.1	228.3	209.3	225.3
Pressure Vessel Length	207.1	320.9	155.0	157.0
Nozzle Length	233.7	320.2	292.0	318.9
Nozzle Exit Diameter	137.9	189.0	172.3	188.2
Approx. Total Engine Length	618.9	869.4	656.3	701.2
Engine Parameters				
No. Elements (FE/TT/HE)	260 / 251 / 0	564 / 241 / 0	163 / 0 / 0	313 / 0 / 12
Core Power Level (MW_t)	157	563	266	564
Chamber Pressure (MPa)	3.89	6.89	3.89	6.89
U-235 Mass (kg)	27.5	36.8	238.5	258.6
Thrust (klb_f)	7.52	25.18	11.92	25.09
Thrust-to-Weight Ratio	1.91	3.42	2.98	4.26
Delivered Isp (s)	894	909	903	906

Conclusions

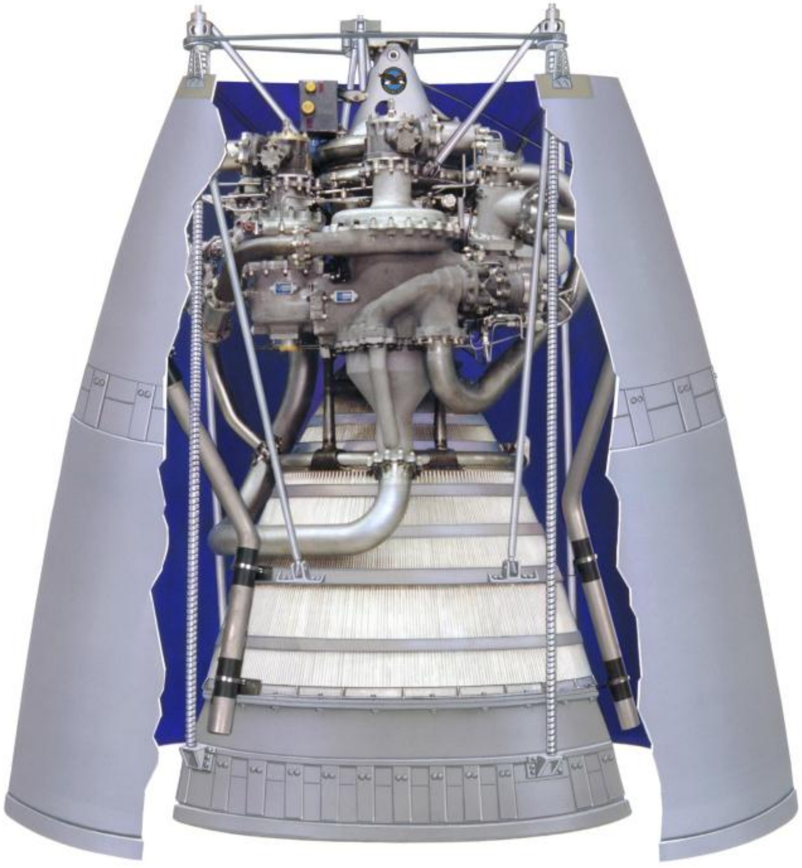
- Four Revised Point of Departure NTR Engines were Designed and Analyzed using MCNP and NESS
- All Four Engines Have Thermodynamically Closed Cycles at Nominal Chamber Pressures
- 111 kN (25 klb_f) Cermet Design Required Dedicated Heater Elements to Close the Cycle
- Cermet Based Designs had Slightly Higher T/W Ratios, but Required Substantially More U-235
- NERVA Derived Criticality Limited Engine Could Operate at Lower Power and Thrust Levels Compared to the Criticality Limited Cermet Design

Back-up Charts

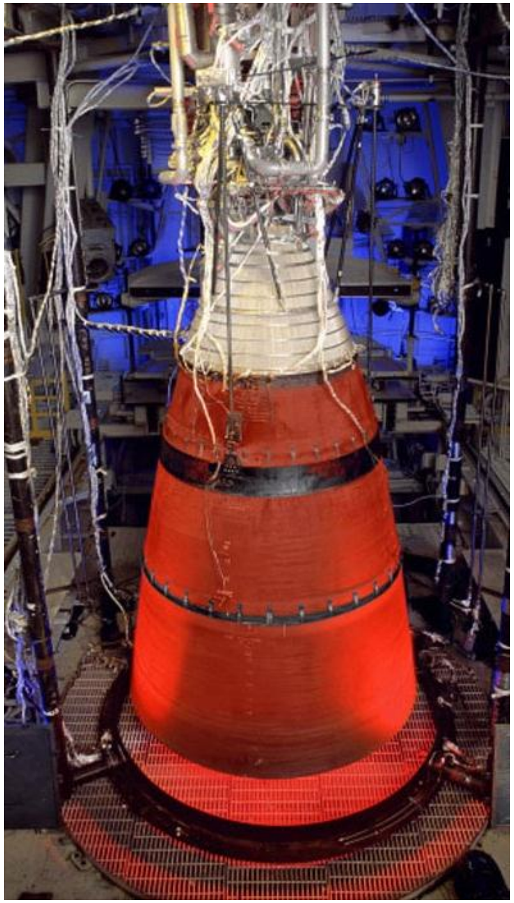
Carbide/Graphite Based Fuels



RL10-B2 Retractable Nozzle

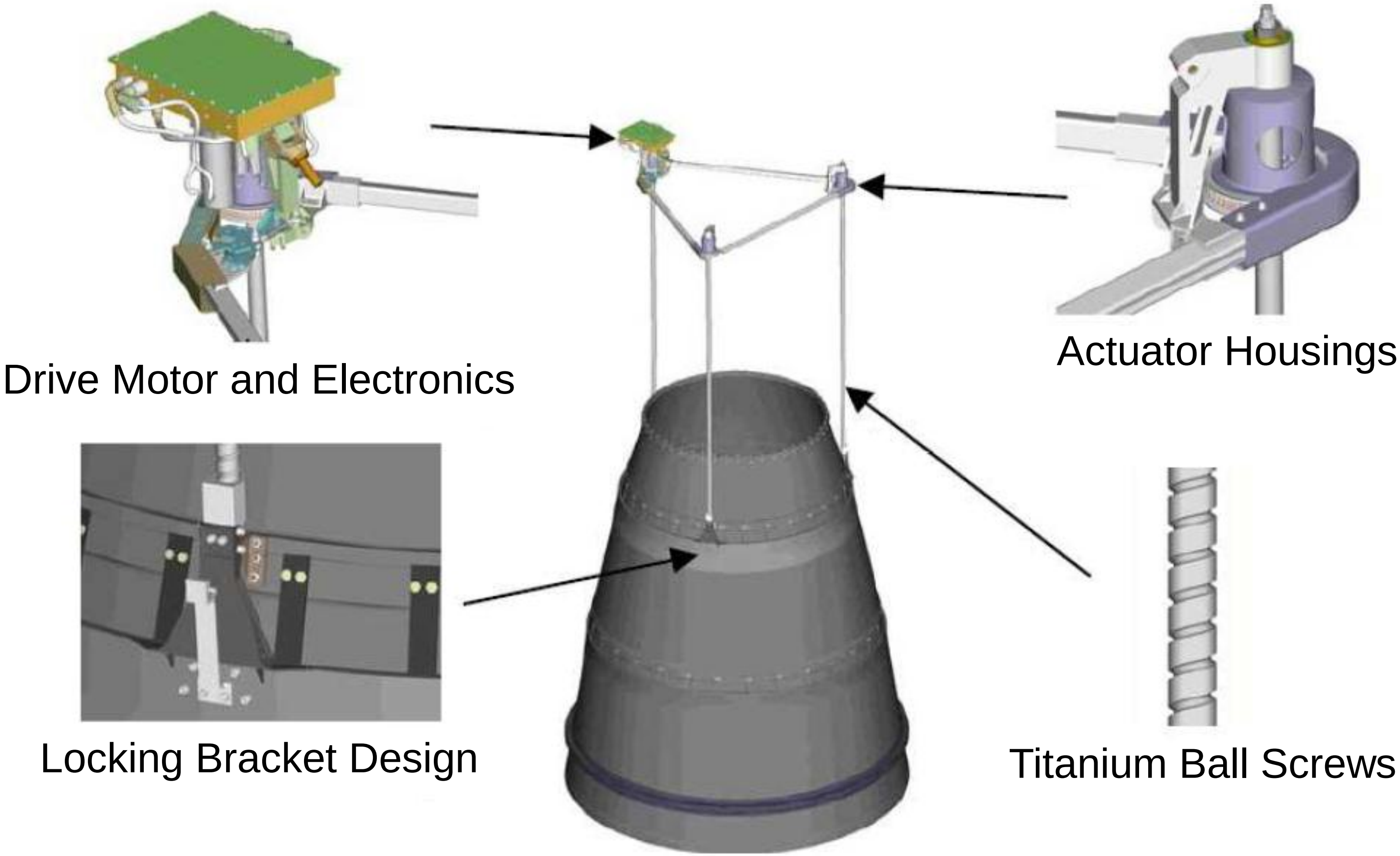


Nozzle Extension Retracted

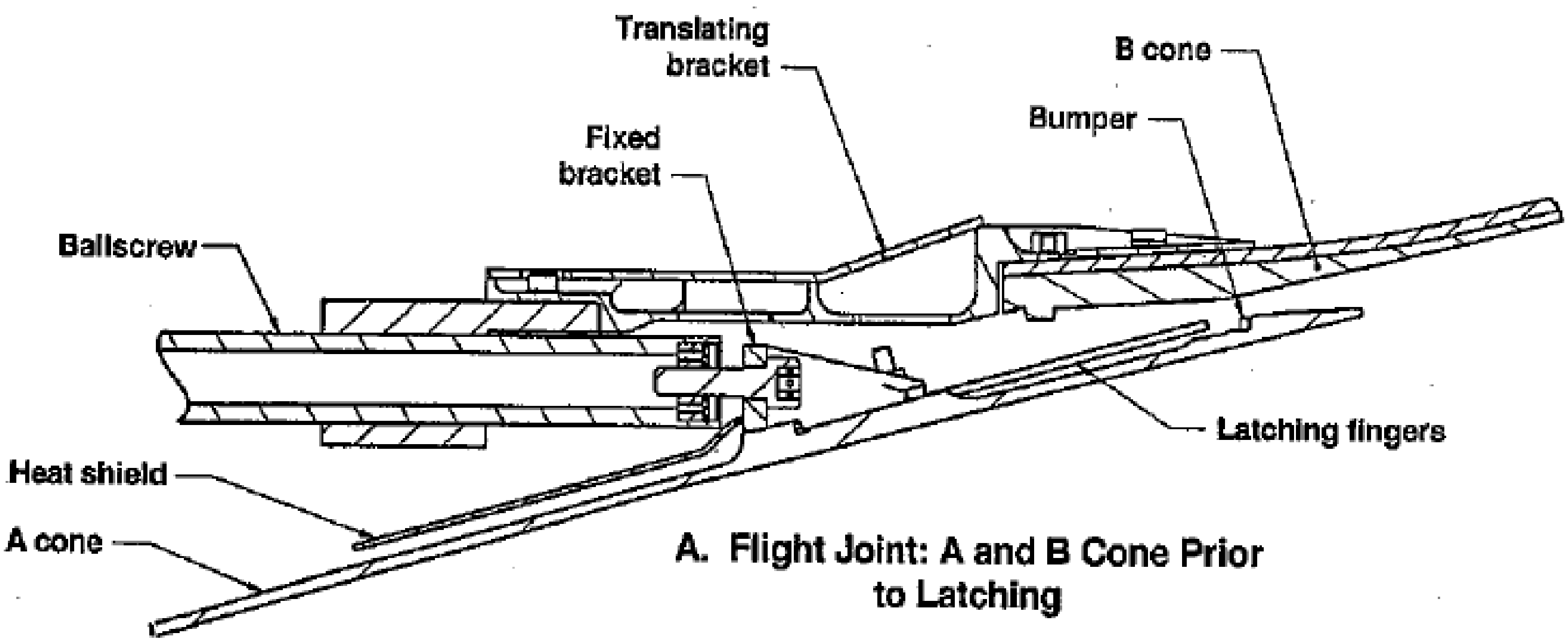


Nozzle Extension Deployed

Deployable Nozzle Components

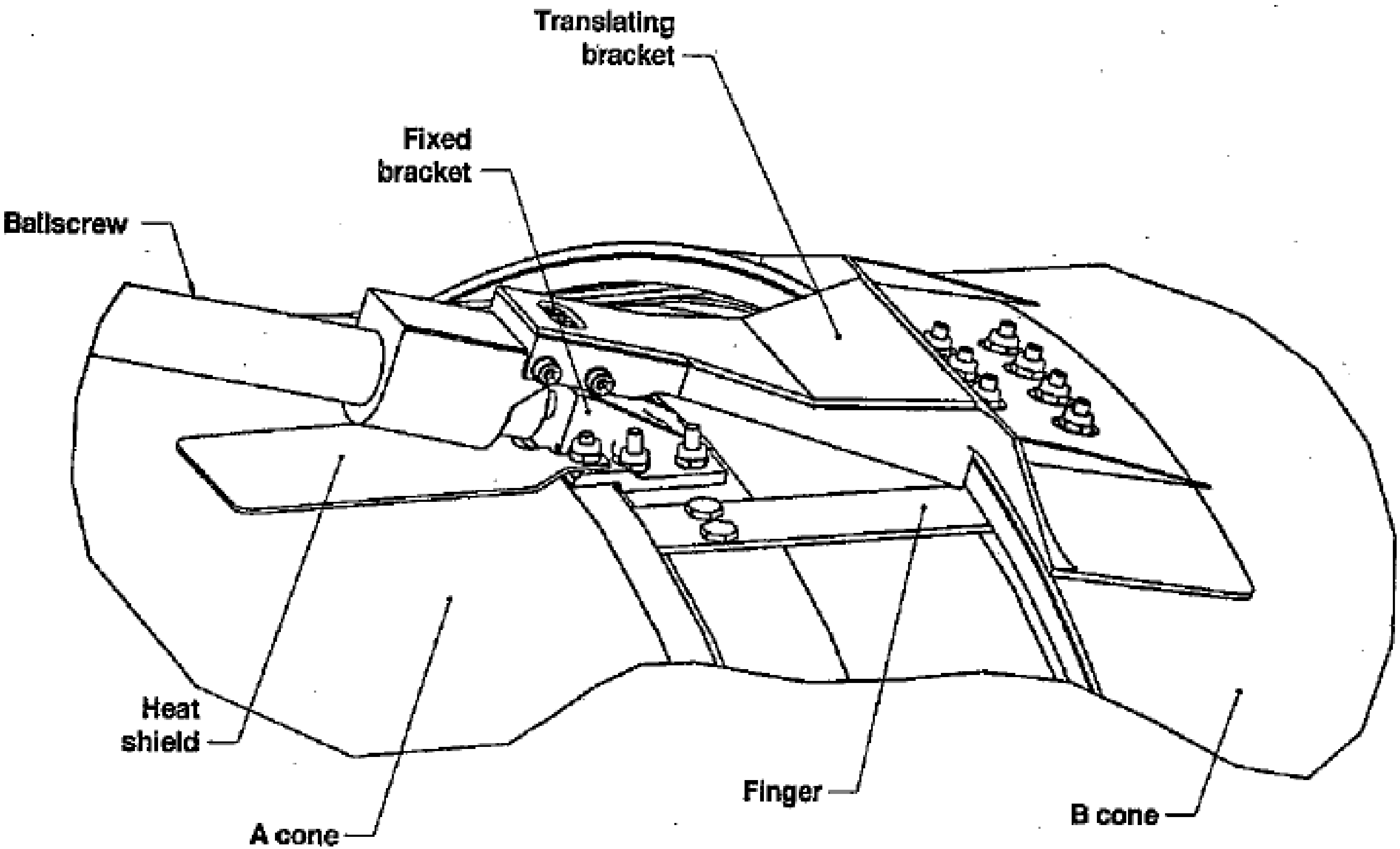


Translating Nozzle Bracket Design



A. Flight Joint: A and B Cone Prior to Latching

Translating Nozzle Bracket, cont.



Thermodynamic State Points for Small (~7.5 klb_f) POD NERVA-derived Engine at 161 MW_t and Isp ~894 s

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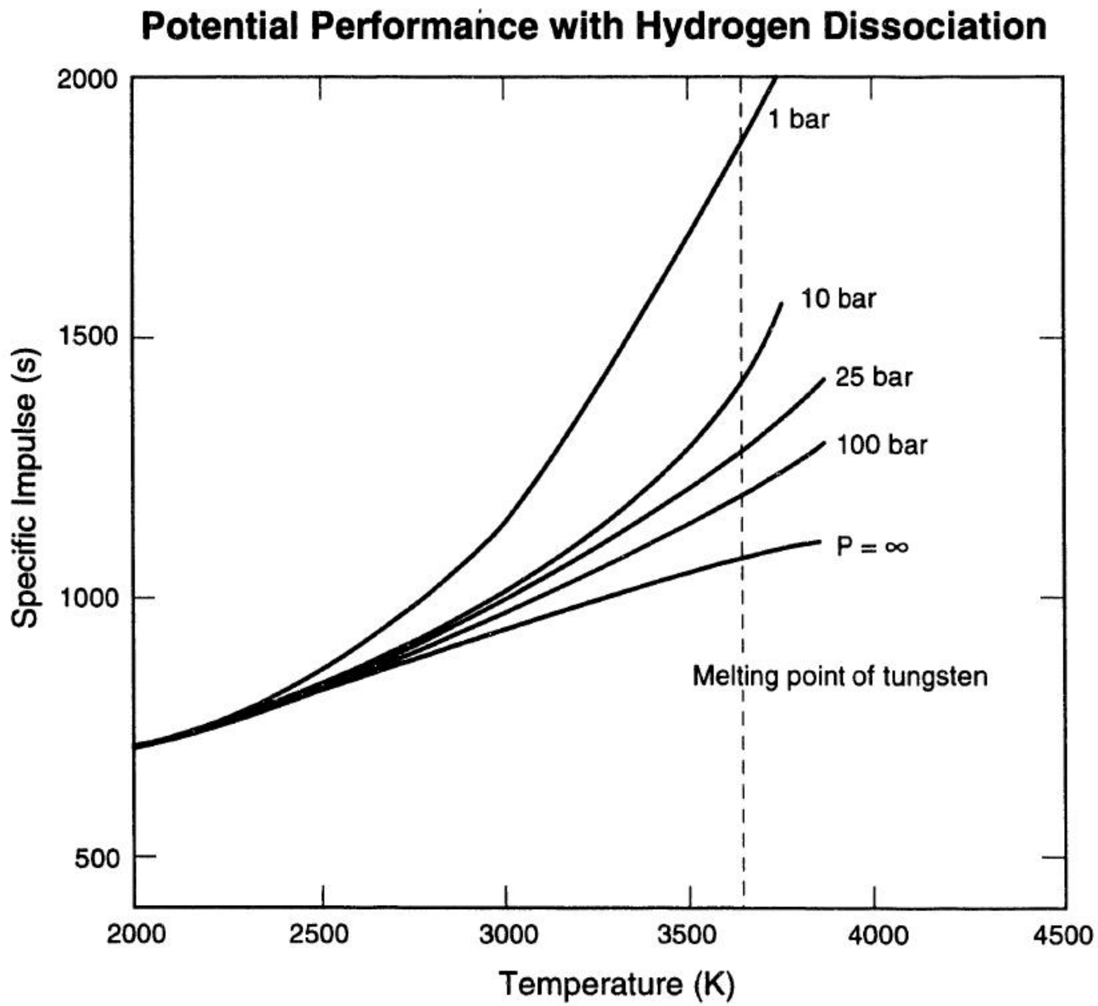
Station	No.	Flow Rate (lbm/s)	Flow Rate (kg/s)	Pressure (psia)	Pressure (MPa)	Temperature (R)	Temperature (K)
Tank Exit	1	8.50	3.86	28.20	0.194	30.6	17.0
Pump Inlet	2	8.50	3.86	18.28	0.126	30.6	17.0
Pump Exit	3	8.50	3.86	976.0	6.728	44.17	24.54
Tie Tube and Slat Inlet	3	4.65	2.11	940.1	6.481	44.17	24.54
Tie Tubeand Slat Exit	7	4.65	2.11	840.1	5.791	749.6	416.5
Nozzle Inlet	4	3.86	1.75	940.1	6.481	44.17	24.54
Reflector Inlet	5	3.86	1.75	865.1	5.964	438.4	243.5
Reflector Exit	6	3.86	1.75	840.1	5.791	530.2	294.5
Turbine Inlet	8a	7.50	3.40	840.1	5.791	677.5	376.4
Turbine Bypass	8b	1.00	0.45	840.1	5.791	677.5	376.4
Turbine Exit	9	7.50	3.40	717.0	4.943	644.5	358.1
Reactor Inlet	10	8.45	3.84	667.3	4.600	644.5	358.1
Fuel Element Inlet	11	8.45	3.84	641.9	4.425	645.8	358.8
Chamber Inlet	12	8.45	3.84	565.0	3.895	4922.7	2734.8
Nozzle Exit (Static)	13	8.45	3.84	0.033	0.0002	196.5	109.2

NOTE: Engine Fuel Element length is 89 cm / 35 inches and uses single TPA

Relative NTR Engine Size

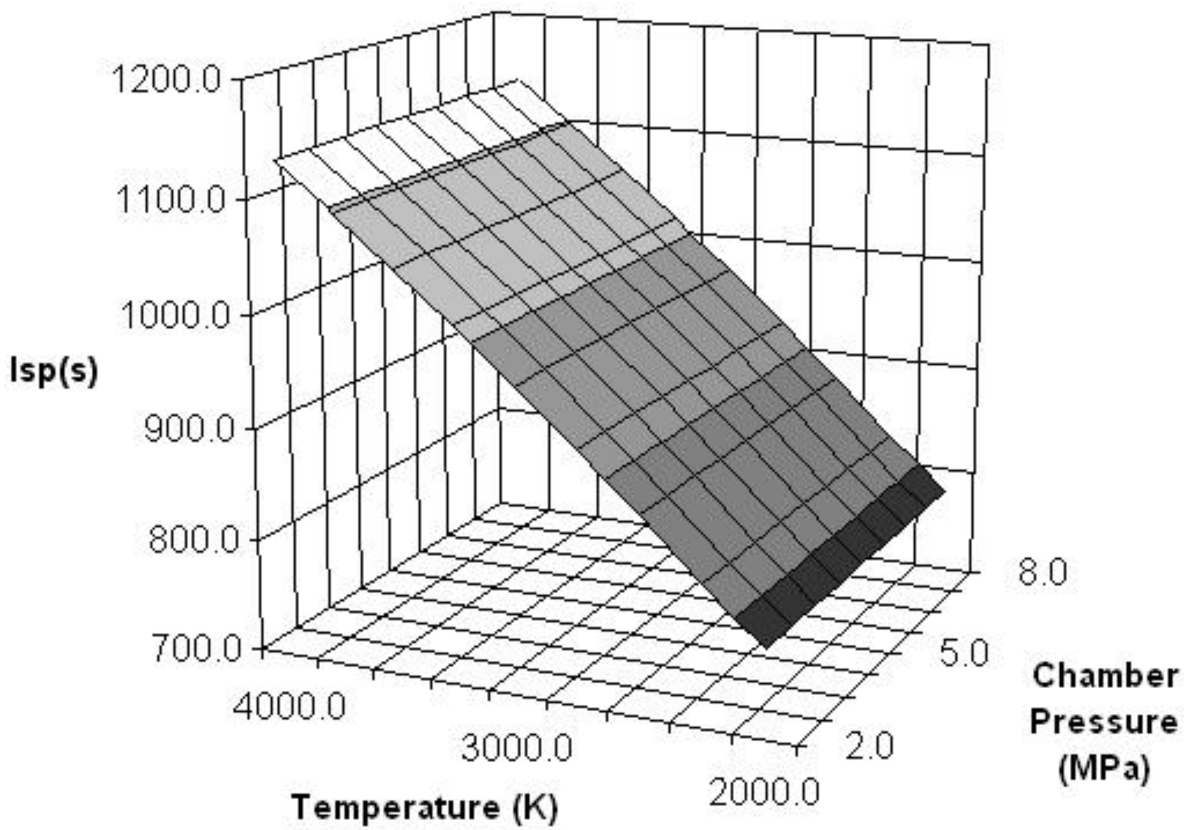
Hydrogen Dissociation

- ISP ~ (Tc/Mw)^0.5
- Potential Performance Increase with Hydrogen Dissociation
- Lower Pressure and Higher Temperature Allow for Dissociation
- NTR System Size and Mass Tend to Increase with Lower Pc



Hydrogen Propellant

- Hydrogen Delivers Highest Possible ISP for Given Tch, Pch, and Nozzle AR
- Current and Well Understood Technology
- Allows for Simpler and more Robust Design if used as Monopropellant
- Dissociation at Lower Pch Yields Even Higher ISP



Hydrogen Propellant Performance (300:1 Nozzle Area Ratio, Isentropic Expansion, Ionized Species)