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 klbf) Thrust Class
- Cermet Based Designs
  - Criticality Limited
  - 111 kN (25 klbf) Thrust Class
- Analysis Results
- Questions
Typical NTR System

- Turbopumps
- Internal Shield
- Control Drum
- Nozzle
- Nozzle Skirt Extension
- Reactor Core
- Propellant Line
- Reflector
- External Disc Shield

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Typical NTR Core Cross Section

- Pressure Vessel
- Control Drum
- Beryllium Reflector
- Beryllium Barrel
- Insulator
- Inboard Slat
- Wrapper
- Outboard Slat
Fuel Element and Tie Tube Arrangement

- Graphite sleeves
- Tube (Inconel)
- ZrH moderator
- Pyrolytic graphite thermal insulation
- External surfaces coated with ZrC

Support element

- Coolant channel and external surface coated with ZrC
- Braided joint
- Fueled
- Unfueled tip

Tie Tube element (NERVA-Rover design)

- Hydrogen stream
- NbC or ZrC coat
- Graphite substrate
- UC-ZrC dispersion

Fuel element (NERVA-Rover design)

Composite matrix
Fuel Element And Tie Tube Cross Sections

(UC-ZrC)C Composite Fuel Matrix

ZrC Coating

Hydrogen Cooling Passage (19 per Element, ~2.54 mm Dia)

0.13 mm Gap

1.913 cm

Hydrogen Supply Passage

Inner Tie Tube (5.21 mm OD x 0.51 mm wall)

ZrH Moderator (5.33 mm ID x 11.68 mm OD)

ZrC Coating

Graphite Filler Structure (16.26 mm ID)

0.13 mm Gap

ZrC, (16.13 mm OD x 14.10 mm ID)

0.13 mm Gap

Outer Tie Tube (13.97 mm OD x 0.205 mm wall)

Hydrogen Return Passage

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NTR Fuel Element Comparison
(Relative Scale)

ANL-200

GE-710/711

NERVA

2.81 cm (1.11 in)

2.361 cm (0.929 in)

1.905 cm (0.750 in)
GE-710 and GE-711 Comparison

91 Coolant Passages

GE-710

50% Larger Coolant Passages

GE-711
## GE-710 and GE-711 Comparison, cont.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GE-710</th>
<th>GE-711</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Element Width w/o Cladding</td>
<td>2.278 cm, 0.8976 in</td>
<td>2.278 cm, 0.8976 in</td>
</tr>
<tr>
<td>Fuel Element Width with Cladding</td>
<td>2.361 cm, 0.9296 in</td>
<td>2.361 cm, 0.9296 in</td>
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<td>Outer Cladding Thickness</td>
<td>0.381 mm, 0.015 in</td>
<td>0.381 mm, 0.015 in</td>
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<td>Fuel Element Length</td>
<td>60.96 cm, 24.00 in</td>
<td>60.96 cm, 24.00 in</td>
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<td>Fuel Composition</td>
<td>W -60% UO₂ -6% Gd₂O₃</td>
<td>W -60% UO₂ -6% Gd₂O₃</td>
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<tr>
<td>Cladding Composition</td>
<td>W / 25% Re</td>
<td>W / 25% Re</td>
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<td>Coolant Channels per Element</td>
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<td>91</td>
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<tr>
<td>Coolant Channel Diameter without Cladding</td>
<td>1.321 mm, 0.052 in</td>
<td>1.524 mm, 0.060 in</td>
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<tr>
<td>Coolant Channel Diameter with Cladding</td>
<td>0.914 mm, 0.036 in</td>
<td>1.118 mm, 0.044 in</td>
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<tr>
<td>Coolant Channel Pitch</td>
<td>2.353 mm, 0.0938 in</td>
<td>2.353 mm, 0.0938 in</td>
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</table>
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 klbf) 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
NERVA Derived Engine Design Results
Normalized Thermal Energy Deposition Rate Profiles
NERVA Derived Engine Designs – Composite Fuel

Criticality Limited NERVA Derived Option

111 kN (25 klbf) 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)
NERVA Derived Engine Summary
Peak Fuel Temperature of ~2860 K and Nozzle Area Ratio (NAR) of ~300:1

<table>
<thead>
<tr>
<th><strong>Masses (kg)</strong></th>
<th><strong>NERVA-Derived (Composite)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Elements (FE)</td>
<td>207.7</td>
</tr>
<tr>
<td>Tie Tubes (TT)</td>
<td>231.0</td>
</tr>
<tr>
<td>Heater Elements (HE)</td>
<td>-</td>
</tr>
<tr>
<td>Reflector Assembly</td>
<td>717.71</td>
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<tr>
<td>Pressure Vessel</td>
<td>87.93</td>
</tr>
<tr>
<td>TPA</td>
<td>9.07</td>
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<tr>
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<td>87.93</td>
</tr>
<tr>
<td>TPA</td>
<td>9.07</td>
</tr>
<tr>
<td>TVC, Lines, and Valves</td>
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<tr>
<td>Nozzle</td>
<td>81.03</td>
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<tr>
<td>Assorted Hardware</td>
<td>416.36</td>
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<tr>
<td>Engine Mass</td>
<td>1789</td>
</tr>
<tr>
<td><strong>Criticality-Limited</strong></td>
<td>25 klb Class</td>
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<tr>
<td>Fuel Elements (FE)</td>
<td>207.7</td>
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<tr>
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<td>81.03</td>
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<tr>
<td>Assorted Hardware</td>
<td>416.36</td>
</tr>
<tr>
<td>Engine Mass</td>
<td>1789</td>
</tr>
</tbody>
</table>

**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**
- Core Power Level (MW) : 157 / 563
- Chamber Pressure (MPa) : 3.89 / 6.89
- U-235 Mass (kg) : 27.5 / 36.8
- Thrust (klb) : 7.52 / 25.18
- Thrust-to-Weight Ratio : 1.91 / 3.42
- Delivered Isp (s) : 894 / 909
Cermet Engine Design Results
Normalized Thermal Energy Deposition Rate Profiles
Cermet Fuel Based Engine Designs

Criticality Limited
ANL-200 Based Design

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

Normalized Thermal Energy Deposition Rate

Fuel Element
Driver Element

1.3 | 1.2 | 1.1 | 1.0 | 0.9 | 0.8
Normalized Axial Thermal Energy Deposition Rate Profiles
(Cermet Designs)

Normalized Thermal Energy Deposition Rate

Criticality Limited Design
GE-711 Growth Design

Normalized Axial Distance
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

<table>
<thead>
<tr>
<th>Masses (kg)</th>
<th>NERVA-Derived (Composite)</th>
<th>ANL-200</th>
<th>GE-711 Variant</th>
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<tbody>
<tr>
<td>Tie Tubes (TT)</td>
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<td>612.84</td>
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<td>Heater Elements (HE)</td>
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<td>Engine Mass</td>
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<td>3338</td>
<td>1812</td>
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### Dimensions (cm)

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>NERVA-Derived (Composite)</th>
<th>ANL-200</th>
<th>GE-711 Variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core / FE Length</td>
<td>89</td>
<td>132</td>
<td>71</td>
</tr>
<tr>
<td>TPA / TVC System Length</td>
<td>178.1</td>
<td>228.3</td>
<td>209.3</td>
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<tr>
<td>Pressure Vessel Length</td>
<td>207.1</td>
<td>320.9</td>
<td>155.0</td>
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<tr>
<td>Nozzle Length</td>
<td>233.7</td>
<td>320.2</td>
<td>292.0</td>
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<td>Nozzle Exit Diameter</td>
<td>137.9</td>
<td>189.0</td>
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<td>Approx. Total Engine Length</td>
<td>618.9</td>
<td>869.4</td>
<td>656.3</td>
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### Engine Parameters

<table>
<thead>
<tr>
<th>Engine Parameters</th>
<th>NERVA-Derived (Composite)</th>
<th>ANL-200</th>
<th>GE-711 Variant</th>
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</thead>
<tbody>
<tr>
<td>No. Elements (FE/TT/HE)</td>
<td>260 / 251 / 0</td>
<td>564 / 241 / 0</td>
<td>163 / 0 / 0</td>
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<tr>
<td>Core Power Level (MWₜ)</td>
<td>157</td>
<td>563</td>
<td>266</td>
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<tr>
<td>Chamber Pressure (MPa)</td>
<td>3.89</td>
<td>6.89</td>
<td>3.89</td>
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<tr>
<td>U-235 Mass (kg)</td>
<td>27.5</td>
<td>36.8</td>
<td>238.5</td>
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<td>Thrust (klb)</td>
<td>7.52</td>
<td>25.18</td>
<td>11.92</td>
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<tr>
<td>Thrust-to-Weight Ratio</td>
<td>1.91</td>
<td>3.42</td>
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<tr>
<td>Delivered Isp (s)</td>
<td>894</td>
<td>909</td>
<td>903</td>
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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 klbf) 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

- Coated-particle matrix
  - NbC or ZrC coat
  - Graphite substrate
  - UC-ZrC dispersion
  - Pyrocarbon coating
  - UC₂ particle

- Composite matrix

Hydrogen stream
RL10-B2 Retractable Nozzle

Nozzle Extension Retracted

Nozzle Extension Deployed
Deployable Nozzle Components

- Drive Motor and Electronics
- Actuator Housings
- Locking Bracket Design
- Titanium Ball Screws
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 klbf) POD NERVA-derived Engine at 161 MW<sub>t</sub> and Isp ~894 s

<table>
<thead>
<tr>
<th>Station</th>
<th>No.</th>
<th>Flow Rate (lbm/s)</th>
<th>Pressure (psia)</th>
<th>Temperature (R)</th>
<th>Temperature (K)</th>
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<tr>
<td>Tank Exit</td>
<td>1</td>
<td>8.50</td>
<td>28.20</td>
<td>30.6</td>
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<td>Pump Inlet</td>
<td>2</td>
<td>8.50</td>
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<td>30.6</td>
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<td>Pump Exit</td>
<td>3</td>
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<td>Tie Tube and Slat Inlet</td>
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<td>4.65</td>
<td>940.1</td>
<td>44.17</td>
<td>24.54</td>
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<td>Tie Tube and Slat Exit</td>
<td>7</td>
<td>4.65</td>
<td>840.1</td>
<td>749.6</td>
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<td>Nozzle Inlet</td>
<td>4</td>
<td>3.86</td>
<td>940.1</td>
<td>44.17</td>
<td>24.54</td>
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<td>Reflector Inlet</td>
<td>5</td>
<td>3.86</td>
<td>865.1</td>
<td>438.4</td>
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<td>Reflector Exit</td>
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<td>3.86</td>
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<td>Turbine Inlet</td>
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<td>358.1</td>
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<td>8.45</td>
<td>667.3</td>
<td>644.5</td>
<td>358.1</td>
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<td>641.9</td>
<td>645.8</td>
<td>358.8</td>
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<td>Chamber Inlet</td>
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<td>8.45</td>
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<td>2734.8</td>
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<tr>
<td>Nozzle Exit (Static)</td>
<td>13</td>
<td>8.45</td>
<td>0.033</td>
<td>196.5</td>
<td>109.2</td>
</tr>
</tbody>
</table>

**NOTE:** Engine Fuel Element length is 89 cm / 35 inches and uses single TPA
Relative NTR Engine Size
Hydrogen Dissociation

- ISP \sim (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)