NUCLEAR ENGINE SYSTEM SIMULATION (NESS)  
VERSION 2.0

- OVERVIEW -

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1992 NUCLEAR PROPULSION - TECHNICAL INTERCHANGE MEETING
NASA LEWIS RESEARCH CENTER
SANDUSKY, OH

TOPICS

- BACKGROUND
- FEATURES
- COMPARISONS
- CONCLUDING REMARKS
BACKGROUND

NUCLEAR THERMAL PROPULSION (NTP) ENGINE SYSTEM ANALYSIS PROGRAM DEVELOPMENT
- Overall Objective -

- Develop a Stand-alone, Versatile NTP Engine System Preliminary Design Analysis Program (Tool) to Support Ongoing and Future SEI Engine System and Vehicle Design Efforts

- Perform Meaningful (Accurate), Preliminary Design Analysis - Tank to Nozzle
- Have Flexibility:
  — To Handle a Wide Range of Design Options to Support Preliminary Design Activities
  — To Be Easily Upgraded in Terms of Analysis Capability
- Be Available to the SEI Community, Possibly as an Industry Standard
- Be Done Promptly and Efficiently
- Initial Effort:
  — Focused on NERVA/NERVA Derivative, Solid-Core NTP Systems
  — Based on Upgrading SAIC's NTP ELRS Design Code by Incorporating Westinghouse's ENABLER Reactor and Internal Shield Models
NUCLEAR THERMAL PROPULSION (NTP) ENGINE
SYSTEM ANALYSIS PROGRAM DEVELOPMENT

- Observations -

- No NTP-Specific Code is Commonly Available for Use in
  SEI Propulsion and Vehicle Design Studies
  - Versatile, Verified NTP Analysis Design Tool Could Be of Great
    Use to the Community

- It Is Envisioned That NESS Is One Key Element in Developing a
  Robust (Industry Standard Type) Analysis Capability (Design
  Workstation) to Support NTP Development Into the 21st Century
  - Enhancements in Terms of Additional Technology/Design Options
    and/or Analysis Capabilities Possible With the NTP ELES Model

NUCLEAR THERMAL PROPULSION ENGINE
DEVELOPMENT ANALYSIS CAPABILITY REQUIREMENTS
TEAM RESOURCES USED TO SUPPORT NESS DEVELOPMENT

SAIC
Extensive Experience In:
- Aerospace Systems
- Engine Systems and Technologies
- Simulation Modeling
Current SAIC NTP ELES Model and Application Experience

NESS Code

Westinghouse
Word-Class Leader In Reactor Systems and Technologies
- Past NERVA Experience
- Current ENABLER Activities
Current ENABLER Top-Level Model Activities

EXPANDED LIQUID ENGINE SIMULATION (ELES) COMPUTER MODEL
- Background -

- Its Major Objective is to Conduct Preliminary System Design Analysis of Liquid Rocket Systems and Vehicles

  - Over $1.2 Million Spent by the Air Force in Its Development
  - Available Through the Air Force

- ELES Has Been Well Distributed and Accepted Within the Propulsion Community for Preliminary Liquid Propulsion System Design Analysis

- ELES Draws on Past Experience and Knowledge From Aerojet and Others
  - Encompasses Aerojet Vast Engineering Base and Expertise in Liquid Propulsion
    - In-house Experience Included in the Model
    - Has Legacy to Experts Active in the Community
EXPANDED LIQUID ENGINE SIMULATION (ELES)
COMPUTER MODEL (Cont.)
- Background -

- ELES Model Uses Mechanistic as Well as Empirical Models of Components/Subsystems
- The Model is Well Structured, User Friendly, Easily Modified, and Documented
- A High Degree of Verification has Been Done on the ELES Code

- ELES is a Comprehensive Industry Type, Standard Code Available to Perform Preliminary Steady-State Liquid Propulsion Design Analysis
- A key Starting Point in Initial NTP Engine System Development

ELES VERIFICATION EXAMPLES

- N-8 DELTA (DELTA 2ND STAGE)
- TITANSTAR (TITAN 3RD STAGE)
- CENTAUR 10 D1-T STAGE
- SPACE SHUTTLE MAIN ENGINE

CENTAUR 10 D1-T VERIFICATION SUMMARY

<table>
<thead>
<tr>
<th>ACTUAL</th>
<th>CALC</th>
<th>ACTUAL/CALC</th>
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<tr>
<td>Turbine Pressure Ratio</td>
<td>1.337</td>
<td>1.799</td>
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<td>Regen Jett A T</td>
<td>41.6</td>
<td>90.3</td>
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<tr>
<td>On Pump Outlet Pressure</td>
<td>917</td>
<td>506</td>
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<tr>
<td>Fuel Pump Outlet Pressure</td>
<td>990</td>
<td>954</td>
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<tr>
<td>Engine System</td>
<td>608.9</td>
<td>634.9</td>
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<tr>
<td>FPA Weigh</td>
<td>15</td>
<td>19</td>
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<tr>
<td>Stage Dry Weight</td>
<td>49.4</td>
<td>39.5</td>
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<tr>
<td>Stage Thermal Weight</td>
<td>62.2</td>
<td>40.4</td>
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<tr>
<td>Stage Length</td>
<td>360</td>
<td>367.3</td>
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<tr>
<td>Engine Performance</td>
<td>444</td>
<td>444.6</td>
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</tbody>
</table>
NESS PROGRAM DEVELOPMENT EVOLUTION

- Extensive Anchors/Verification of the Program Performed For Each Development Phase
- BETA Versions of NESS - Versions 1&2 Are Successfully in Operation At NASA Lewis

PAST NTP ELES ANALYSIS CODE MODIFICATIONS AND VERIFICATIONS

- ELES-NTP Version Developed and Verified
  - Modifications Performed
    - Incorporation of H₂ and CO Property Tables
    - Monopropellant Turbopump-fed System Modifications
    - Reactor Weight and Dimension Correlations Added
    - Off-Design Engine Operation Capability
  - Verification Conducted
    - Rocketdyne Performance and Weight Data
    - Westinghouse NERVA Data
    - Compared with NASA 90-Day Study Input
    - Much Developed Under SAIC In-House Fund Sponsorship
GENERAL NTP ENGINE SYSTEM FEATURES
MODELED BY NESS

- Incorporates a Near-Term Solid-Core NERVA/
  NERVA-Derivative Reactor Designs
  - Westinghouse ENABLER R&I NTP Reactor Designs
  - Strong Westinghouse R-1 Reactor Design Legacy

- Incorporates State-of-the-Art Propulsion System
  Technologies and Design Practices

REPRESENTATIVE NTP EXPANDER, GAS GENERATOR, AND
BLEED ENGINE SYSTEM CYCLES MODELED BY NESS
TOP-LEVEL KEY NESS FLAGS AND INPUT VARIABLES

ENABLER (NERVA TYPE) NUCLEAR THERMAL ROCKET ENGINE

- Bath Shield
- Core Support
- Reflector and Control Drums
- Fuel Element
**PRISMATIC FUEL ELEMENTS AND SUPPORTS**

**REACTOR FUEL AND SUPPORT ELEMENT PARAMETERS**

<table>
<thead>
<tr>
<th>Fuel Element Composition</th>
<th>Graphite Composition</th>
<th>Composite Composition</th>
<th>Carbide Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Range (K)</td>
<td>2200-2500</td>
<td>2500-2900</td>
<td>2900-3300</td>
</tr>
<tr>
<td>Fuel</td>
<td>Coated Particle</td>
<td>UC, ZrC Solid Solution and Carbon</td>
<td>(UZr)C Solid Solution</td>
</tr>
<tr>
<td>Coating</td>
<td>ZrC</td>
<td>ZrC</td>
<td>—</td>
</tr>
<tr>
<td>Untuited Support Element Composition</td>
<td>Graphite</td>
<td>ZrC-Graphite Composite</td>
<td>ZrC</td>
</tr>
<tr>
<td>Untuited Element Coating</td>
<td>ZrC</td>
<td>ZrC</td>
<td>—</td>
</tr>
</tbody>
</table>
REACTOR PARAMETERS AS A FUNCTION OF THRUST LEVEL

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>15,000</td>
<td>275-400</td>
<td>35</td>
<td>82.5</td>
<td>0.629</td>
<td>0.778</td>
<td>2:1</td>
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<tr>
<td>25,000</td>
<td>480-670</td>
<td>35</td>
<td>84</td>
<td>0.808</td>
<td>1.0</td>
<td>3:1</td>
</tr>
<tr>
<td>&gt;50,000</td>
<td>920-8700</td>
<td>52</td>
<td>101.6</td>
<td>1.29</td>
<td>1.0</td>
<td>6:1</td>
</tr>
</tbody>
</table>

INTERNAL SHIELD SIZING

- Sized to Meet Radiation Leakage Requirements Established for the NERVA Program

- Radiation Leakage Limits at a Plane 63 Inches Forward of the Core Center

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Radiation Leakage Limits Within Pressure Vessel Outside Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Carbon KERMA Rate</td>
<td>$1.8 \times 10^7 \text{Rad/(cy/hr)}$</td>
</tr>
<tr>
<td>Fast Neutron Flux</td>
<td>$2.0 \times 10^{12} \text{n/cm}^2\text{-sec}$</td>
</tr>
<tr>
<td>Intermediate Neutron Flux</td>
<td>$3.0 \times 10^{12} \text{n/cm}^2\text{-sec}$, $0.4 \text{eV} \leq E_n \leq 1.0 \text{MeV}$</td>
</tr>
<tr>
<td>Thermal Neutron Flux</td>
<td>$8.0 \times 10^{11} \text{n/cm}^2\text{-sec}$, $E_n &lt; 0.4 \text{eV}$</td>
</tr>
</tbody>
</table>

- Materials and Thickness
  - For Thrust Level $\geq 50,000$ lbf
    - 12.5 inches of Borated Aluminum Titanium Hydride (BATH)
    - 1.3 inches Lead
  - For Thrust Levels $< 50,000$ lbf, BATH and Lead Thickness Slightly Reduced Due to Lower Core Power Density
LAYOUT DRAWING OF THE R-1 REACTOR

REACTOR THERMAL MODEL

HEAT GENERATION
Core ~ 1,500 MW
Tie Tubes 3.7%
Reflector 1-2%
Central Shield ~0.2%
Ext. Shield ~0.03%

COMPONENT BLOCK DIAGRAM

TIE TUBE SUPPORTS

CHAMBER
**REACTOR WEIGHT MODEL**

- Based On R-1 Engine Design
- 53 Reactor Regions Itemized
- Masses Adjusted With Changes In Core Size

**MODELED REGIONS IN THE R-1 REACTOR**

**REACTOR WEIGHT MODEL REGIONS (EXAMPLE)**

<table>
<thead>
<tr>
<th>REGION NUMBER</th>
<th>REGION DESCRIPTION</th>
<th>MATERIAL</th>
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<tbody>
<tr>
<td>1 – 15</td>
<td>Core</td>
<td>Carbon</td>
</tr>
<tr>
<td>16</td>
<td>Core Periphery</td>
<td>Carbon</td>
</tr>
<tr>
<td>17</td>
<td>Lateral Support</td>
<td>Graphite</td>
</tr>
<tr>
<td>18</td>
<td>Structure</td>
<td>Graphite</td>
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</table>

**NON-NUCLEAR AUXILIARY COMPONENT WEIGHTS**

- Updated Weight Correlations Incorporated for the Following Auxiliary Components:
  - Instrumentation
  - Pneumatic Supply System
  - Reactor Cool Down Assembly
  - Thrust Structure

- Based on Past Work by TRW (1965) Which Developed Detailed Weight Correlations for Such Components Based on Evolving NERVA Designs
  - Updated to Take into Account Advances In Technology and Design Practices
NESS NOZZLE DESIGN OPTIONS

- STATE-OF-THE-ART NOZZLE DESIGN OPTIONS AVAILABLE
  - Regenerative Cooled Slotted-Tube Construction, Radiation Cooled Extension
  - Initialized With Up-to-Date Materials
  - Capable of Analyzing Nonconventional Nozzle Designs
  - Translating and/or Gimballing Nozzles Possible

AXIAL TURBOPUMP DESIGN MODULE DEVELOPED AND INTEGRATED INTO NESS VERSION 2.0

AXIAL TURBOPUMP

- Design Correlations Draw on Past Axial Turbopump Design and Test:
  - Axial Turbopump Weight Model Anchored on:
    - Recent Rocket Engine Design Studies
    - Past German NTP System Design Study

DESIGN LOGIC

Correlation axial pump: RPM based on NTPM, steady-state speed, temperature data

Correlation mass flow rate: RPM based on mass flow rate, temperature data

Correlation of pump efficiency:

Determine pump RPM using the speed, head, and efficiency

Determine mass flow rate using correlation between RPM and mass flow rate

Determine pump efficiency using correlation between RPM and efficiency

Determine pump head using correlation between RPM and head

Check pump performance on selected cases of pump operation

Compare pump performance with similar pump

Check pump performance on similar cases of pump operation

Compare pump performance with similar cases of pump operation
MAJOR NESS ENGINE SYSTEM ENGINEERING DESCRIPTION AREAS

- System Pressure, Temperature and Mass Flow Schedule
- Turbopump Design and Operation
- Nozzle Performance Losses
- Regeneratively Cooled Nozzle Design
- Reactor Subsystem Design and Operation

TYPICAL ENGINE SYSTEM DESIGN SUMMARY
SAMPLE DESIGN CASE SUMMARY

<table>
<thead>
<tr>
<th>Case No/ Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td>Cycle Type</td>
<td>Expander</td>
<td>Expander</td>
<td>Cased</td>
<td>Case Composed</td>
<td>Case Composed</td>
<td>Case Composed</td>
<td>Case Composed</td>
<td>Expander</td>
</tr>
<tr>
<td>Threat Level (kN)</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
<td>75,000</td>
<td>350,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Propellant Type</td>
<td>ENABLER I</td>
<td>ENABLER II</td>
<td>ENABLER III</td>
<td>ENABLER II</td>
<td>ENABLER II</td>
<td>ENABLER II</td>
<td>ENABLER II</td>
<td>ENABLER I</td>
</tr>
<tr>
<td>Reactor Type</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
<td>Composite</td>
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<tr>
<td>Chamber Pressure (psia/MPa)</td>
<td>6,895</td>
<td>500/0.67</td>
<td>500/0.67</td>
<td>500/0.67</td>
<td>500/0.67</td>
<td>500/0.67</td>
<td>500/0.67</td>
<td>6,895/1</td>
</tr>
<tr>
<td>Chamber Temperature (°F/K)</td>
<td>4,860</td>
<td>4,860</td>
<td>4,860</td>
<td>4,860</td>
<td>4,860</td>
<td>4,860</td>
<td>4,860</td>
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<tr>
<td>Needle Area Ratio</td>
<td>500.1</td>
<td>300.1</td>
<td>200.1</td>
<td>300.1</td>
<td>300.1</td>
<td>300.1</td>
<td>300.1</td>
<td>500.1</td>
</tr>
<tr>
<td>No. of Propellant Pools</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Turbopump Type</td>
<td>Counter-Prop</td>
<td>Counter-Prop</td>
<td>Counter-Prop</td>
<td>Counter-Prop</td>
<td>Axial</td>
<td>Counter-Prop</td>
<td>Axial</td>
<td>Axial</td>
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<tr>
<td>Reactor Pool Sealing Factor</td>
<td>1.00</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

NESS VERSION 2.0 OPERATING ENVIRONMENT

- Well Organized Worksheet to Initialize Your Design Are Provided
- Uses Improved Name List Input File
  - Each Input Variable is Defined
- Operates on VMS/VAX System
  - Over 30,000 Lines of Code
- Personal Computer Compatible Version is Available
  - Requirements
    - 486-33 MHz Computer
    - 6 MB RAM
    - 80 MB Hard Drive
    - Lehigh Fortran with Extended Memory Required
NESS PROGRAM USER'S GUIDE

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COMPARISONS
**CYCLE PARAMETER COMPARISON**

- 75,000 lbf, ENABLER I, Expander Cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rocketdyne</th>
<th>SAIC - BLRS NTP</th>
<th>SAIC NTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Flowrate (lbf/h)</td>
<td>36.7</td>
<td>36.9</td>
<td>37.21</td>
</tr>
<tr>
<td>Pump Discharge Pres. (psig)</td>
<td>1,544</td>
<td>1,518.3</td>
<td>2,298.3</td>
</tr>
<tr>
<td>Turbine Flowrate, % Pump</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Turbine Inlet Temp. (%K)</td>
<td>555.6</td>
<td>555.3</td>
<td>622.3</td>
</tr>
<tr>
<td>Turbine Inlet Pres. (psig)</td>
<td>1,412</td>
<td>1,416.8</td>
<td>1,969.0</td>
</tr>
<tr>
<td>Turbine Pressure Ratio</td>
<td>1.25</td>
<td>1.295</td>
<td>1.338</td>
</tr>
<tr>
<td>Reactor Inlet Pres. (psig)</td>
<td>1,130</td>
<td>1,255.4</td>
<td>1,132.1</td>
</tr>
<tr>
<td>Reactor Power, (MW)</td>
<td>1,645</td>
<td>-</td>
<td>1,587</td>
</tr>
<tr>
<td>Reactor Core Flowrate (lbf/h)</td>
<td>36.7</td>
<td>36.9</td>
<td>36.3</td>
</tr>
<tr>
<td>Nacelle Chamber Temp. (%K)</td>
<td>2,700</td>
<td>2,700</td>
<td>2,700</td>
</tr>
<tr>
<td>Nacelle Chamber Pres. (psig)</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Nacelle Exit Diameter (in)</td>
<td>4.15</td>
<td>4.15</td>
<td>4.22</td>
</tr>
<tr>
<td>Nacelle Expansion Ratio</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Specific Impulse: Vac (sec)</td>
<td>923</td>
<td>922.8</td>
<td>912.9</td>
</tr>
<tr>
<td>Pump Speed (rpm)</td>
<td>37,300</td>
<td>34,913</td>
<td>40,583</td>
</tr>
</tbody>
</table>

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC BLRS-NTP uses 1 single-stage centrifugal pump; SAIC NTP; Sample Case No. 8, uses a 5-stage axial pump.

**ENGINE SUBSYSTEM WEIGHT COMPARISON**

- 75,000 lbf, ENABLER I, Expander Cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rocketdyne</th>
<th>SAIC BLRS-NTP</th>
<th>SAIC NTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Impulse - Vac (sec)</td>
<td>0.15</td>
<td>0.1529</td>
<td>0.1529</td>
</tr>
<tr>
<td>Reactor (kg)</td>
<td>8,824</td>
<td>5,823</td>
<td>4,783</td>
</tr>
<tr>
<td>Internal Shield (kg)</td>
<td>—</td>
<td>1,523</td>
<td>1,108</td>
</tr>
<tr>
<td>Nacelle Assembly (kg)</td>
<td>440</td>
<td>421</td>
<td>555</td>
</tr>
<tr>
<td>Turbopump Assembly (kg)</td>
<td>304</td>
<td>104</td>
<td>221</td>
</tr>
<tr>
<td>Nacelle Support Hardware (kg)</td>
<td>1,815</td>
<td>1,264</td>
<td>1,495</td>
</tr>
</tbody>
</table>

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC BLRS-NTP uses a single-stage centrifugal pump; SAIC NTP; Sample Case No. 8, uses a 5-stage axial pump.
EFFECT OF WALL TEMPERATURE ON PERFORMANCE*

<table>
<thead>
<tr>
<th>Wall Temperature (*F)</th>
<th>Barrier Temperature (*F)</th>
<th>Isp (Sec.)</th>
<th>Fuel Film Cooling Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1460</td>
<td>1630</td>
<td>912.9</td>
<td>0.03</td>
</tr>
<tr>
<td>1800</td>
<td>2106</td>
<td>915.9</td>
<td>0.03</td>
</tr>
<tr>
<td>2000</td>
<td>2429</td>
<td>917.5</td>
<td>0.02</td>
</tr>
<tr>
<td>2400</td>
<td>2892</td>
<td>919.4</td>
<td>0.02</td>
</tr>
<tr>
<td>2800</td>
<td>3418</td>
<td>921.2</td>
<td>0.02</td>
</tr>
<tr>
<td>3000</td>
<td>3651</td>
<td>921.9</td>
<td>0.02</td>
</tr>
<tr>
<td>3200</td>
<td>3864</td>
<td>922.4</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* Core Temperature = 4860°F (2700°K)

DESIGN CASE COMPARISON OBSERVATIONS

- NESS Design Exhibits 1% Lower Performance Than Other Designs
  - NESS Model More Accurately Predicts Nozzle Cooling Losses-Upstream Film Cooling Required to Meet Maximum Wall Temperature Requirements

- Integrated Reactor/Engine System Design Effects Accounted for in the NESS Design
  - Sized to Take Into Account Heat Captured by the Coolant Before It Enters the Reactor
  - Corresponds to Some Difference in Cycle Pressures, Temperatures, and Turbopump Operating Parameters

- Other Weight Differences From Improvements in NESS Weight Correlations
  - 3-Section Nozzle Design
  - Non-Nuclear Auxiliary Components
  - Update H₂ Properties
CONCLUDING REMARKS

• The NESS Preliminary (ENABLER I&II) Design Analysis Program Characterizes a Complete Near-Term Solid-Core NTP Engine System in Terms of Performance, Weight, Size, and Key Operating Parameters for the Overall System and Its Associated Subsystem
  - Incorporates Numerous State-of-the-Art Engine System Technology Design Options
  - Extensively Verified and Documented

• The NESS Program is Deemed Accurate to Support Future Preliminary Engine and Vehicle System Design and Mission Analysis Studies
  - NESS Has Been Successfully Operated and Checked Out at NASA Lewis

• Future Recommendations:
  - Incorporate Other NTP Reactor Types
    -- Particle Bed
    -- Pellet Bed
    -- Low Pressure
    -- Wire Core
  -- In situ Propellant Based Reactor Designs
  - Incorporate a Radiative Heating Model
  - Update the Material Library
  - Upgrade the NESS Performance Prediction Module

• NESS Development Is One of Many Key First Steps Required to Support NTP Development
• It is Envisioned that NESS Will Be One Key Element of an Advanced NTP Engine System Design Workstation