NUCLEAR ENGINE SYSTEM SIMULATION (NESS)
VERSION 2.0

- OVERVIEW -

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PRESENTED AT:
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 ELBS 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
TEAM RESOURCES USED TO SUPPORT NESS DEVELOPMENT

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-2 DELTA (DELTA 2ND STAGE)
- TRANSTAR (TITAN 3RD STAGE)
- CENTAUR-10 DT-1 STAGE
- SPACE SHUTTLE MAIN ENGINE

CENTAUR-10 DT-1 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>1.237</td>
<td>1.399</td>
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<tr>
<td>Regen Jacket AT</td>
<td>501</td>
<td>500</td>
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<tr>
<td>Oil Pump Outlet Pressure</td>
<td>897</td>
<td>899</td>
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<tr>
<td>Fuel Pump Outlet Pressure</td>
<td>900</td>
<td>954</td>
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<td>Engine System</td>
<td>602</td>
<td>634.9</td>
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<tr>
<td>T/P Weight</td>
<td>181</td>
<td>178.6</td>
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<tr>
<td>Dry Stage Weight</td>
<td>478</td>
<td>295.2</td>
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<tr>
<td>Stage Thermal Weight</td>
<td>602</td>
<td>635.9</td>
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<tr>
<td>Stage Length</td>
<td>360</td>
<td>357.3</td>
</tr>
<tr>
<td>Engine Performance</td>
<td>444</td>
<td>444.0</td>
</tr>
</tbody>
</table>
NESS PROGRAM DEVELOPMENT EVOLUTION

- Extensive Anchors/Verifications 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

SAMPLE OUTPUT

NP-TIM-92 12
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
NESS PROGRAM OVERVIEW

NESS
- INITIALIZE
- STAGE DESIGN
- TRAJECTORY
- OPTIMIZER

YES
- OPTIMIZER

NO
- OUTPUT RESULTS
- STOP

NESS PROGRAM FLOW LOGIC

Key inputs: Throat, Pressure, Temperature, Flow Path, Reactions, Number of Feed Loops

Initiates Properties and Properties

Estimates Fluids characteristic based on input data

Calculates Reactor Core Flow Rate

Estimates Reactor Core Heat Load

Calculates Reactor Performance

Calculates Reactor Schedule

Calculates Reactor Sustained Cooling Requirements

Calculates Reactor Heat Load

Are actual and simulated heat load values tolerable?

YES

Calculates Reactor Schedule

NO

Design, Settage

Calc. Temperature Schedule

Calc. Vortexing/Dispersion Schedule and Check for cyclones

Result, Time Schedule

Result, Missing Schedule

Calculates Reactor Weights

Calc. Vortexing/Dispersion Weights

Calc. Mass, Volume, etc.

Result, Mass Flows

Calc. Lengths and Dimensions

Potential Summary
### PRISMATIC FUEL ELEMENTS AND SUPPORTS

![Diagram of PRISMATIC FUEL ELEMENTS AND SUPPORTS]

### REACTOR FUELD AND SUPPORT ELEMENT PARAMETERS

<table>
<thead>
<tr>
<th>Fuel Element Composition</th>
<th>Graphite</th>
<th>Composite</th>
<th>Carbide</th>
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<tbody>
<tr>
<td>Temperature Range (K)</td>
<td>2200-2500</td>
<td>2500-2900</td>
<td>2900-3300</td>
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<tr>
<td>Fuel</td>
<td>Coated Particle</td>
<td>UC . ZrC Solid Solution and Carbon</td>
<td>(U,Zr)C Solid Solution</td>
</tr>
<tr>
<td>Coating</td>
<td>ZrC</td>
<td>ZrC</td>
<td>—</td>
</tr>
<tr>
<td>Untuased Support Element Composition</td>
<td>Graphite</td>
<td>ZrC-Graphite Composite</td>
<td>ZrC</td>
</tr>
<tr>
<td>Untuased 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>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15,000</td>
<td>275-400</td>
<td>35</td>
<td>82.6</td>
<td>0.629</td>
<td>0.778</td>
<td>2:1</td>
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<tr>
<td>25,000</td>
<td>460-670</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>920-6700</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>$1.8 \times 10^7$ Rad/(cy/hr)</td>
</tr>
<tr>
<td>Fast Neutron Flux</td>
<td>$2.0 \times 10^{12}$ n/cm$^2$-sec</td>
</tr>
<tr>
<td>Intermediate Neutron Flux</td>
<td>$3.0 \times 10^{12}$ n/cm$^2$-sec, $0.4$ eV $\leq$ $E_n$ $\leq$ $1.0$ MeV</td>
</tr>
<tr>
<td>Thermal Neutron Flux</td>
<td>$6.0 \times 10^{11}$ n/cm$^2$-sec, $E_n &lt; 0.4$ eV</td>
</tr>
</tbody>
</table>

- Materials and Thickness
  - For Thrust Levels $\geq$ 50,000 lbf
    - 1.5 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

HEAT GENERATION
- Core: ~1,500 MW
- Tie Tubes: 3-7%
- Reflector: 1-2%
- Central Shield: ~0.2%
- Ext. Shield: ~0.03%

COMPONENT BLOCK DIAGRAM

CHAMBER

REACTOR THERMAL MODEL
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>Fuel Element</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unfueled Element</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pure Boron</td>
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<tr>
<td>16</td>
<td>Core Pitching</td>
<td>85/15 Boron Tungsten</td>
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<tr>
<td>17</td>
<td>Lateral Support</td>
<td>Graphite-O</td>
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<tr>
<td>18</td>
<td>Structure</td>
<td>PGS Graphite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZTA Graphite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pendulum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydride</td>
</tr>
</tbody>
</table>

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

NON-NUCLEAR AUXILIARY COMPONENT WEIGHTS

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

NTP: Systems Modeling
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 Decisions and Tests:
  - Liquid Rocket Engine Axial Flow Turbopumps
  - NASA SP-8125, April 1978
- Axial Turbopump Weight Model Anchored on:
  - Recent Rocketdyne Design Studies
  - Past German NTP System Design Study

DESIGN LOGIC
- Correlation main pump NPSH based on NPSH, specific speed, temperature stresses.
- Correlation main pump head loss.
- Correlation induction head loss.
- Compressor pump head loss.
- Axial pump NPSH using the same head losses.
- Design main pump on number of stages, diameter, efficiency, temperature.
- Axial induction performance on specific speed, efficiency, temperature.
- Load temperature - main pump, induction.
- Loading efficiency - complex geometry of pump, induction efficiency - using temperature at the operating point.
- Axial duty weight and length, main pump weight - main pump, induction. Weight optimization is a lengthy process based on existing axial pump designs.
MAJOR NESS ENGINE SYSTEM ENGINEERING DESCRIPTION AREAS

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

TYPICAL ENGINE SYSTEM DESIGN SUMMARY

Note: In addition to Normal Flight Design/Operating Conditions Proposed Pump Out Operating and Launch Weight Parameters are Given.

NTP: Systems Modeling
## SAMPLE DESIGN CASE SUMMARY

<table>
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<tr>
<th>Case No./ Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>Expaner</td>
<td>Expaner</td>
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<td>Expaner</td>
<td>Expaner</td>
<td>Expaner</td>
<td>Expaner</td>
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<tr>
<td>Threat Level (kN/P)</td>
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<td>75,500/</td>
<td>75,500/</td>
<td>75,500/</td>
<td>75,500/</td>
<td>75,500/</td>
<td>320,000/</td>
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<tr>
<td></td>
<td>233,000/</td>
<td>233,000/</td>
<td>233,000/</td>
<td>233,000/</td>
<td>233,000/</td>
<td>233,000/</td>
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<tr>
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<td>ENABLER I</td>
<td>ENABLER I</td>
<td>ENABLER I</td>
<td>ENABLER I</td>
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<td>Reactor Pool Type</td>
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<td>Composite</td>
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<tr>
<td>Chamber Pressure</td>
<td>1,000/</td>
<td>500/</td>
<td>500/</td>
<td>500/</td>
<td>500/</td>
<td>500/</td>
<td>500/</td>
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<td>(psi/MPa)</td>
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<td>3,348</td>
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<td>Chamber Temperature (%)</td>
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<td>4.86%</td>
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<tr>
<td></td>
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<td>Nozzle Area Ratio</td>
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<td>500:1</td>
<td>500:1</td>
<td>500:1</td>
<td>500:1</td>
<td>500:1</td>
<td>500:1</td>
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<td>No. of Propellant Pool Legs</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Turbopump Type</td>
<td>Counter-</td>
<td>Counter-</td>
<td>Counter-</td>
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<td>Counter-</td>
<td>Counter-</td>
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<td>leafal</td>
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<tr>
<td>Reactor Pool Sizing Factor</td>
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<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>1.00</td>
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</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
    - Leheay Fortran with Extended Memory Required
NESS PROGRAM USER'S GUIDE

Contents

10 INTRODUCTION 11
20 ENGINE SYSTEM MODEL 12
30 THERMODYNAMIC SYSTEM 13
40 COOLING SYSTEM 14
50 REACTOR SYSTEM 15
60 REFERENCE 16
70 SAMPLE NP SAMPLE SYSTEM DESIGN CASE
80 MODEL VERIFICATION/COMPARISON 17
90 CONCLUSIONS 18
100 APPENDIX A. OTHER WORKSHOPS 19

Comparisons
## CYCLE PARAMETER COMPARISON*

- 75,000 lbf, ENABLER I, Expander Cycle -

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rockbridge</th>
<th>SAIC - BERS NTP</th>
<th>SAIC NRRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Flowrate (kg/h)</td>
<td>36.7</td>
<td>36.9</td>
<td>37.23</td>
</tr>
<tr>
<td>Pump Discharge Press. (psig)</td>
<td>1,584</td>
<td>1,538.3</td>
<td>2,206.3</td>
</tr>
<tr>
<td>Turbine Flowrate, % Pump</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Turbine Inlet Temp. (°C)</td>
<td>555.6</td>
<td>555.3</td>
<td>622.3</td>
</tr>
<tr>
<td>Turbine Inlet Press. (psig)</td>
<td>1,412</td>
<td>1,416.8</td>
<td>1,969.0</td>
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<tr>
<td>Turbine Pressure Ratio</td>
<td>1.25</td>
<td>1.295</td>
<td>1.739</td>
</tr>
<tr>
<td>Reactor Inlet Press. (psig)</td>
<td>1,130</td>
<td>1,155.4</td>
<td>1,172.1</td>
</tr>
<tr>
<td>Reactor Power (MW)</td>
<td>1,645</td>
<td>-</td>
<td>1,287</td>
</tr>
<tr>
<td>Reactor Core Flowrate (kg/h)</td>
<td>36.7</td>
<td>36.9</td>
<td>36.2</td>
</tr>
<tr>
<td>Nozzle Chamber Temp. (°C)</td>
<td>2,700</td>
<td>2,700</td>
<td>2,700</td>
</tr>
<tr>
<td>Nozzle Chamber Press. (psig)</td>
<td>2,000</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Nozzle Exit Diameter (in)</td>
<td>4.15</td>
<td>4.15</td>
<td>4.12</td>
</tr>
<tr>
<td>Nozzle Expansion Ratio</td>
<td>300</td>
<td>300</td>
<td>300</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>37,500</td>
<td>34,913</td>
<td>40,583</td>
</tr>
</tbody>
</table>

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

## ENGINE SUBSYSTEM WEIGHT COMPARISON*

- 75,000 lbf, ENABLER I, Expander Cycle -

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rockbridge</th>
<th>SAIC BERS-NTP</th>
<th>SAIC NRRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Impulse - Vac (sec)</td>
<td>923</td>
<td>922.8</td>
<td>912.9</td>
</tr>
<tr>
<td>Reactor (kg)</td>
<td>5,824</td>
<td>5,823</td>
<td>4,783</td>
</tr>
<tr>
<td>Internal Heat (kg)</td>
<td>-</td>
<td>1,523</td>
<td>1,108</td>
</tr>
<tr>
<td>Nozzle 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>Nozzles Support Hardware (kg)</td>
<td>1,015</td>
<td>1,264</td>
<td>1,495</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Wall Temperature (°R)</th>
<th>Barrier Temperature (°R)</th>
<th>Isp (Sec.)</th>
<th>Fuel Film Cooling Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1460</td>
<td>1830</td>
<td>912.9</td>
<td>0.03</td>
</tr>
<tr>
<td>1800</td>
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* Core Temperature = 4986°R (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
- Upgrade 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