NTRE Extended Life Feasibility Assessment

Final Report

23 OCT 92

Presented to

NASA LeRC

By

Aerojet Propulsion Division
Energopool, Babcock & Wilcox
We Have an Effective NTRE Team

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Sacramento, California

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Engineering
Lynchburg, Virginia

Energopool – Moscow, Russia

NASA LeRC TOC
Program Objectives

- Assess Feasibility of a Long Life, Reusable Nuclear Thermal Rocket
- Two Reactor Concepts
  - Particle Bed Reactor (PBR)
  - Commonwealth of Independent States (CIS)
- Tasks
  - Conceptual Layouts (75K lbf)
  - Thermodynamic Cycle Balance
  - Preliminary Neutronic and Thermal – Hydraulic Analysis
  - System Mass Estimates
  - Preliminary Life and Reliability Assessment
  - Safety Assessment
  - Scaling to 25 and 40K lbf (PBR Only)
The NASA LeRC TOC Addresses the Emerging NTRE Requirements

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>25K, 40K, 75K</td>
</tr>
<tr>
<td>Thrust/Wt (With Internal Shield)</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Isp</td>
<td>&gt; 850 sec</td>
</tr>
<tr>
<td>Length</td>
<td>30 Meters</td>
</tr>
<tr>
<td>Diameter</td>
<td>10 Meters</td>
</tr>
<tr>
<td>Throttling</td>
<td>25%</td>
</tr>
<tr>
<td>Restarts</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Single Burn Duration</td>
<td>60 Min (Max)</td>
</tr>
<tr>
<td>Life</td>
<td>&gt; 270 Min at Rated Thrust</td>
</tr>
<tr>
<td>Reliability</td>
<td>Manned</td>
</tr>
</tbody>
</table>

NASA LeRC TOC Final Report

Agenda

- Introduction
  - Wayne Dahl
- Technical Overview
  - Mel Bulman
- Concept Definition
  - Don Culver
- Engine Design
  - Roy Squires
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  - Mel Bulman
- PBR Reactor System
  - Richard Rochow
- CIS Engine
  - Don Culver
- CIS Reactor System
  - Richard Rochow
- Technology Road Maps
  - Mel Bulman
- Summary
  - Mel Bulman
The NTRE is a highly integrated machine. As we will show, interactions between reactor and engine level operations are significant. Our systems approach to NTRE design reveals exciting new possibilities for improving the reliability and performance of spacecraft.
Our basic NTREs meet all current NASA requirements.

The thrust to weight ratio of the PBR engine is 6.3. The CIS engine is somewhat heavier with a T/W of 4.7. The PBR Isp is 65 seconds higher than the requirement at 915 sec. The higher temperature of the CIS engine produces an Isp of 959. Both engines fit well within the space allowed for in the SOW.

Our advanced pump design and engine management system permits throttling 20:1 compared to the requirement of 4:1.

Our preliminary life evaluation indicates the engines will be able to operate longer than currently required. Our preliminary reliability and hazards analysis indicate man rating of these engines is achievable within the scope of the engine development.
With our recuperated cycle, we avoid complex core designs that produce heat to drive the turbopumps, yet we have increased the engine operating pressure to reduce its size and weight and to increase its performance.

We have studied two NTREs with heterogeneous reactors. One employs the particle bed reactor concept developed in the U.S. The other is based on 20+ years of development in the CIS. The CIS reactor utilizes a twisted ribbon type fuel and has been tested at over 3000K for over 1 hour.

- PBR
  In order to meet the NASA life requirement we have changed the fuel stoichiometry and lowered the operating temperature. We have arranged for deep throttling and closed loop decay heat removal.

- CIS
  We have modified our engine drive cycle and structure slightly to best make use of CIS fuel assembly technologies.

**Technical Approach: Apply Our Recommended Engine Cycles to Two Heterogeneous Reactor Types**

- **Engine Cycle**
  - Delete Gas Heater Fuel Assemblies
  - Raise Operating Pressure
  - Integrated Engine Option

- **Particle Bed Reactor**
  - Increase Design Life
  - Provide Deep Throttling/Decay Heat Removal
  - Integrated Engine Option

- **CIS Reactor**
  - Fuel Developed
  - High Operating Temperature
  - Integrated Engine Option

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NTP: System Concepts
There are several ways in which heterogeneous reactors are superior to homogeneous ones, and all result from physically separating fuel and moderator, the characteristic of the heterogeneous concept. Moderator and fuel have different requirements, and separating them allows selection of optimum solid materials for each function.

High temperature carbides are suitable for fuel, because, when used correctly, they can deliver high reactor gas outlet temperatures, which enables high engine specific impulse. High gas temperatures are available, because carbide fuel can operate at high temperatures and because it forms into thin elements, internally generated heat need pass only a small distance to the coolant. Thus, it need not pass through moderator material to reach a cooled surface, as in the homogeneous reactor concept. Propellant gas can attain a temperature very close to the fuel's maximum internal temperature. The PBR attains this advantage by using small diameter spheres in fuel particle beds, while the CIS reactor uses bundles of thin, twisted ribbons of fuel.

Efficient neutron moderators are hydrogenous, and no solid materials of this type can withstand temperatures in the range of fuel or desired outlet gas temperatures. Efficient neutron moderators are important, because uranium fission cross-sections are very low at fission neutron energy levels, and without good moderator material a larger amount of fissionable material is needed in the reactor. Several negative features occur simultaneously when large amounts of highly enriched U235 are used in a reactor. First, the safeguards problem is worsened. Secondly, launch safety is inherently less. Third, fast reactors need a more rapid control system, which exacerbates development and safety risks, and fourth, fuel cost is much greater than that of the moderator which may replace it in a heterogeneous reactor. The PBR moderator is a hexagonal bed of beryllium containing cavities filled with LH that surround each fuel bed, while the CIS moderator is ZrH2 rods close-packed between the fuel assemblies.

For Mars mission NTFIE we need a specific impulse loss-free turbopump power cycle to minimize total mission costs, including Earth-to-orbit launch. Thus, topping cycles are used, which have turbine like advantages over bleed cycles. In a heterogeneous engine the lower temperature moderator and reflector materials are cooled with a separate hydrogen loop prior to final heating by the fuel elements. This moderator and reflector heat is automatically the major portion of the topping heat needed for turbine inlet gas heating – for turbine drive power. In a homogeneous engine, at least the moderator heat is lost for turbine drive use. Lower engine operating pressure results, all other things being equal, and this lends to large, heavy engines with inferior Mars mission performance. Further, the moderator cooling loop also enables integration of a closed engine cooling and electric power generating system that can reduce Mars mission IMLEO by about 100 tons.

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**Heterogeneous Reactors Superior to Homogeneous Types (NERVA)**

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
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<tbody>
<tr>
<td>• Fuel Separated from Moderator</td>
<td>• Moderator Cooling Powers</td>
</tr>
<tr>
<td>• Fuel More Efficient</td>
<td>• Turbine and Enables Closed Loop Cooling (Reliability and Weight)</td>
</tr>
<tr>
<td>• PBR</td>
<td>• Higher Gas Outlet Temperature (High ISP)</td>
</tr>
<tr>
<td>• CIS</td>
<td>• Lower Fissile Inventory (Safety and Weight)</td>
</tr>
<tr>
<td>• Fuel More Efficient</td>
<td>• Be Hex with ZrH2</td>
</tr>
<tr>
<td>• Spheres</td>
<td>• Rods</td>
</tr>
<tr>
<td>• Twisted Ribbon</td>
<td>• Cavities</td>
</tr>
</tbody>
</table>

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NTP: System Concepts 252  NP: TIM-92
Our basic engine meets or exceeds all NASA requirements. It provides for robust operation and takes up little room in the launch vehicle.

As we studied these engines we recognized some significant and beneficial differences between these heterogeneously moderated reactors and the homogeneously moderated NERVA type reactors. The separate moderator allows us to extract significant heat from the core without the need to flow hydrogen through the fuel elements. The full utilization of this in our Integrated engine provides many benefits including: (1) reliable, efficient NTRE start up, (2) reduced decay cooling losses; (3) RCS and OMS at high Isp, (4) electrical power up to 100 kW (E) per engine.

Technical Approach: Two Engine Options Are Presented

- **Basic Engine**
  - Meets or Exceeds All Current NASA Specs
  - Robust Operation
  - Reliable, Efficient Engine Starting
  - Small Size

- **Integrated Engine**
  - Builds on Basic Engine
  - Reduces Decay Cooling Losses
  - Improves Mission Reliability and Performance by:
    - Integrating Stage and Engine Subsystem
    - Main Propulsion
    - RCS
    - OMS
    - Option for Electric Power (~ 100 kWe)

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Our platelet technology enables us to turn the requirement to cool the internal gamma shield into a cycle-enhancing recuperator without mass penalty. This allows us to operate the engine at higher chamber pressures than otherwise possible, resulting in a smaller and lighter weight engine. In addition, the recuperator provides the bulk of the energy for the engine start. Sufficient energy is stored in the recuperator to accelerate the turbopumps to full power without additional heat. With this magnitude of stored energy, it would take over 10 aborted starts to significantly reduce the starting power of our cycle.

In addition to providing power, the recuperator provides thermal and hydraulic stability during all modes of engine operation. The reactor and feed system are effectively decoupled during high reactor transients.

Recuperated Cycle Provides
Superior Engine Operation

- Provides Cooled, Internal Gamma Shield
- Enables High Chamber Pressure
- Provides Thermal Energy for Turbopump Start
  - Energy Available for Many Starts
- Provides Safe, Controllable Reactor Start
  - Prevents Liquid Hydrogen Entry Into the Core
  - Decouples and Damps System Oscillations
Engine Concept Definition

Don Culver

Our engine and major component design concepts are selected to meet all current NASA requirements. Any concepts that cannot meet these safety and reliability, performance, and operational requirements in the near term were discarded. In addition, many NASA goals that impact safety and reliability, mission benefits, development cost and technical risk were used to guide system configuration selections and design and operating parameter optimization studies.

NASA Goals and Requirements
Impact APD NTRE Selection

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Goals</th>
</tr>
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<tbody>
<tr>
<td>Safety</td>
<td>Safety</td>
</tr>
<tr>
<td>- Radiation Protection</td>
<td>- Minimize Radioactive Materials</td>
</tr>
<tr>
<td>- Manrate, Verify, Automate</td>
<td>Hazard Mitigation and Reliability</td>
</tr>
<tr>
<td>Performance</td>
<td>Mission Benefit</td>
</tr>
<tr>
<td>- 850 sec isp</td>
<td>- IMLEO/Trip Time (Isp and F/W)</td>
</tr>
<tr>
<td>- 4:1 Thrust Weight</td>
<td>- Mission Commonality</td>
</tr>
<tr>
<td>- Throttling @ Tmax</td>
<td>- 2006 Availability</td>
</tr>
<tr>
<td>- 15-75K lb Thrust</td>
<td>- Simplicity (Inherent Reliability)</td>
</tr>
<tr>
<td>Operation</td>
<td>Technical Risk and Development Cost</td>
</tr>
<tr>
<td>- Reusable, Long Life</td>
<td>- Technology Readiness and Tests Needed</td>
</tr>
<tr>
<td>- Bootstrap Start w/o Power</td>
<td>- Propulsion System Integration</td>
</tr>
<tr>
<td>- Degraded/Failed Tolerance</td>
<td>- Facility Requirements</td>
</tr>
</tbody>
</table>

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We begin our concept definition studies with trade studies. Of course, we perform trade studies in each important area of requirements and goals.

When trade studies are completed, optimum design parameters are known, and engine layout and component design studies can be finalized. When the point design is known, sensitivity studies are made to check the impact of important design and operating parameters on engine characteristics.

Trade Studies Define Engine Concept and Design Point

- Safety and Reliability
  - Nuclear
  - Non Nuclear
  - Criticality Trades (B&W)
  - Feed System Reliability

- Performance and Mission Benefit
  - Mission Payload
  - Power Cycle
  - Control System
  - Versus Cycle Type, Pc, Nozzle Design
  - Definition (Shield Integration)
  - Architecture Study

- Operation and Technical Risk
  - System Operation
  - Propulsion System Integration
  - Technology Readiness
  - Modes and Procedures Identified
  - Shield, Decay Heat, Deep Throttling
  - Major Component Status
Our Reliability Plan Is Tailored to Project Phase

- Concept Phase (TOC)
  - Reliability Block Diagrams With Typical Component Failure Rates
  - Preliminary FMEA to Component Level
  - Hazards Analysis (Crew, Ground Support and Populace)

- Design Phase
  - FMEA
  - Fault Tree Analysis
  - Safety Studies
A result of our feed system reliability block diagram study is that use of twin turbopumps on NTRE should improve mission reliability by reducing the probability of total failure and engine loss to about 1/4 of that of single turbopump fed engine. However, the twin turbopump engine has nearly twice the probability of failing to a degraded mode of performance. This usually means that one turbopump fails and the other continues to operate the engine at nearly 3/4 thrust. This is of little consequence at any time except a TMI (or TLI) burn.

Twin Turbopumps Improve Mission Reliability*

- Single TPA System Has ~ 4 Times the Probability of Total Failure vs 2 TPAs
- Twin TPA System Has ~ 1.7 Times the Probability of Failure to Degraded Mode (~ 70% Thrust) vs 1 TPA

* Industry Standard Component Failure Rates Applied to Feed Systems

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Mission performance depends on rocket engine thrust/weight and mission average specific impulse (isp). Engine thrust/weight depends largely on reactor type and power density, engine configuration, and operating conditions. Mission average isp depends mainly on engine isp and on operational isp losses, and they depend on mission type, engine design details, and operating conditions. We will discuss our trade study results for each of these factors in the following charts and in the reactor design sections.

Mission Isp Depends on Engine Isp and Operational H₂ Losses

- Engine Isp = f (Tout)^1/2
  - Theoretical Isp (Tout and c)
  - Tout max – Tout Mixed Mean
  - Nozzle Losses (Cooling, Divergence)
  - Power Cycle Bleed Losses

- Operational H₂ Losses
  - Open Loop Cooldown @ T < Tmax
  - Boiloff and Leaks
  - Start-up Bleed

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We have studied three fundamental engine configurations:

(1) DeLaval nozzle behind thermal reactor

(2) Forward flow thermal reactor within an expansion-deflection (E-D) nozzle

(3) Forward flow thermal reactor within a plug nozzle

The E-D nozzled engine appears to have the best mission performance potential, but it needs further study, and at this time it is recommended for a second-generation engine. However, we recommend this concept be studied in more detail soon, because it is rapidly developing into a more practical concept than was believed possible earlier.

The plug nozzled engine does not seem competitive, because of its large nozzle surface area in the high heat flux region of the throat and its consequent low Isp and high weight potentials.

The DeLaval nozzled design is, thereby, recommended for a near-term engine.

DeLaval Nozzle Is Attractive for Near Term NTRE

- Low Losses
- Long and Heavy

E/D

- Good Integration
- Short and Lightweight

Plug

- Highest Nozzle Heat Flux and Losses
- Short

F = 75k lbf
\( P_c = 1,000 \text{ psia} \)
A trade study evaluated both engine weight and specific impulse by estimating the Mars mission payload delivery capability of identical vehicles powered by similar engines of conventional geometry having different power cycles, operating pressures, and nozzle area ratios. Both hot bleed cycle engines and topping cycle engines were evaluated over reactor outlet pressures (Pc) from 1000 to 3000 psia, with nozzle area ratios from 150 to 500, and with nozzle lengths from 80 to 120 percent bell. In each case a cooled, copper and steel nozzle was used with a carbon-carbon nozzle extension from area ratio 10 to the exit.

Results showed that bleed cycle engines are not competitive, based on their lower delivered specific impulse. Their payload carrying capabilities were consistently low by about 20 percent. Nozzle contours of 110 percent bell length were found to be best for nearly all engine variants. Engines with high nozzle area ratios benefited most from high engine pressure, because their nozzles are smaller and lighter in weight, better offsetting the increased turbopump weight required of high pressure feed systems. Conversely, engines with low nozzle area ratios are relatively insensitive to engine design pressure. (Both reactor design teams agreed that reactor, vessel, and shield weight totals are not greatly affected by design pressure in the range of our study.)

The design point selected was area ratio 300 with pressure of 2000 psia, because it appeared to be the lowest pressure - lowest area ratio combination to attain high mission performance. At 200 nozzle area ratio about five percent payload is lost, regardless of engine pressure selection.

**High Pressure Topping Provides Maximum Mission Performance**

<table>
<thead>
<tr>
<th>Study Results</th>
<th>Engine Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Point</strong></td>
<td><strong>Topping Cycle</strong></td>
</tr>
<tr>
<td><strong>Topping Cycles</strong></td>
<td>Pc = 2,000 psia</td>
</tr>
<tr>
<td>E</td>
<td>300 (Da = 92 In.)</td>
</tr>
<tr>
<td>Lnoz</td>
<td>110% Bell (210)</td>
</tr>
<tr>
<td>Tc</td>
<td>2,700K</td>
</tr>
</tbody>
</table>

- 4 Burn, All-Up, Manned Mars Mission with C3 = 16 km²/s²
- IMLEO = 775 Tonnes

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We examined all reasonable turbopump drive power cycles, based on examination of heat sources for turbine inlet gas and destinations for turbine exhaust gases. Those cycles which bleed turbine exhaust gas overboard rather than through the throat of the engine’s nozzle lose specific impulse, because they cannot expand low pressure and temperature turbine exhaust gas to high velocities. We found that these engines are not in contention for Mars missions on a performance basis.

Three topping cycles were analyzed. The simple expander cycle cannot provide enough heat to power the engine reliably to pressures of 1000 psia or above. We have seen the Mars mission performance decrement of low pressure engines. Therefore, extra heat must be added to the topping heat that can be recovered indirectly from the reactor core by cooling engine components, such as moderator, reflector, pressure vessel, shields, etc. One way to do this is to devote a portion of the fuel assemblies to turbine drive heat. This requires additional manifolding in the reactor core, an unwanted complexity which may reduce neutronic efficiency and cost engine size and weight. Another way is to use a high heat rate heat exchanger to transfer turbine exhaust heat to the pump discharge to augment the topping cycle heat. This is the scheme we selected, in spite of the fact that engine designers usually feel that highly effective recuperators are large and heavy.

Recuperated Expander Cycle Selected

<table>
<thead>
<tr>
<th>Turbine Exhaust Destination</th>
<th>Heat Sources for Turbine</th>
<th>Reactor Core</th>
<th>System (Expander)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overboard = Bleed Cycles</td>
<td></td>
<td>Recup. Bleed</td>
<td>Cold Bleed</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>Hot Bleed</td>
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<tr>
<td></td>
<td>Hot Turbine</td>
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<td></td>
<td>Nozzle Port</td>
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<tr>
<td></td>
<td>Mixer Fatigue</td>
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<tr>
<td></td>
<td>~20% P/L Loss</td>
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<tr>
<td></td>
<td>Augmented</td>
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<tr>
<td></td>
<td>Core Complexity</td>
<td></td>
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<tr>
<td></td>
<td>Reactor Size and Weight</td>
<td></td>
<td></td>
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<tr>
<td>Reactor = Topping Cycles</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Recuperated</td>
<td>Expander</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Limited Power</td>
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<td></td>
<td>Restart Heat?</td>
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<td></td>
<td></td>
<td></td>
<td>7% P/L Loss</td>
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<tr>
<td></td>
<td></td>
<td>Expander</td>
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<td></td>
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</tbody>
</table>

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The impacts of the recuperator on our engines' size and weight is nil, because:

1. We have demonstrated our ability to fabricate large heat rate heat exchangers of very compact dimensions with our platelet technology, for example in the SSME heat exchanger program.

2. The steel recuperator can function as the gamma shield for the NTRE and the forward closure of the reactor vessel. We have shown that the sum of these two weights in a conventionally designed engine are greater than the required recuperator weight. Thus, we incur no weight penalty for the heat exchanger itself.

3. Low density material, such as steel may be used efficiently for a gamma shadow shield, because it is located close to the large diameter reactor, and the radiation tends to be planar to all surfaces, because of the self shielding provided at all other angles.

Recuperator Weight Impact Is Nil

Problem – Large Recuperator Size and Weight

Solution – Compact Stainless Steel Platelet HEX Doubles as Cooled Internal Gamma Shield and Forward Pressure Vessel Head

Distributed Source Shield Weight Is Not Dependent on Material Density
Recuperated Cycle Provides Superior Engine Operation

- Provides Cooled, Internal Gamma Shield
- Enables High Chamber Pressure
- Provides Thermal Energy for Turbopump Start
  - Energy Available for Many Starts
- Provides Safe, Controllable Reactor Start
  - Prevents Liquid Hydrogen Entry Into the Core
  - Decouples and Damps System Oscillations

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The power cycle we have selected for both engines uses a recuperator to transfer heat from turbine exhaust to pump discharge, and each cool the nozzle with a small side stream of liquid hydrogen from the pump. The PBR cycle variation is shown here; it requires a pump discharge pressure of 4750 psia to deliver an engine Pe of 2000 psia. It does this with a low turbine inlet temperature of 475 R (479 K) and a low turbine pressure ratio of less than 1.5 to 1. Pump stage pressure ratios are low, too, because four stages of pumping are used. However, four stage rotating assemblies are not needed with our concept, because our turbopumps emulate a quad-redundant valve set. We use two turbopumps In parallel to provide the total engine flow, and each turbopump consists of two identical rotating assemblies operating in series. Each rotating assembly is the simplest configuration possible, two pumps and a turbine on the shaft with two bearings between the three rotors. Reliability, performance, risk, and cost benefits result from this subcritical speed design.

The recuperator heat rate is about 125,000 Btus/sec, which is larger than the sum of the topping heat. If more power is needed this cycle has two main design variables, turbine pressure ratio and recuperator heat rate. The latter controls the turbine inlet temperature. The power balance shown has ten percent excess turbine power for turbine bypass control authority.

The flow scheme through the engine is as follows: through the pumps in parallel, with a 5-1 flow split after their flows join; the small flow cools the nozzle and pressure vessel; the large flow gets heated in the high pressure side of the radial outflow recuperator, where it enters the moderator and reflector cooling flow at the front of the core; the full flow passes through the turbines in parallel to rejoin and cool in the low pressure, radial inflow passages of the recuperator; cooled flow is manifolded to the inlets of each fuel assembly for heating to full outlet temperature and passage through the rocket nozzle.

Flow control elements include a low power electric feed pump, pump and turbine inlet and outlet valves, a turbine bypass control valve, and a pulse cooling valve. Reflector drive motor shafts penetrate the recuperator at its periphery, outside of the heat exchanger region, and a launch poison rod penetrates it at its center.

A High-Power, Loss Free Engine Power Cycle is Selected
The basic engine has five operating states in addition to two additional control states, checkout and emergency. Before starting the engine, the pumps are chilled with tank head or feed pump flow, and GH2 is vented overboard as required. However, much of the GH2 is pumped under pressure into the engine power loop by the feed pump. The engine can be held in this stage of chilled and pressurized readiness for long periods, with occasional chill down flows until impulse is needed.

Starting the engine consists of opening the turbine inlet valves and blowing down the loop, spin starting the turbines. The large, available amount of sensible heat in the recuperator bootstraps the feed system until reactor heat is available. The recuperator prevents liquid hydrogen from ever entering the reactor.

During engine operation at high power the engine thrust is controlled with turbine bypass valve position and specific impulse with reactor control drum position. The propellant tank is pressurized by a bleed from the low pressure recuperator outlet manifold.

Following reactor shutdown with control drum rotations, the 10-1 throttling turbopumps are throttled to maintain outlet temperature by their bypass control valves. When they have reached their minimum flow, one turbopump is shut down and the other (throttled up 2-1) will follow the reactor power down to about five percent and then begin to overcool the core, reducing specific impulse at this low thrust level. The electromechanical feed pump is started, and propellant is pumped under pressure at low flow rate into the cooling loop. When the loop pressure is high and the core cool, the second turbopump is shut down and the pulse cooling valve actuated. The core heats during pump shutdown and overcools during the cooling pulse. The pulse valve shuts, the feed pump pressurizes the loop while the core heats, and the core cycles again, holding the average core outlet temperature and ISP above what it would be without pulse cooling.

While the core power decays the duty cycle of the pulse cooling valve changes continually, and eventually it stays closed. This happens when the pressure vessel is able to radiate the residual core afterheat to space.

Operation Features Robust Start and Efficient Cooldown

- Readiness
  - Pressurize Loop With Feed Pump
  - Chill Pumps and Vent GH2
- Start
  - Blowdown Start TPAs With Start Valves
  - Bootstrap on Recuperator and Reactor Heat
- Run
  - Control Valve Throttling
  - Bleed-Pressurize Tank Ullage
- Cooldown
  - Shutdown Reactor
  - Throttle on Decay Heat
  - Shutdown 1 TPA and Throttle to 5%
  - Overcool Fuel and Start Feed Pump
  - Shutdown 2nd TPA and Pulse Cool
- Soakout
  - Stop Pulse Cooling and Radiate

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Recuperated Cycle Provides Superior Engine Operation

- Provides Cooled, Internal Gamma Shield
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  - Energy Available for Many Starts
- Provides Safe, Controllable Reactor Start
  - Prevents Liquid Hydrogen Entry Into the Core
  - Decouples and Damps System Oscillations

Engine Design
Roy Squires
Aerojet NTRE Is Small and Lightweight

- Thrust, lbf: 75000
- Chamber Pressure, psia: 20000
- Nozzle Area Ratio, Av/A: 300
- Engine Specific Impulse, sec: 2915
- Mass Mission Specific Impulse, sec: 882
- Engine Total Weight, lbfm: 11879
- Thrust/Weight: 6.1
- Engines per Vehicle: 2
- Payload Returned to Earth, lbfm: 44900

Engine Weight Breakdown

Component

- Uncooled Nozzle
- Cooled Nozzle
- Pressure Vessel, Reactor Manifolds & CSS
- Reactor, Reactor IOC
- Turbopump Assemblies (2)
- Recuperator / Shield
- Secondary Shield
- Plumbing/Valves
- Controls and Shielding

NTRE w/ Stage Power/Heat Removal

- Stage Power & Heat Removal Sys Wt., lbfm: 2000
- Engine with Power Sys Wt., lbfm: 13879
- Mass Mission Specific Impulse, sec: 882
- Payload Returned to Earth, lbfm: 56726

Aerojet NTRE

GENCORP
AEROJET
- Energopool - Babcock & Wilcox

NITP System Concepts
The XLR-134 program addressed the need for a relatively low thrust engine to move large fragile structures from low earth orbit into higher orbits. It was an Air Force program originating from the Phillips Lab at Edwards Air Force Base and spanned 1986 through 1990.

The program included initial studies to define the requirements and the engine size/cycle. From these requirements the engine and component designs were derived. The selected engine was a 500 lbf. LOX/LH₂ single expander cycle engine (gaseous hydrogen turbine drive). The turbopumps for both the LOX and LH₂ were designed and fabricated at Aerojet. The general arrangement consists of two shafts with 3 pump stages and one turbine stage on each mounted "end to end." In this configuration the turbines are counter-rotating. The LOX TPA is basically a two stage single spool machine of a similar design as the LH₂ TPA with appropriate material and tolerance changes.

The LH₂ TPA was tested both as a single spool (3 stage) TPA and finally as the complete dual spool TPA. No development problems were encountered, due to the robust design and subcritical shaft speed. Of significant merit during dual spool testing was the start up and steady state operation of the two pump spools. This highly successful testing demonstrated over 4200 seconds of run time in LH₂ with full speed TPA operation, speed tracking of the two spools, successful bearing performance and subcritical shaft speed.

Aerojet TPA Technology
Increases Life and Reliability

Features
- Dual Spool
- Short Shafts With 3 Rotors per
- Operate Below Design Speed
- Hydrostatic Bearings

Benefits
- High Turbine Efficiency
- Low Weight
- Commonality of Parts
- Subcritical Shaft Speed Operation for Deep Throttling
- Increased Life and Reliability
- Increased Life
Radiation transmission through manifolds includes 36 2.5 cm holes for gas flow. Shield penetrations for drum control rods and the central "polson" rod were ignored.

Heating in the LiH/Pb dedicated shield will be of the order 40-60 kW and may require some cooling during extended operation at full power.

"Internal Shield" Concept for NTRE Provides Significant Reduction in Accountable Shielding Mass
Source strength and shield attenuation calculated by B&W using MCNP (Monte Carlo Neutron Photon transport code).

NASA radiation specification met or exceeded at a point 1 meter above the top reflector on the core axis.

Shields for electronics and controls assumes optimum placement and 100K-rad hardened electronics.

Engine Components and Dedicated Shielding
Attenuate Radiation to Meet NASA Requirements and Protect Electronics and Controls

<table>
<thead>
<tr>
<th>Components</th>
<th>Gamma Factor</th>
<th>Fast Neutron Factor</th>
<th>Mass (Kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Manifolds and Recuperator</td>
<td>101</td>
<td>21</td>
<td>1178</td>
<td>Dual Function: Cools and Shields</td>
</tr>
<tr>
<td>Dedicated Shield</td>
<td>4.4</td>
<td>80</td>
<td>236</td>
<td>Additional Shield Necessary to Meet NASA Spec</td>
</tr>
<tr>
<td>Distributed Electronics and Controls Shield</td>
<td>$6.3 \times 10^4$</td>
<td>$1.75 \times 10^3$</td>
<td>130</td>
<td>Required Beyond NASA Spec for 3.5 Hours at Full Power</td>
</tr>
</tbody>
</table>

GenCorp • Energopool • Babcock & Wilcox

NTP: System Concepts 272 NP: TIM-92
Recuperator

Function
- Internal gamma shield cooled by LH₂
- Provides thermal energy for starting and operating TPA
- Enables high chamber pressure for lightweight, compact NTRE

Design and Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>H₂</td>
</tr>
<tr>
<td>Cold-Side Inlet Pressure</td>
<td>4750 psia</td>
</tr>
<tr>
<td>Cold-Side Inlet Temperature</td>
<td>87 °F</td>
</tr>
<tr>
<td>Cold-Side Flow Rate</td>
<td>68 lbm/sec</td>
</tr>
<tr>
<td>Cold-Side Pressure Drop</td>
<td>150 psid</td>
</tr>
<tr>
<td>Hot-Side Inlet Pressure</td>
<td>2650 psia</td>
</tr>
<tr>
<td>Hot-Side Inlet Temperature</td>
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</tr>
<tr>
<td>Hot-Side Pressure Drop</td>
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<td>Thermal Load</td>
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<td>Envelope</td>
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<tr>
<td>Weight</td>
<td>2500 lbm</td>
</tr>
<tr>
<td>Material</td>
<td>CRES SS (A-286)</td>
</tr>
</tbody>
</table>

Characteristics

The 300 series stainless steel, platelet design, countercflow HEX accepts 83% of the LH₂ flow from the TPAs and heats the hydrogen to 572 °F gas in the high pressure circuit of the HEX. The outflow cools the reflector and moderator, ensuring that LH₂ does not enter these components. This gas is combined with the 17% flow, which bypassed the HEX, to cool the nozzle and pressure vessel and was gasified in the process, to provide 100% flow at 847 °F to drive the turbine. The turbine effluent then passes through the low pressure circuit of the HEX giving up much of its heat to the high pressure circuit before delivery to the reactors many fuel elements.

NTRE Recuperator Is Based on Aerojet SSME HEX Technology

SSME HEX

GENCORP
AEROJET

- Energopool - Babcock & Wilcox

NTP System Concepts

ORIGINAL PAGE IS OF POOR QUALITY
Cooled Nozzle

Function
- Provides DeLaval nozzle entrance section and exit to area ratio 10:1

Design and Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>H₂</td>
</tr>
<tr>
<td>Coolant Inlet Temperature</td>
<td>87 R</td>
</tr>
<tr>
<td>Coolant Inlet Pressure</td>
<td>4750 psia</td>
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<td>Coolant Flow Rate</td>
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<td>Coolant Pressure Drop</td>
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<td>Throat Diameter</td>
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<td>Exit Area Ratio</td>
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<tr>
<td>Chamber Pressure</td>
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<tr>
<td>Flowrate</td>
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<td>Material</td>
<td>ZrCu Liner/A286 SS Structure</td>
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<td>Envelope</td>
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<td>Weight</td>
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<tr>
<td>Cylindrical Length</td>
<td>5.00 in.</td>
</tr>
<tr>
<td>Wall Temperature</td>
<td>600 °F</td>
</tr>
</tbody>
</table>

Characteristics

The cooled nozzle uses a zirconium/copper, formed platelet liner to maintain wall temperature below the life limit. The liner will consist of 8 to 10 panels and include an approximate total of 400 coolant channels. It is bonded to a two-piece, A-286 jacket by a hot isostatic press (HIP) process. A two-piece, formed platelet A-286 throat stiffening shell provides structural support against bending moments. Its construction and cooling approach is similar to that of the pressure vessel shell. Coolant enters a manifold at the 10:1 area ratio and flows forward through the liner and shell wall as shown. It exits into the aft closure ring manifold of the pressure vessel.

Cooled Nozzle Concept Is Based on Current Technology

Formed Platelet Liner 40 Klb/F Chamber

- Energopool - Babcock & Wilcox

NTP: System Concepts 274

NP-TIM 92
Cooled Nozzle Concept

- Studies of the SSME main combustion chamber show wall temperature reductions of up to 200 F using platelet liner technology.
- Cooled hot gas wall
  - Formed platelet liner
  - ZrCu platelets
  - ~400 channels
  - 8-10 panels
- A-286 structure
- Cooled throat support ring
  - Platelet A-286 structure with internal coolant channels formed into conical shape

Common Manifolding Provides Coolant for Nozzle and Throat Support Ring

Energopool • Babcock & Wilcox

NP-TIM-92 275
Pressure Vessel Function / Concept

- Pressure Containment
- Plenums / Manifolding for:
  - Moderator coolant
  - Control drum coolant
  - Core flow
  - Pressure vessel wall
- Interfaces
  - Recuperator
  - Cooled nozzle
  - Reactor
  - Core support

Pressure Vessel Provides Pressure Containment, Core Support and Manifolding

- Cooled Hot Gas Wall
- Formed Platelet Design
- A-286 Stainless
- 3-4 Sections

Energopool · Babcock & Wilcox
Pressure Vessel (PV)

Function
- Contains pressure and supports reactor
- Provides manifolding for GH₂
  - Directs recuperator cold flow to control drum and moderator/reflector outflow
  - Combines nozzle/PV coolant outflow with moderator/reflector outflow for delivery to turbine
  - Delivers recuperator warm flow to reactor heating elements

Design & Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>H₂</td>
</tr>
<tr>
<td>Coolant Inlet Temperature</td>
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</tr>
<tr>
<td>Coolant Inlet Pressure</td>
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<tr>
<td>Coolant Outlet Temperature</td>
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<tr>
<td>Coolant Flowrate</td>
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<tr>
<td>Coolant Pressure Drop</td>
<td>150 psid</td>
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<tr>
<td>Core Propellant Temperature</td>
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<td>Core Propellant Flowrate</td>
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<tr>
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<tr>
<td>Moderator Coolant Pressure</td>
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<td>Moderator Coolant Flowrate</td>
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<tr>
<td>Reflector Coolant Temperature</td>
<td>572°F</td>
</tr>
<tr>
<td>Reflector Coolant Pressure</td>
<td>4600 psia</td>
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<tr>
<td>Reflector Coolant Flowrate</td>
<td>14.5 lbm/sec</td>
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<tr>
<td>Weight</td>
<td>2610 lbm</td>
</tr>
<tr>
<td>Envelope</td>
<td>40 in. dia x 53 in. long</td>
</tr>
<tr>
<td>Material</td>
<td>A286 SS</td>
</tr>
</tbody>
</table>

Characteristics

Formed, A-286, diffusion bonded platelet wall sections are welded together to make the right circular shell of the pressure vessel. The forward end of the shell is welded to a manifold assembly, which is welded to the recuperator. A coolant ring manifold is welded to the aft end of the shell. Annular closure rings are welded fore and aft as shown to combine flows per the engine system schematic.

Hydrogen gas enters the aft end manifold from the cooled nozzle. It flows through the shell coolant passages, etched into the wall platelets, and into a forward closure ring, where it mixes with the moderator/reflector coolant outflow for delivery to the TPA turbines. The foremost closure ring delivers recuperator flow to the moderator/reflector coolant passages.

Core Support Structure Provides Reactor Manifolding
A carbon-carbon nozzle extension is a cost-effective, low-weight component. Carbon-carbon has good mechanical properties for temperatures in excess of 5000°F and will only suffer a total recession of less than 0.005 inch due to hydrogen chemical attack (assuming a temperature of 2500°F, pressure of 20 psia, and total duration of 4.5 hrs). Carbon-carbon is noted for radiation resistance and was baselined as the nozzle extension for the NERVA rocket engine at Aerojet.

Carbon-carbon structures can be fabricated in many different ways, but only several are appropriate for thin wall nozzle extensions. Involute, 3-D cylindrical, braided, and Novotex™ preforming are the four most realistic techniques to provide carbon-carbon nozzle extensions. None of these techniques can provide a single-piece nozzle the size required without facility capitalization and development.

A one-piece carbon-carbon nozzle extension is estimated to weigh about 170 lbs and 240 lbs for area ratios of 200:1 and 300:1, respectively. The thicknesses reflect minimum wall thicknesses of approximately 0.5 in. and 0.2 inch for the entry and exit regions.

### Propellant
- H2

### Temperature
- 4860° R

### Flowrate
- 82 lbm/sec

### Attach Area Ratio
- 18:1

### Exit Area Ratio
- 200:1

### Nozzle Shape
- 110% Bell

### Material
- Carbon-Carbon

### Envelope
- 8.7 in. dia x 160 in. long

### Weight
- 450 lbm

A Full Size One Piece Carbon-Carbon Nozzle Extension Will Weigh Less Than 450 lbs

However, Facilities Must Be Upgraded for Size and Nozzle Fabrication Must be Validated
Instead of fabricating a one-piece carbon-carbon nozzle extension, fabricating carbon-carbon segments is an option which will not require facilitating nor extensive validation. A defect in a large one-piece carbon-carbon nozzle would cause the rejection of the whole nozzle or acceptance of materials of lower mechanical properties, while an unacceptable nozzle segment will only require the rejection of that one segment. The segmented carbon-carbon nozzle extension concept shortens the design and fabrication cycle by at least one year.

Aerojet has pursued the segmented nozzle approach under IRAD and has validated the mechanical approach via demonstration aluminum and fiberglass epoxy segments. The main drawback corresponds to the thickened sections in the nozzle to effect the segments attachment. The segmentation approach is estimated to increase the weight 30%.

A Segmented Carbon-Carbon Nozzle, Though Heavier, Is Robust and Cost Effective

- **Fabricability**
  - Present Facilities Are Large Enough to Produce Required Segmented Pieces
  - Lower Rejectable (Only Bad Segments Need to Be Replaced, Not Whole Nozzle)

- **Compactness**
  - Disassembled Pieces Are Easy to Store, Ship, and Reassemble

- **Robustness**
  - Smaller Pieces Are Easier to Fabricate and Inspect → Stronger and Less Flaw Sensitivity

- **Cost Effectiveness**
  - Facility Upgrade Is Not Required
  - Shorter Schedule (Start With Design Plus Fab)

- **Penalties Are Acceptable**
  - Attachment Will Add Only 150 lbs
COMPONENT: Quad Channel Fault Tolerant Controller (Three Channel Version Depicted)

FUNCTION: The Engine Controller is responsible for closed loop control of the NTRE engine and auxiliary power generation components.

The engine controller performs a complete engine system checkout and calibration prior to engine operation. This includes calibration of the individual instruments and control system components. During the start sequence the controller controls reactor reactivity, pump chill, turbomill ramp up, and power ramp up. The engine controller actively controls engine steady state operation to maximize engine lsp. Engine power down and post firing cool down is actively controlled to minimize propellant usage and maximize total engine lsp.

The engine controller performs periodic engine system health monitoring and life prediction throughout engine operation.

Brayton cycle power generation is actively controlled throughout the mission. The controller is capable of adjusting the power output level over a 5:1 range to meet varying mission demands.

ARCHITECTURE: The NTRE engine controller is a 32 bit full voting four channel fault tolerant processor (FTP) that is derived from the Charles Stark Draper FTP architecture. The four channel controller provides full Fail Op/Fail Safe operation (higher levels of fault tolerance are available with degraded fault coverage).

Additionally the four channels are electrically and mechanically isolated from each other. This prevents a catastrophic electrical failure from propagating from one channel to the next.

The 32 bit Intel 80960 microprocessor provides the processing power for the engine controller. The 80960 is optimized to efficiently execute the Ada language. This central processor provides many advanced enhancements such as automatic exception handling and memory management that facilitate the efficient processing of Ada language. Over 2Mb of memory is provided on the digital computer unit module. This complement of memory is more than sufficient for both engine system control code and advanced health monitoring and life prediction algorithms.


SIZE: 8 in. x 16 in. x 10 in.
WEIGHT: 59 lbs (46 lbs Electronics + 13 lbs Shield)
TOTAL DOSE: 100 K Rads (50)

Advanced Fault Tolerant Controller Improves Mission Reliability
COMPONENT: Dual Channel Electro-Mechanical Actuator

FUNCTION: Provide actuation for modulating valves over a -1 to 90 deg arc. The EMA feature load insensitivity and high positional accuracy/repeatability.

ARCHITECTURE: The EMA is a fully redundant actuator featuring dual channel redundant bus interfaces, dual redundant power interfaces, dual channel redundant control electronics, dual electric redundant motors on a common shaft, and dual resolvers on a common shaft. The two EMA channels contain no electrical cross strapping and are mechanically isolated from each other. This prevents a catastrophic electronics failure in one channel from propagating to the other channel.

INTERFACES: 2 MIL-STD-1553B Valve Command Channels, 2 Power Buses

SIZE: 4 in. x 6 in. x 10 in.

WEIGHT: 31 lbs (9 lbs Electronics/Mechanics + 32 lbs Shield)

TOTAL DOSE: 100K RAD(SI)

TORQUE: 600 In.-lb

SLEW RATE: 360 deg/sec

POSITIONAL ACCURACY/REPEATABILITY: ± 0.5 deg

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Advanced Electro-Mechanical Actuator Combines High Torque and Small Size

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Energopool • Babcock & Wilcox

GenCorp
AERONET
COMPONENT: Quad Channel Control System

FUNCTION: Provide full Fall Op/Fall Safe engine and auxiliary power generation control.

ARCHITECTURE: The control system is designed with a high degree of symmetry and redundancy. The symmetry of the control system greatly reduces the complexity of the redundancy management software and improves system reliability and verifiability. Critical control valves such as the engine isolation valves are fully quadded thus allowing them to tolerate one stuck open or one stuck shut failure. Other valves are either simplex or dual (serial or parallel) depending upon the function of the valve.

There are two interfaces to the electro-mechanical actuators. These two interfaces are referred to as the Active Effector Control Bus and the Passive Effector Control Bus. Each control bus is actually a redundant MIL-STD-1553B implementation. This provides a total of four data paths to each actuator thus providing full Fall Op/Fall Safe capabilities of the control system.

Each solenoid actuator has dual coils. This provides fully redundant interfaces to the engine controller. Like the effector control buses the solenoid interfaces are organized as active and passive interfaces. Additionally solenoids contain a mechanical preload that forces the solenoid into a safe position in the event of a total interface failure.

Critical engine parameters, such as chamber pressure, are fully quad redundant. Other parameters such as moderator temperature are simplex or dual per moderator element as called for by FEMA/reliability analysis.

Heavy use will be made of sensor analytical redundancy techniques. These techniques allow a failed parameter to be substituted by using a physical model and related measurements.

INTERFACES: 2 MIL-STD-1553B Valve Command Channels, 2 Power Buses
SIZE: 8 in. x 16 in. x 10 in.
WEIGHT: 31 lbs (9 lbs Electronics/Mechanics + 32 lbs Shield)
TOTAL DOSE: 100K RADs(SI)
TORQUE: 600 in.-lb

Quad Channel Control System
Improves Mission Reliability

Quad Redundant Sensor
- Active Sensor Interface 0
- Active Sensor Interface 1
- Active Sensor Interface 2
- Active Sensor Interface 3

Quad Channel Controller

- Energopool - Babcock & Wilcox

NTP: System Concepts 282
COMPONENT: Operational Flight Program

FUNCTION: The Operational Flight Program (OFP) provides the control, health monitoring and life prediction capabilities seen in the control system. All of the dynamic engine control laws are found in the OFP. Engine system health monitoring and life prediction algorithms are also resident within the OFP. Additionally the OFP manages the interface hardware within the engine controller.

The OFP implements the required vehicle communications protocols and validates commands. Additionally status and data packets are sent back to the vehicle.

ARCHITECTURE: The OFP design is based on a highly modular, structured, functional decomposition of the required functionality. Related functions are combined into modules. Thus all the engine control functions are grouped into the Engine Control Module, all the Health Monitoring functions are grouped within the Health Monitoring Module. Modules have rigid functional, interface, protocol, and temporal specifications. These specifications minimize the interactions between modules, increasing software reliability and reducing verification and validation efforts.

The modular architecture allows individual modules to be upgraded throughout the life of the NTRE program while preserving the software investment. Modules are designed to be "plugged in" in a manner similar to mechanical components thus reducing the costs associated with software verification and validation.

INTERFACES: Controller/I/O Devices

Plug In Software Modules Improves Controller Development

HEALTH MONITORING DATA FLOW

GENCORP AEROJET • Energopool • Babcock & Wilcox

NP-TIM-92 283 NTP: System Concepts
Integrated Engine

Mel Bulman

Integrated NTRE Improves Mission Performance

The SEI stage will require many subsystems in addition to the engine and tanks. Our integrated NTRE includes a number of systems normally assigned to the stage. It can provide reaction control and orbit maneuvering thrust during coast. During the main burn, the engine can provide autogenous tank pressurization and electrical power. After shutdown, the reactor can be used as a heat source for generating up to 100 kW (e) per engine. All of this is accomplished at lower weight than if separate systems are employed to achieve these functions.

Mission Benefits of Integrated NTRE
- Robust, Low Loss Start
- High Performance, Lightweight Engine
- Safe, Efficient Shutdown
  - Five Core Cooling Systems
  - Closed Cycle Decay Heat Removal Saves 100,000+ lbm IMLEO
- Dual Mode Option
  - 100 kW Available Any Time During Mission
  - No Deep Thermal Cycles
  - Refrigeration Option
- OMS and RCS Impulse Available at High Isp
- One or Two Cold Flow Starts/Mission
Integrated NTRE Start Sequence

- Engine Prestart Conditioning
  - Pump Chill In
  - Moderator Loop Pressurization With TPA Chill H₂ (First Start Only)
  - Closed Loop Engine Warm Up (First Start Only)
  - Engine Now on Standby Mode For Starting
- Start
  - Spin Start TPAs With Warm Pressurized H₂ From Moderator Loop
  - TPA Acceleration Dominated by Engine Thermal Mass (Power For Approximately 10 Starts In Recuperator Alone)

Integrated Engine Increases Start Reliability and Safety

- Pre-Chill Pumps
- Fast Start Reduces Isp Loss, Improves Navigational Accuracy
- Immediate Restart Capability (x10 times)
Enhanced Multiple Engine Start

- Energopool - Babcock & Wilcox
Our Propellant Feed System Dynamics Are Efficiently Controlled

- Engine Prestart Conditioning
  - Pumps Chilled In
  - Reactor Warmed
  - Feed System Pressurized (Reduces Inrush Dynamics)

- Aerojet Pumps Are Designed With Greater Stall Margin

- Our Recuperated Cycle Greatly Aids the Start Up
  - Ample Thermal Power Accelerates Bootstrap
  - Provides Thermal and Hydraulic Damping
  - Isolates Fuel Assembly From Feed System

- Our Integrated Controller Can Choose the Optimum Path to Full Power, Balancing:
  - Isp Loss
  - Fuel Element Thermal Shock

---

Our Integrated Engine Starts More Reliably
And With Less Impulse Loss than Nerva Type Engines

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GENCORP - Energopool - Babcock & Wilcox
Tapping into the hot $\text{H}_2$ in the moderator loop of our Integrated NTRE during operation allows us to generate up to 100 kW(e), attitude control impulse, and tank pressurization at lower cost than if provided by separate systems.

**Integrated Engine Provides RCS and Tank Pressurization During “Burns”**

*Two TPAAs Allow 20:1 Throttling*
The decay heat build up in the engine during the main burn must be removed from the reactor or it will overheat. Decay heat persists for days even after a short fifteen minute burn. Our integrated engine can reject a significant portion of the heat through its radiators, greatly reducing the expenditure of propellant to cool the engine. This reduces vehicle mass (IMLEO).

Integrated Engine Saves Over 100,000 lbm LH₂
Our Closed Cycle Cooling System Saves Over 7500 lbm During Perigee Pulsing

<table>
<thead>
<tr>
<th>Conventional Cooling System</th>
<th>Phase 1</th>
<th>Cool 1</th>
<th>Plume 2</th>
<th>Cool 2</th>
<th>Plume 3</th>
<th>Cool 3</th>
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</thead>
<tbody>
<tr>
<td>Initial Mass (Lbm)</td>
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<tr>
<td>Effective Isp (Sec)</td>
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<td>640</td>
<td>915</td>
<td>600</td>
<td>915</td>
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<td>Final Mass (Lbm)</td>
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<td>AV (I/sec)</td>
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<td>Mission Velocity (Ft/Sec)</td>
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<td>Mission Effective Isp (Sec)</td>
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<table>
<thead>
<tr>
<th>Closed Cycle Cooling System</th>
<th>Phase 1</th>
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<th>Plume 2</th>
<th>Cool 2</th>
<th>Plume 3</th>
<th>Cool 3</th>
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</thead>
<tbody>
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<tr>
<td>Burn Time (Sec)</td>
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<td>174</td>
<td>955</td>
<td>1006</td>
<td>148094</td>
<td>1200</td>
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<td>Propellant Consumed (Lbm)</td>
<td>154280</td>
<td>2200</td>
<td>151240</td>
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<tr>
<td>Effective Isp (Sec)</td>
<td>915</td>
<td>760</td>
<td>915</td>
<td>760</td>
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<td>Final Mass (Lbm)</td>
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<td>843520</td>
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<td>AV (I/sec)</td>
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<td>64</td>
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<tr>
<td>Mission Velocity (Ft/Sec)</td>
<td>4932</td>
<td>4996</td>
<td>10812</td>
<td>10890</td>
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<td>18100</td>
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<tr>
<td>Mission Effective Isp (Sec)</td>
<td>913</td>
<td>914</td>
<td>913</td>
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<td>913</td>
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<tr>
<td>Propellant Savings (Lbm)</td>
<td>2578</td>
<td>5415</td>
<td></td>
<td></td>
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</tbody>
</table>

Mission Average Isp Improved 21 Seconds With Closed Cycle Cooling

Closed Cycle Cooling Reduces IMLEO Over 8%
950 Sec. Burn @ 150,000 lbf (2-3 Engines)

Closed Cycle Benefits
- Reduced Coolant Ejection
- Higher Ejection Isp (cut off low Temp. Tail)
- 75% Reduction Mission Isp Loss (ΔIsp & ΔMass)
- Reduced g Loss (Cooldown Impulse Delivered Faster)
- Closed Cycle Has All Brayton Power Cycle Components (Except Generator)

GenCorp
Aerojet - Energopool - Babcock & Wilcox

NP-11M-92 289
NTP: System Concepts
Our Integrated NTRE Can Reduce IMLEO 100-200+ Klb/m

<table>
<thead>
<tr>
<th>Conventional Cooling System (H2/O2 OME: System)</th>
<th>Burn 1</th>
<th>OMS-1</th>
<th>Burn 2</th>
<th>Burn 3</th>
<th>OMS-2</th>
<th>Burn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Mass (lbm)</td>
<td>1803170</td>
<td>871599</td>
<td>813424</td>
<td>397457</td>
<td>243699</td>
<td>228645</td>
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<tr>
<td>Propellant Consumed (lbm)</td>
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<td>287547</td>
<td>140353</td>
<td>162724</td>
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<tr>
<td>Effective isp (Sec)</td>
<td>892</td>
<td>456</td>
<td>892</td>
<td>892</td>
<td>450</td>
<td>692</td>
</tr>
<tr>
<td>Final Mass (lbm)</td>
<td>956288</td>
<td>813424</td>
<td>526182</td>
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<tr>
<td>AV (ft/sec)</td>
<td>18700</td>
<td>10900</td>
<td>12500</td>
<td>12500</td>
<td>10000</td>
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<tr>
<td>Mission Velocity (ft/sec.)</td>
<td>18200</td>
<td>19200</td>
<td>31700</td>
<td>44200</td>
<td>45200</td>
<td>63400</td>
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<tr>
<td>A IMLEO (Kilm/%)</td>
<td>257</td>
<td>16.64</td>
<td></td>
<td></td>
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<td>50000</td>
</tr>
<tr>
<td>Over Integ. NTRE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Conventional Cooling System With Main Engine Restart for</th>
<th>Burn 1</th>
<th>OMS-1</th>
<th>Burn 2</th>
<th>Burn 3</th>
<th>OMS-2</th>
<th>Burn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Mass (lbm)</td>
<td>1578020</td>
<td>811106</td>
<td>75385</td>
<td>374494</td>
<td>229025</td>
<td>21961/</td>
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<tr>
<td>Propellant Consumed (lbm)</td>
<td>760164</td>
<td>30251</td>
<td>271801</td>
<td>132744</td>
<td>59447</td>
<td>11006/</td>
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<tr>
<td>Effective isp (Sec)</td>
<td>897</td>
<td>760</td>
<td>892</td>
<td>892</td>
<td>760</td>
<td>892</td>
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<tr>
<td>Final Mass (lbm)</td>
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<td>242250</td>
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<td>116185</td>
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<tr>
<td>AV (ft/sec)</td>
<td>18200</td>
<td>10900</td>
<td>12500</td>
<td>12500</td>
<td>10000</td>
<td>18200</td>
</tr>
<tr>
<td>Mission Velocity (ft/sec.)</td>
<td>18200</td>
<td>19200</td>
<td>31700</td>
<td>44200</td>
<td>45200</td>
<td>63400</td>
</tr>
<tr>
<td>A IMLEO (Kilm/%)</td>
<td>132</td>
<td>8.55</td>
<td></td>
<td></td>
<td></td>
<td>50000</td>
</tr>
<tr>
<td>Over Integ. NTRE</td>
<td></td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Integrated NTRE Closed Cycle Cooling System</th>
<th>Burn 1</th>
<th>OMS-1</th>
<th>Burn 2</th>
<th>Burn 3</th>
<th>OMS-2</th>
<th>Burn 4</th>
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</thead>
<tbody>
<tr>
<td>Initial Mass (lbm)</td>
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<td>160485</td>
<td>774553</td>
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<td>297703</td>
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<tr>
<td>Propellant Consumed (lbm)</td>
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<td>37032</td>
<td>252145</td>
<td>121347</td>
<td>9409</td>
<td>95/11</td>
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<tr>
<td>Effective isp (Sec)</td>
<td>913</td>
<td>760</td>
<td>913</td>
<td>913</td>
<td>760</td>
<td>913</td>
</tr>
<tr>
<td>Final Mass (lbm)</td>
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<td>774553</td>
<td>475308</td>
<td>226746</td>
<td>267209</td>
<td>111502</td>
</tr>
<tr>
<td>AV (ft/sec)</td>
<td>18200</td>
<td>9900</td>
<td>12500</td>
<td>12500</td>
<td>9400</td>
<td>18200</td>
</tr>
<tr>
<td>Mission Velocity (ft/sec.)</td>
<td>18200</td>
<td>19200</td>
<td>31700</td>
<td>44200</td>
<td>45200</td>
<td>63400</td>
</tr>
<tr>
<td>A IMLEO (Kilm/%)</td>
<td>132</td>
<td>8.55</td>
<td></td>
<td></td>
<td></td>
<td>50000</td>
</tr>
<tr>
<td>Over Integ. NTRE</td>
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<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nuclear OMS (without restart)</th>
<th>Burn 1</th>
<th>OMS-1</th>
<th>Burn 2</th>
<th>Burn 3</th>
<th>OMS-2</th>
<th>Burn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Returned</td>
<td>100 Klb (top 69 Mars, 10% tank fraction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Four Burn Full Up Mars Mission

Energoool - Babcock & Wilcox

Aerojet

NTP: System Concepts 290 NP-TIM-92

Closed Cycle Cooling Can Reduce IMLEO Over 100K lb*

<table>
<thead>
<tr>
<th>Conventional with Chemical OMS</th>
<th>Burn 1</th>
<th>OMS-1</th>
<th>Burn 2</th>
<th>Burn 3</th>
<th>OMS-2</th>
<th>Burn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Returned</td>
<td>100 Klb (top 69 Mars, 10% tank fraction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Four Burn Full Up Mars Mission
During coast, our integrated engine is kept warm while generating up to 100 kW(e). The mean electrical power will be less than 100 kW(e). At 20 kW(e) the Brayton cycle efficiency is approximately 30% requiring a thermal power of approximately 60 kW(t), which causes only a small additional burn up of the reactor fuel.
The integrated engine adds life to the fuel, because it allows fuel to be kept warm during coast (~1800 K). Therefore, the fuel will see only ~1000K AT's during startup and shutdown. 1800K was chosen to balance the effects of vaporization rate, thermal cycling, and power cycle efficiency.

**Engine Does Not Cool Fully Between Major Burns**

Aerojet Cycle Benefits
- Reduced Thermal Shock
- Integrated Power Supply
- ACS and OMS Power
- Full Thrust Available on Short Notice

**GENCORP**

- Energopool
- Babcock & Wilcox

NTP: System Concepts 292
Reliability and Safety

Mel Bulman

Our Turbopump System Improves Mission Reliability*

- Single TPA System Has ~ 4 Times the Probability of Total Failure vs 2 TPAs
- Twin Spool 4 Stage Pump Is More Reliable Than Single Shaft TPAs at the Same Discharge Pressure

*Industry Standard Component Failure Rates Applied to Feed Systems
Dual Spool TPA Provides High Margin for NTRE

- Impellers Stressed Less for Same Weight and Performance – Less AP Per Impeller
- Four Bearings to Share Loads Rather Than Two
- Unshrouded, Machined Impellers Have Higher Strength Than Casting
- Runs Subcritical for Less Dynamic Stress

Reliability Increased With Lower Stressed Parts

Margin A Stronger Influence On Reliability Than Parts Count
NTRE – Concept Design

Failure Modes and Effects Analysis

A Failure Modes and Effects Analysis was completed for the Particle Bed Reactor concept. The failure modes of the major components were identified. The criticality and effect of each mode was determined and possible ways to minimize the occurrence of each mode were also identified. This analysis will be expanded and updated during the preliminary design phase to reflect design maturation. The FMEA will be the basis for developing a Reliability Fault Tree, which will show system interactions graphically. Quantitative evaluation of the base events of the Fault Tree will allow reliability predictions to be made of the system. The Fault Tree will be developed using CAFTA, a Computer Aided Fault Tree Analysis code, which facilitates reliability and system safety analysis of complex systems.

NTRE – Concept Design

Failure Modes and Effects Analysis

- Preliminary FMEA Has Been Completed for Engine Concept
  - Component Failure Modes Identified
  - Actions to Minimize Occurrence Are Incorporated
    - Redundancy
    - Robust Design
    - Adequate Testing and Inspection
- FMEA to Be Updated During Design Phase to Reflect Maturing Design
NTRE – Concept Design

Reliability

Methodology to Evaluate the Effect of Redundant Components on the System

Reliability block diagrams and industry standard failure rates of like components will be used to assist in the evaluation of the effect of redundancies of various components on the reliability of the system.

A system level Fault Tree will be developed which will be used to analyze the reliability of the system during the various operating phases of the proposed mission.

A system Fault Tree has the advantage of being able to see graphically the interactions of a complex system. It is difficult to model these interactions using only block diagrams. Block diagrams are useful in studying effects on the system of series redundancy or parallel redundancy of a few components. But the overall system reliability is better evaluated by doing a quantitative evaluation of a system Fault Tree.

A reliability Fault Tree differs from a system safety Fault Tree only in the definition of the top event. Process and human errors resulting in system failure are always included in the system safety Fault Tree. They can also be included in the Reliability Fault Tree. If the purpose of the Reliability Fault Tree is to assess the reliability of the design then the possible process and human errors would not be included in this Fault Tree.

• Reliability Block Diagrams and Failure Probabilities Using Industry Standard Failure Rates for Like Components Will Be Used to Evaluate Need for Redundant Components

• Reliability Fault Tree Will be Developed of Overall System to Be Used in Evaluating System Reliability
NTRE Design Criteria

- Safety Factors

**Pressure Loads**

Yield Safety Factor \( F_{Sy} \) = 1.25
Ultimate Safety Factor \( F_{Su} \) = 1.50

**Thermal Loads**

Yield Safety Factor \( F_{Sy} \) = 1.00
Ultimate Safety Factor \( F_{Su} \) = 1.00

- Margin of Safety

\[
MS = (\text{Allowable Stress}) (FS \times \text{Applied Stress}) - 1.0
\]

System Safety

Design Includes Hazard Elimination and Control Provisions for Wide Range of Potential Hazards

- A Preliminary Hazard Analysis Has Been Accomplished

- This Analysis is the Initial System Safety Task Which Included a Review of the NTRE Components, Potential Hazardous Conditions, Effect on the System if an Undesirable Condition Took Place, and Recommended Controls in the Design to Prevent an Occurrence From Happening

- In Addition to Component Review, Natural Environment, Oxygen Rich Environment, and Aerospace Ground Equipment Hazards Were Considered

- This Study Illustrates a Combination of 17 Hazardous Conditions That Were Considered
Nuclear Safety

- Water Immersion
  - Most Reactor Voids Filled With Poison During Launch
  - Reactor Design Remains Subcritical
    - Fuel Internally Retained
  - Launch Safety/Emergency Shutdown Procedures
  - Qualification and Acceptance Tests

- Impact Compaction (Ground)
  - Collision Reduces Void Fraction
  - Reactor Design Ensures/Remains Subcritical
    - Fuel Internally Retained
  - Launch Safety/Emergency Shutdown Procedures
  - Qualification and Acceptance Tests

---

Nuclear Safety
Emergency Cooldown Procedure

- 1 TPA Failure
  - Fast (~1 sec) or Slow (~30 Seconds) Single Failure
    - Normal Reactor Shutdown
      - Cooldown at High Power With 2nd TPA
    - Continue Mission With 2nd TPA

- 2 TPA Failure
  - 1 Fails Fast, 1 Fails Slowly
    - Shutdown Reaction at High Power With Slowly Failing TPA
    - Employ Pulsed Cooling System Prior to 2nd TPA Failure

- 2 TPA Failure
  - 2 Fail Fast or Nearly Simultaneously
    - Shutdown Reactor
    - Cooldown at High Power With Crossover System
Nuclear Safety
Reactor Leakage Potential Is Minimized

- Use of Non-Radiation Embrittlement Materials
- Maintain Within Temperature Extremes
- Develop Approved Installation Procedures
- Post-Reactor Installation Leak Checks
- Test Area Monitored for Leakage
- Non-Nuclear Qualification and Acceptance Tests

Minimize Leakage Effect

- Radiation Hardened Material/Electronics
- Shielding
- Qualification and Acceptance Tests

Nuclear Safety
Design Controls Radiation Hazards to a Minimum

- Shielding Material – “Burn-In” Process
- Internal Shielding
  - Attenuates Levels at Propellant Tank
  - Reduces Levels to Engine and Stage Components
- External Shielding
  - Reduces Level to Crew and Stage
- Components Nuclear Hardened
- Proof-of-Concept Testing
Nuclear Safety

Reactor Risks and Hazards Are Minimized, i.e., System Design

- Controller Architecture
  - Diagnostic Instrumentation Monitors Reactor
  - Quad Channel Fault Tolerance Operation
  - Software Redundancy Design
  - Multiple Signals Required to Activate Valves
- Reactor
  - Control Drums Have Redundant Drive Motors and Couplings
  - Safety Rods Have Redundant Drive Motors and Couplings
- Shielding of Safety Rod Drives Ensures Rod In or Out Control Capability
- Non-Nuclear Vibration, Thermal and Shock Tests to Verify Structural Integrity

Nuclear Safety

Design Controls All Identified Energy Sources

- Reactor
- Pressurized Propellant Feed Lines/Fittings/Valves
- Turbopump Assembly
- Pyrotechnic Isolation Valves
- Electronics
- Hydrogen in Tank

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System Safety
Summary

- Nuclear Safety Hazards Will Be Controlled Through Preventative Measures
  - Margins
  - Redundancy
  - Diversity
- NTRE Design Will Meet the Applicable Safety Requirements for Operation on the Eastern Test Range or Western Test Range
- The APD/B&W Team Will:
  - Ensure Design Meets Proof-of-Concept Objectives With Risk Reduced to as Low as Reasonably Achievable
  - Support the Nuclear Safety Policy Working Group Recommendations as Applicable

PBR Engine Sensitivity Studies
Mel Bulman
High Thrust and Power Density Increase Engine Thrust-to-Weight

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight, lbm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncleared Nozzle</td>
<td>232</td>
</tr>
<tr>
<td>Cleared Nozzle</td>
<td>965</td>
</tr>
<tr>
<td>Pressure Vessel, Reactor Manifolds &amp; CIS</td>
<td>3536</td>
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<tr>
<td>Reactor, Reactor &amp; CIS</td>
<td>6613</td>
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<tr>
<td>Turbopump Assemblies (2)</td>
<td>419</td>
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<tr>
<td>Turboreactor/Thrust Shield</td>
<td>2615</td>
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<tr>
<td>Secondary Shield</td>
<td>642</td>
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<tr>
<td>Plumbing/Valves</td>
<td>1270</td>
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<tr>
<td>Controls and Shielding</td>
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</table>

**NTRC Stage Power & Heat Removal**

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight, lbm</th>
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</thead>
<tbody>
<tr>
<td>Stage Power &amp; Heat Removal Sys Wt, lbm</td>
<td>2000</td>
</tr>
<tr>
<td>Engine with Power Sys Wt, lbm</td>
<td>17900</td>
</tr>
<tr>
<td>Masa Mission Specific Impulse, sec</td>
<td>849</td>
</tr>
<tr>
<td>Payload Returned to Earth, lbm</td>
<td>5929</td>
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</tbody>
</table>

* CIS Engine Fuel Bundle Power Density is 12 MW/liter. Therefore we expect its weight to scale approximately as the PBR engine with power density.
Our PBR engine concept is best summarized by including the rationale behind the selection of each major subsystem concept or operating parameter. 2700 K mixed mean reactor outlet gas temperature is selected by B&W fuel experts to meet the 4.5 hour life requirement with an appropriate margin by the end of fuel assembly development. The engine design/operating selection of 300:1 nozzle area ratio and nozzle inlet pressure of 2,000 psia is the result of a Mars mission payload trade study; it gives the best combination of engine specific impulse and weight. A recuperated turbopump drive cycle was selected for several reasons: (1) nozzle inlet pressures of 1000 psia and above are enabled by recycling topping heat through the turbine, and no reactor manifolding need be added to extract turbine drive heat directly from the core, (2) engine start and shutdown transients are smoothed and assisted by the large, available heat capacity of the high surface area recuperator, (3) the steel heat exchanger adds no weight to the engine, because its weight is determined by its other duties as a large part of its internal gamma shield and as the forward closure of the reactor vessel. A forward core support structure was selected, largely because it is the American experience base. The forward structure is cool, it forms part of the gamma shield, and it is used as propellant manifolding. Fuel assemblies operate in tension and are constructed of steel and beryllium, according to U.S. experience. A single DeLaval nozzle is selected that is internally cooled with hydrogen; no hydrogen bleed is necessary, because our formed platelet nozzle operates with low internal wall temperatures at high heat fluxes. A 40 Kbit nozzle of similar design, material and coolant is now in test at NASA. The nozzle is small, because of the engine’s high operating pressure, and we use a low weight, carbon-carbon nozzle extension. Its surface may be converted to ZrC to improve its life in hydrogen environment, using near term technology processes similar to those in work at Aerojet, however this is probably unnecessary, because total surface recession in 4.5 hours of operation is expected to be less than 0.025 in. (0.64 mm). A LiH neutron shield is encapsulated in aluminum and located external to the recuperator in order to simplify the core support structure. A secondary gamma shield is located at its forward face to provide sufficient gamma attenuation at all times during engine life. Both shields are cooled by propellant flow.

Design Rationale for NTRE With PBR Is Clear

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Rationale</th>
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<tbody>
<tr>
<td>1 H2 Mixed Mean Outlet Temperature (2,700K)</td>
<td>Expected 4.5 Hours Fuel Life</td>
</tr>
<tr>
<td>2 Pc (2,000 psia)</td>
<td>Best Mars Mission Performance With Reusable Engines</td>
</tr>
<tr>
<td>3 Ae/At (300)</td>
<td>Enable High Pressure With Simple Reactor</td>
</tr>
<tr>
<td>4 Power Cycle (Recuperated)</td>
<td>Enhances Transient Operation</td>
</tr>
<tr>
<td>5 Core Support (forward)</td>
<td>No Weight Penalty (γ Shield)</td>
</tr>
<tr>
<td>6 Nozzle (Single DeLaval) (H2 Cooled Without Bleed Flow) (C-C Extension)</td>
<td>U.S. Experience Base</td>
</tr>
<tr>
<td>7 Neutron Shield (External)</td>
<td>Near Term Technology Use (Formed Cu Platelet)</td>
</tr>
<tr>
<td></td>
<td>Simplifies Core Support</td>
</tr>
</tbody>
</table>

Gencorp - Energopool - Babcock & Wilcox
REACTOR DESIGN PHILOSOPHY

BABCOCK & WILCOX HAS APPLIED ITS KNOWLEDGE OF THE PARTICLE BED REACTOR (PBR) TO MEET THE NASA DESIGN REQUIREMENTS. THE OBJECTIVES OF THE DESIGN WERE TO STAY WITHIN THE TECHNOLOGY BASE FOR THE PBR. THIS INCLUDES THE MIXED MEAN EXHAUST GAS TEMPERATURE, ENGINE PERFORMANCE AND PRIMARILY THE SYSTEM SAFETY. THE PBR IS CAPABLE OF VERY HIGH T/W RATIOS HOWEVER, FOR MAN-FLATED SYSTEMS OUR BASELINE DESIGN HAS BEEN CONSERVATIVELY DESIGNED AND INCORPORATES ROBUST AND THEREFORE RELIABLE COMPONENTS. THE PBR CONCEPT HAS THEREFORE INCURRED SOME MASS PENALTIES WHICH ARE BELIEVED TO BE PRUDENT IN TERMS OF SAFETY FOR THE CREW.

REACTOR DESIGN PHILOSOPHY:

STAY WITHIN THE TECHNOLOGY:

- NASA Requirements - Isp/Gas Temperature
- Mass Penalties Accepted
- Highest Possible Performance is NOT Top Priority

- SAFETY IS-

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NTP: System Concepts 304 NP-TIM-92
THE PBR IS A PARTICULARLY ATTRACTION CONCEPT DUE TO THE HIGH SURFACE AREA AND THE PARTICULATE FUEL FORM. THE HEAT TRANSFER CAPABILITY IS UNSURPASSED SMALL PARTICLES, BY DEFINITION, ALSO LIMIT THE THERMAL STRESSES WITHIN THE PARTICLES DUE TO THE SHORT CONDUCTION PATH LENGTH. THESE FEATURES ALLOW THE PBR TO OPERATE AT HIGH POWER DENSITY AND THEREFORE REQUIRE LESS CORE VOLUME. SMALLER CORE VOLUME TRANSFORMS TO REDUCTIONS IN VESSEL DIAMETER AND SHIELD DIAMETER, ALL OF WHICH TRANSLATES TO LOWER MASS (OR HIGHER T/W).

THE HETEROGENEOUS CORE UTILIZES 36 FUEL ELEMENTS ON A PITCH OF 3.44 M. THE SUPPORT FOR THE CORE IS ACCOMMODATED BY THE MANIFOLD STRUCTURE. THE CORE IS "HUNG" FROM THE TOP WHERE CORE GAS KEEPS THE STRUCTURE WITHIN ITS ALLOWABLE TEMPERATURE REGIME. BERYLIO MODERATOR HEXAGONS SURROUND EACH FUEL ELEMENT AND ACT AS ITS PRIMARY STRUCTURAL SUPPORT.

A TOTAL OF 18 ROTATING CONTROL DRUMS SURROUND THE CORE. THESE DRUMS CONTAIN A NEUTRON POISON (B,C) SEGMENT TO CONTROL THE POWER OF THE REACTOR. A SAFETY ROD IS LOCATED AT THE CENTERLINE OF THE CORE. IT IS AN AXIALLY CONTROLLED POISON ROD (B,C) AND IS A REDUNDANT SHUT DOWN SYSTEM IN THE EVENT THE CONTROL DRUMS BECOME INOPERABLE.

THE RECUPERATOR SERVES MANY FUNCTIONS AND IS NECESSARY FOR POWER BALANCE. IT RECIRCULATES WASTE THERMAL ENERGY TO DRIVE THE TURBOPUMPS. IN ADDITION, IT PROVIDES A SIGNIFICANT PORTION OF THE INTERNAL SHIELDING FOR THE TURBOPUMPS. PLATELET TECHNOLOGY WILL BE USED TO FABRICATE THE RECUPERATOR AND THE COOLED PORTION OF THE NOZZLE.

PBR Provides a Compact High Power Engine

![Diagram of PBR](image-url)
Recuperated Cycle Provides Superior Engine Operation

- Provides Cooled, Internal Gamma Shield
- Enables High Chamber Pressure
- Provides Thermal Energy for Turbopump Start
  - Energy available for many starts
- Provides Safe, Controllable Reactor Start
  - Prevents Liquid Hydrogen entry into the core
  - Decouples and damps system oscillations
REACTOR SUMMARY, KEY SPECS

There are several noteworthy reactor specifications. Perhaps the most important is the average power density that was chosen for the baseline. The value of 33 MW/l was chosen for this mission because we believe it is achievable. Furthermore, the Russian engineers have demonstrated up to 50 MW/l (for minutes) with similar fuel composition. It is important to note that the power density determines the size of the reactor and therefore the engine size. The change in mass of the reactor with power density variations is shown separately.

The baseline fuel composition is (U,Zr)C which is coated with NbC. This combination offers high temperature capability (i.e. melting is approx. 3,300-3,400K) and the coating provides the fission product retention and is selected to match the thermal expansion of the binary fuel better than Zircaloy.

REACTOR SUMMARY: KEY SPECS

- Reactor Power: 56.4 MW
- Thrust (260 l nozzle): 75,000 lbf
- Gas Outlet Temp (mixed mean): 2,700 K (4,940°F)
- Propellant Flow Rate: 82 l/sec
- Fuel Form: Uranus (U/Zr) U/Pu/2
- Particle Diameter: 500 Micron (20 mils)
- Rod Power Density (ave): 33 MW/l
- Core Power Density: 3.6 MW/l
- Fuel Volume: 47.7 liters
- Number of Elements: 36
- Safety Shutdown: Central Poison Rod
- Vessel Diameter: 1.0 l/sec
- Reactor Fueled Length: 92.5 ft
- Reactor Mass (no recapt shielding): 5.3 lb (2.4 kg)
THE FUEL ELEMENTS ARE LOCATED ON A HEXAGONAL ARRAY. THIS ALLOWS THE 36 FUEL ELEMENTS TO BE EFFICIENTLY INTEGRATED INTO THE SMALLEST POSSIBLE VOLUME WHILE MEETING CRITICALITY LIMITS, THERMAL HYDRAULIC AND STRUCTURAL REQUIREMENTS. A SATISFACTORY PITCH WAS FOUND TO BE 11 CM. THIS WAS PRIMARILY SIZED FOR HYDRAULIC CONSIDERATIONS (LOW PRESSURE DROP THROUGH THE MODERATOR AND INLET PLENUM). FURTHER STUDIES AND OPTIMIZATION WILL LIKELY RESULT IN A CHANGE IN THE PITCH.

THE CONTROL DRUMS ACT AS THE REFLECTOR AND THE CONTROL SYSTEM FOR THE REACTOR. THEY ARE APPROXIMATELY 11 CM IN DIAMETER WITH AN OUTER SEGMENT OF 12 MM THICKNESS AND 120 DEGREE ARC CONTAINING B4C. THEY ARE PLACED AS CLOSE TO THE CORE AS POSSIBLE. ORIGINALLY THERE WERE 24 CONTROL DRUMS BUT THE 'CORNER' SIX WERE PROVIDING LITTLE CONTROL BENEFIT AND WERE THEREFORE REMOVED. THE SAFETY ROD IS LOCATED IN THE CENTER OF THE CORE WHERE ITS WORTH IS MAXIMIZED.

**Reactor Features Efficient Integration of Components**

- CONTROL DRUM (18)
- FUEL ELEMENT (36)
- SAFETY ROD
- STEEL VESSEL

NTP: System Concepts

NP-TIM-92
The various flow loops of the engine system have been greatly simplified through the use of an innovative manifold/core support structure. This component is unique in that it not only provides a very rigid structure to which the fuel elements are attached but also contains two plenums for the moderator cooling loop and a feed-through for the fuel element propellant loop.

The fabrication of the core support structure is similar to that of a honeycomb composite. The internal webs carry the shear loads while the top and bottom skins of steel carry the membrane loads. As the aircraft industry is aware, this configuration is extremely efficient in its specific load carrying capability and stiffness, therefore the thicknesses of the steel skins and web are minimized.
THE CONTROL DRUMS ARE LOCATED CLOSE TO THE CORE, WITH AS LARGE A DRUM SIZE AS POSSIBLE WITHOUT INTERFERENCE, (APPROXIMATELY 11 CM OUTSIDE DIAMETER) TO ENHANCE NEUTRON REFLECTION AND CONTROL WORTH, WHILE MINIMIZING THE SURROUNDING PRESSURE VESSEL SIZE. THE DRUM HEIGHT IS SLIGHTLY LONGER THAN THE ACTIVE FUEL BED HEIGHT OF ABOUT 92 CM. THE CONTROL DRUMS FOR THE CONCEPTUAL DESIGN ARE MADE OF BERYLLIUM WITH A B,C POISON SEGMENT 12 MM THICK OVER A 120 DEGREE ARC SEGMENT. THE CONTROL DRUM WORTH IS 0.10 DELTA-K/K WITH THE SAFETY ROD WITHDRAWN, AND 0.14 WITH THE SAFETY ROD INSERTED. TOTAL CONTROL WORTH IS 0.26 DELTA-K/K, FOR A SHUTDOWN REACTIVITY OF 0.20 DELTA-K/K (K-EFFECTIVE = 0.83). NOMINAL HYDROGEN GAS DENSITIES, OR WORTH IS 0.07 DELTA-K/K, WERE INCLUDED. THUS, WITHOUT HYDROGEN GAS, THE REACTOR WILL BE 0.01 DELTA-K/K SHUTDOWN EVEN IN THE MOST REACTIVE CONTROL POSITIONS. A STUDY OF INDIVIDUAL DRUM WORLTHS SHOWED THAT A FIXED BERYLLIUM REFLECTOR SECTION IN THE CORNER POSITION ENHANCES REFLECTION AND CONTROL WORTH, INCREASING TOTAL DRUM WORTH BY ABOUT 0.01 DELTA-K/K, WHILE ALSO ALLOWING SMALLER PRESSURE VESSEL SIZE. A TRADE STUDY SHOWED POISON THICKNESS AS THIN AS 1 MM IS QUITE EFFECTIVE AND THAT THE MAXIMUM WORTH WAS REACHED AT APPROXIMATELY 10 TO 15 MM.
SAFETY ROD LOCATED FOR MAXIMUM WORTH

The central safety rod is located in a position of high neutron flux, resulting in a control worth which exceeds the combined worth of the 18 control drums. It contains B/C in a cylindrical shape with outside diameter of almost 11 cm. A rod reflector segment is mounted on the aft end to minimize neutron streaming through the safety rod opening and to reduce heating during operation. The safety rod worth is 0.12 Delta-K/K with the control drums' poison outward, and 0.16 Delta-K/K with the control drums' poison inward. The total control worth is 0.26 Delta-K/K, for a shutdown reactivity of -0.20 Delta-K/K (K-effective - 0.83). Nominal hydrogen gas densities, worth 0.07 Delta-K/K, were included. Thus, without hydrogen gas, the reactor will exhibit 0.01 Delta-K/K shutdown even in the most reactive control positions.

SAFETY ROD LOCATED FOR MAXIMUM WORTH

[Diagram of reactor components, including fuel element, poison rod, and manifolds]
FUEL ELEMENT INTEGRATED EFFICIENTLY

THE PBR CORP IS HETEROGENEOUS WITH A COOLED MODERATOR JACKET SURROUNDING THE COLD FUEL, COOL AND HOT FRIT. THE MODERATOR CONSISTS OF MACHINED BLOCKS OF BERYLLIUM JOINED TOGETHER TO FORM A HIOP JACKET NEARLY 1 METER IN LENGTH. THE BLOCKS ARE PRE-DRILLED WITH CAVITY LOVELY SIZED HOLES. TWELVE OF THE 36 HOLES ARE FILLED WITH ZIRCONIUM HYDRIDE AND THE REMAINDEr ARE USED FOR MODERATOR COOLING THE RATIOS OF ZIRCONIUM HYDRIDE, BERYLLIUM AND HYDROGEN YIELD PROPER NEUTRONICS, STRUCTURAL AND THERMAL HYDRAULIC PERFORMANCE. THE BASELINE DESIGN UTILIZES A RATIO OF 82% Be, 8% ZrH AND 10% H. THE PRESSURE DROP WITHIN THE COOLANT LOOP OF THE MODERATOR IS APPROXIMATELY 300 PSI, THE THICK BERYLLIUM WALLS ARE MORE THAN ADEQUATE TO PROVIDE STRUCTURAL SUPPORT AND THE ZIRCONIUM HYDRIDE, EVEN IN SUCH SMALL QUANTITIES PROVIDES ENHANCED MODERATION FOR THE CORP. FURTHER OPTIMIZATION CAN SIGNIFICANTLY ENHANCE THE PERFORMANCE OF THE MODERATOR AND REACTOR.

THE COLD FRIT DISTRIBUTES THE FLOW TO THE FUEL RED IN PROPORTION TO THE LOCAL HEAT GENERATION. COOLANT FLOW IS DIRECTED RADILY INWARD AND IS HEATED BY THE FUEL BED. THE HOT GAS PASSES THROUGH HOLES IN THE HOT FRIT WHERE IT COLLECTS IN THE HOT CHANNEL AND IS EXHAUSTED TO THE NOZZLE. THE COLD FRIT IS MADE OF STEEL AND WILL LIKELY BE OF PLATFLET DESIGN. THE HOT FRIT IS MADE OF NIOBIUM CARBIDE COATED GRAPHITE. GRAPHITE TECHNOLOGY HAS EVOLVED OVER THE YEARS AND IT IS NOW POSSIBLE TO OBTAIN GRAPHITE WITH A THERMAL EXPANSION COEFFICIENT THAT MATCHES THAT OF NIOBIUM CARBIDE EXACTLY.

THE HOT CHANNEL (THE AREA INSIDE THE HOT FRIT) IS SIZED SUCH THAT THE MAXIMUM VELOCITY OF THE HOT HYDROGEN IS NOT GREATER THAN MACH 0.2% TO AVOID COMPRESSIBILITY EFFECTS.

FUEL ELEMENT INTEGRATED EFFICIENTLY
FUEL ELEMENT FLOW IS SELF CONTAINED

The fuel element was analyzed using Fotive, a 1.0 BWX proprietary computer code which predicts pressure losses in the different components of an element, as well as temperatures of the propellant and fuel. Each fuel element was initially allotted a pressure drop of 500 psid. Results from Fotive indicate maximum pressure drops of about 300 psid. The propellant feed channel was designed to minimize pressure loss over the length of the channel without impacting the weight and size of the fuel element assembly. Results of a study to compare pressure losses to the different gap sizes between the moderator and cold frit indicated that the optimum gap was at 0.3 cm. The cold frit is designed to be the primary flow controller. In FOTYF runs, the minimum cold frit pressure drop to the bed pressure drop ratio is maintained at 8 to 1. This ratio ensures that the cold frit has considerably more control over the flow distribution to the fuel bed than the propellant feed channel or the bed itself.

The moderator design was analyzed using a channel flow code called PIPTH, another BWX proprietary code. The code calculates pressures, temperatures and film coefficients along the length of a heated channel. The moderators were initially allotted a pressure drop of 500 psid. Results indicate a maximum drop of about 300 psid.

This core design has not been optimized. However, a fuel element and moderator from one of the six assemblies which surround the safety rod were analyzed for this core configuration. These analyses demonstrate a workable design but detailed analyses must be performed on a core system level to provide insight on flow split characteristics and its impact on pressures and temperatures for full power, throttling and decay heat conditions.

FUEL ELEMENT FLOW IS SELF CONTAINED

Features

- Moderator Cooling Channel
- Propellant Feed Channel
- Cold Frit
- Fuel Bed
- Hot Frit
- Hot Channel
- Moderator

Fuel Element Cross-Section (with Afterburner)

From H.P. Recuperator
P = 4800 psia
T = 317°C

From L.P. Recuperator
P = 2500 psia
T = 197°C

To Turbine
P = 3000 psia
T = 483°C

To Nozzle
P = 2000 psia
T = 2700°C

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FUEL PARTICLE DESIGN IS BASED ON MISSION REQUIREMENTS AND WITHIN LIMITS, DOES NOT SIGNIFICANTLY AFFECT THE REACTOR DESIGN.

IN GENERAL, PARTICLE DESIGN IS SELECTED ON THE BASIS OF ENGINE BURN DURATION, NUMBER OF CYCLES, EXHAUST GAS TEMPERATURE, AND SYSTEM RELIABILITY REQUIREMENTS. CURRENTLY, THERE ARE FOUR COATED PARTICLE DESIGNS UNDER CONSIDERATION FOR USE IN PWRS, EACH CAPABLE OF MEETING DIFFERENT SETS OF MISSION REQUIREMENTS.

1. THE EARLIEST PARTICLE B&W DEVELOPED WAS THE SO-CALLED BASELINE PARTICLE. IT WAS BASED ON THE TRISO PARTICLE DEVELOPED FOR GAS-COOLED POWER REACTORS. IT CONSISTS OF A URANIUM CARBIDE KERNEL SURROUNDED BY TWO LAYERS OF CARBON BUFFER, FOR CTE MISMATCH AND SEALANT, AND AN OUTER SHELL OF UC OR NiC. THIS PARTICLE IS CAPABLE OF OPERATING FOR 10'S TO 100'S OF SECONDS IN THE RANGE OF 2500-2800 K FOR 5-10 THERMAL CYCLES. THESE PARTICLES HAVE BEEN PRODUCED BY B&W IN SIGNIFICANT QUANTITIES AND THE PROCESS IS WELL UNDERSTOOD. TESTING HAS INCLUDED BOTH IN-PILE AND OUT-PILE TESTS. THIS PARTICLE WOULD NOT SUSTAIN 2700 K FOR SEI APPLICATIONS.

2. WE ARE PRESENTLY DEVELOPING MIXED CARBIDE PARTICLES WHICH ARE DESIGNED TO REACH MAX. FUEL TEMPERATURES OF 3000-3400 K. THEY ARE DESIGNED TO OPERATE FOR 100'S TO 1000'S OF SECONDS. MIXED CARBIDES SUCH AS (U,2zr)C AND (U,3Nb)C WITH NiC COATINGS ARE BEING DEVELOPED. IT IS EXPECTED THAT THIS PARTICLE WILL WITHSTAND MORE THAN 10 THERMAL CYCLES AND SUSTAIN 2700 K EXIT GAS TEMPERATURE OR GREATER. THESE ARE CONSIDERED THE APD/B&W BASELINE SEI FUEL. B&W EXPECTS TO BE IN FULL PRODUCTION OF THESE PARTICLES WITHIN 1 YEAR.

3. UNDER REVIEW IS A PARTICLE DESIGN CONSISTING OF A POROUS UC KERNEL COATED WITH TUNGSTEN. B&W EXPECTS IT TO BE EASILY FABRICABLE, HAVE GREATER LONG TERM (1000'S OF SECONDS) RELIABILITY THAN CARBIDE FUELS, BE VERY RESISTANT TO THERMAL CYCLES IF KEPT ABOVE ABOUT 270 K, AND HAVE VERY GOOD FISSION PRODUCT RETENTION BUT BE LIMITED TO A MAXIMUM TEMPERATURE OF ABOUT 3000-3100 K.

4. IN THE EARLY STAGES OF LAB DEVELOPMENT ARE ADDITIONAL ADVANCED PARTICLE CONCEPTS WHICH ARE THEORETICALLY CAPABLE OF OPERATING FOR 1000'S SECONDS AT 3400 K AND MANY THERMAL CYCLES. IT IS EXPECTED THAT THESE COULD BE BROUGHT TO PRODUCTION READINESS IN SEVERAL YEARS.

FUEL PARTICLE PROVIDES
HIGH POWER DENSITY & TEMP

- 48 Liters of Fuel
- 33 MWt (ave)
- 500 Micron Dia.
- Loading:
  - 127 kg Uranium
  - 21 kg Carbon
  - 57 kg Zirconium
  - 60 kg Niobium
  - 265 kg Total Bed
- 73% Enrichment
- 3300+ K Melt Approx.

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NTP: System Concepts

NP-TIM-92
THE PBR NTRE IS THERMALLY STABLE

THE PBR IS THERMALLY STABLE. THE FUEL TEMPERATURE ON'T RAISE AT ABOUT 2900K WHEN THE MIXED MEAN GAS TEMPERATURE IS 2700K. THE AMOUNT OF LOCAL FLOW CAN BE REDUCED BY 15-22% BEFORE THE FUEL KERNEL REACHES ITS MELT TEMPERATURE. BASED ON THERMAL HYDRAULIC STABILITY STUDIES A LOCAL FLOW DISRUPTION DOES NOT CAUSE A PROPAGATION BUT RATHER A STABLE TRANSITION TO A NEW TEMPERATURE. THIS IS DUE TO THE HIGH REYNOLDS NUMBER AND TURBULENT REGIME OVER WHICH THIS PBR OPERATES. FOR HIGH POWER REACTOR OPERATION THE PBR IS QUITE STABLE (AS IS EXPECTED).

THERMAL HYDRAULIC INSTABILITY CAN OCCUR FOR LOW FLOW REGIMES (IE. LOW POWER). THE BED HYDRAULIC RESISTANCE, WHICH IS FORMED BY VISCOUS AND INERTIAL FORCES (TYPIFIED BY THE ERGUN CORRELATION) IS DOMINATED BY INERTIAL FORCES FOR HIGH POWER, HIGH FLOW OPERATION. HOWEVER, FOR LOW FLOW OPERATION THE VISCOUS TERM CAN DOMINATE. FOR SUCH CASES, A PERTURBATION IN FLOW CAN CAUSE INCREASED LOCAL GAS TEMPERATURE AND THUS HIGHER PRESSURE WHICH CAUSES HIGHER GAS TEMPERATURES... AND SO ON. B&W UNDERSTANDS THE MECHANISMS INVOLVED AND THE REGIMES OF OPERATION WHICH MUST BE AVOIDED. IT IS SHOWN THAT FOR A THREE DIMENSIONAL ANALYSES IT IS POSSIBLE TO RETAIN NEARLY ALL THE PBR PERFORMANCE (IMPULSE) WHILE THROTTLING TO 5-10% OF FULL FLOW. ANOTHER SOLUTION TO THE LOW FLOW INSTABILITY CAN BE FOUND BY REDUCING THE CHANGE IN GAS TEMPERATURE AS IT FLOWS THROUGH THE FUEL BED. BY INCREASING THE INLET GAS TEMPERATURE TO 450K, THE FLOW STABILITY CAN BE MAINTAINED EVEN FOR CONSERVATIVE ANALYSES.

The PBR NTRE is Thermally Stable

![Diagram showing fuel temp and percent of local coolant flow during main burns and cooling down](image)

*GenCorp, AEROSTAR, Energopool, Babcock & Wilcox*
FUEL DESIGN BALANCES REACTIVITY AND CONTROL

The reactor and fuel design is flexible. The 45 liter fuel volume was based on 33 MW/LITER Power density and 150 MW TOTAL POWER. The 36 fuel element core with 11 cm pitch and moderator composed of 82% beryllium, 8% ZrH, and 10% hydrogen coolant passages were based primarily on mechanical and thermo-hydraulic considerations, and physics trade-offs.

For high reactivity, the fuel particle maximizes uranium loading. The baseline particle is 70% UC/ZrC kernel surrounded by 30% NbC coating, by volume, and the kernel contains 10% UC. For average bed uranium density of 2.7 g/cc, it is expected the uranium loading will be reduced by 50% or more through optimization of the core. With fully enriched fuel, and no HIC HOT CHANNEL INSERTS, the maximum reactivity is 0.19 DELTA K/K. HIGH EXCESS REACTIVITY PROVIDES FLEXIBILITY FOR OPTIMIZING THE DESIGN, AND ALLOWS MARGIN FOR MODELING UNCERTAINTIES AND OVERCOMING REACTIVITY LOSSES DUE TO XENON TRANSIENTS AND FUEL DEPLETION DURING OPERATION.

Design variables to balance high reactivity and control are fuel particle uranium content, uranium enrichment, installed neutron poisons, moderator materials, fuel element pitch, and core reflector and controls design. Conical HIC INSERTS were placed in the hot channels to provide fixed neutron poison hold down of 0.07 DELTA K/K and 1% of total power in extra-hydrogen gas heating. HAFNIUM also provides resonance neutron absorption which will improve prompt temperature feedback, however, hydrogen flow distribution must compensate for the shift in axial power shape. The U238 Enrichment was also reduced, increasing the negative prompt temperature feedback of the fuel due to the Doppler coefficient of the larger fraction of U238. Increasing prompt nuclear feedback enhances the stability, and thus control and safety of the reactor. The final maximum reactivity of the conceptual design is 0.06 DELTA K/K. The controls have large reactivity worths. The safety rod worth of 0.17 DELTA K/K is somewhat higher than the control drums worth of 0.10 DELTA K/K.

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FUEL DESIGN BALANCES REACTIVITY AND CONTROL

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THE PBR IS DESIGNED FOR SAFETY

THE PBR WILL BE MAINTAINED SUBCRITICAL FOR ALL LAUNCH ACCIDENT SCENARIOS. PRELIMINARY ESTIMATES FOUND THAT, FOR THE CONCEPTUAL DESIGN, ADDITIONAL MITIGATING MEASURES ARE NEEDED IN ORDER TO MAINTAIN THE REACTOR SUBCRITICAL IF THE PRIMARY VOID REGIONS, THE COLD AND HOT CHANNELS, ARE FILLED WITH WATER AND THE REACTOR IS SURROUNDED BY WATER TO SIMULATE A WATER IMMERSION ACCIDENT. WHEN THE HOT CHANNELS ARE FILLED WITH TEMPORARY LAUNCH INSERTS MADE OF HIC, FOR EXAMPLE, THE CALCULATED REACTIVITY AFTER IMMERSION IS 0.22 DELTA-K/K (EFFECTIVE = 0.82). THE REACTIVITY PRIOR TO IMMERSION IS ABOUT -0.32 FOR THE UNCHANGED BASELINE DESIGN. THE REACTIVITY AFTER IMMERSION WAS 0.87 DELTA-K/K, WHICH IS CLEARLY UNACCEPTABLE. FOR THESE ESTIMATES, THE CHANGES IN THE VOID REGIONS OF THE HOT FRIT, COLD FRIT, FUEL BED, AND MODERATOR COOLING PASSAGES WERE NEGLECTED. IT WILL BE POSSIBLE, THROUGH ADDITIONAL STUDY, TO OBTAIN ACCEPTABLE RESULTS WITHOUT RESORTING TO TEMPORARY LAUNCH INSERTS BY MAKING OTHER MODIFICATIONS. FOR EXAMPLE, WITH CHANGES IN PITCH AND/OR MODERATOR HYDROGEN CONTENT, BALANCED BY DECREASES IN PARTICLE URANIUM CONTENT AND/OR ENRICHMENT. IT WILL BE POSSIBLE TO OBTAIN A MORE NEUTRONICALLY OPTIMUM INITIAL CORE CONDITION, SUCH THAT THE WATER IMMERSION WILL RESULT IN EITHER OVER-MODERATION AND A DECREASE IN REACTIVITY, OR AT LEAST A SMALLER INCREASE IN REACTIVITY. THESE SAME CHANGES WILL ALSO HELP MITIGATE POTENTIAL REACTIVITY INCREASES DUE TO ANY EXCESSIVE HYDROGEN GAS DENSITY IN THE CORE DURING STARTUP OR TRANSIENTS.

BASED ON PITCH TRADE STUDIES PERFORMED USING DIFFERENT PITCH THICKNESSES, THE IMPACT OF GEOMETRY CHANGES ASSOCIATED WITH A LAUNCH ACCIDENT (E.G. DEFORMATION OR COMPACTION) IS EXPECTED TO BE LESS SEVERE THAN THE WATER IMMERSION. THE NEUTRONIC OPTIMIZATION DISCUSSED ABOVE WILL SERVE TO MITIGATE THIS EVENT AS WELL.

THE PBR IS DESIGNED FOR SAFETY

- **NUCLEAR CRITICALITY**
  - Subcritical in Water Immersion
  - 0.82 Keff using hot frit plugs
  - Two Independent Shut-down Systems
  - Recuperator Prevents Excessive Hydrogen reactivity insertion in core (i.e. no 1.12)

- **THERMAL PROTECTION**
  - Five Systems to Cool the Reactor
    - Twin Turbopumps (70 % full flow capacity each)
    - One Electrical Pump (Approx. 5 % capacity)
    - One Circulation Pump (Several Megawatt cap.)
    - Tank Bleed
  - Cross Feed Is an Option

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THE PBR IS SCALABLE IN POWER DENSITY.

The PBR can operate over a wide range of power densities. For power densities above 33 MW/l, there is only a small improvement in reactor mass. The knee in the curve appears to be around 20 MW/l. The lower exhaust gas temperature (2500K) does not have a significant impact on reactor mass but will impact performance in terms of impulse and therefore hydrogen tankage. The lower chamber pressure reactor (1000 psi) appears attractive from a reactor mass standpoint, however, the reduction in reactor mass will almost certainly be negated by the increase in shield mass since the vessel is larger.

The key features of the 33, 20 and 10 MW/l reactors are:

**SCALABILITY - Power Density**

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<th>Feature</th>
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<tr>
<td>Reactor Power</td>
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<tr>
<td>Reactor Mass</td>
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<td>2,270</td>
<td>1,807 kg</td>
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<tr>
<td>Fuel/Inlet Temp</td>
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<td>2,600 K</td>
<td>2,600 K</td>
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<tr>
<td>Fuel Volume</td>
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<tr>
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<td>Reactor Fuel Mass Length</td>
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</table>

The PBR is Scalable in Power Density

Reactor Mass (kg)

Power Density (MW/l)

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THE PBR IS SCALABLE WITH THRUST

**SCALABILITY**

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<th>Metric</th>
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<th>Reactor Power</th>
<th>Reactor Mass</th>
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<th>Outlet Gas Temp</th>
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<td>18</td>
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The PBR is Scalable with Thrust

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NP-TIM 92 319 NTP: System Concepts
THE FUEL IS THE NTRE's KEY TECHNOLOGY

THE PARTICLE BED REACTOR IS UNIQUE BECAUSE OF THE FUEL FORM. ITS SMALL SIZE MEANS THAT IT IS COMPLETELY "PRE-CRACKED". THE DIAMETER OF THE FUEL PARTICLES ARE NEARLY AS SMALL AS THE MANUFACTURING PROCESS WILL ALLOW. OVER 10 MILLION PARTICLES ARE CONTAINED WITHIN EACH OF 36 FUEL ELEMENTS. BECAUSE THE FUEL PARTICLES ARE SO SMALL THE STRESSES WITHIN THE PARTICLES ARE REDUCED AND THEREFORE THE RELIABILITY IS IMPROVED. HIGHLY STRESSED FUELS FORMS WILL FAIL DURING OPERATION.


FINALLY, THOUSANDS OF INDIVIDUAL PARTICLES CAN FAIL WITH LITTLE OR NO EFFECT ON REACTOR PERFORMANCE. WHEREAS MONOLITHIC FUEL FORMS MAY NOT DEGRADE SO GRACEFULLY.

THE FUEL IS THE NTRE's KEY TECHNOLOGY

FUEL FORM AND ARRANGEMENT FAVOR
FISSION PRODUCT RETENTION

PBR FUEL FORM IS ATTRACTIVE BECAUSE:
- Design options permit reduction of fission product retention with additional coatings
- Individual particle failures have little or no effect on reactor performance
- Particles have low thermal gradients (small size)

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NP-11M-92
CONCLUSIONS

The results of this work indicates that the PBR design meets all the NASA requirements. The recuperated PBR appears to be well suited for the SEI mission. Throughout the design process, trades were performed to find appropriate blends of safety, reliability and strong robust components. Very few optimization studies were performed to exceed the performance requirements but it is believed that significant gains can be accomplished from such optimization. The PBR technology appears to be capable of very high performance.

CONCLUSIONS

The PBR Design has been Successfully Adapted for the SEI Mission

- High Performance *(with mass penalties)*
- Throttling Capability *(>>4:1)*
- Superior Decay Heat Removal System
- Integrated into Practical Engine Design
- High Reactivity, Control and Safety

GenCorp - Energopool - Babcock & Wilcox
CIS Engine Design
Don Culver

Our CIS engine concept is best summarized by including the rationale behind the selection of each major subsystem concept or operating parameter. 2900 K mixed mean reactor outlet gas temperature is selected to meet the 4.5 hour life requirement with an appropriate margin by the end of fuel assembly development. The engine design/operating selection of 300:1 nozzle area ratio and nozzle inlet pressure of 2,000 psia is the result of a Mars mission payload trade study; it gives the best combination of engine specific impulse and weight. A recuperated turbopump drive cycle was selected for several reasons: (1) nozzle inlet pressures of 1000 psia and above are enabled by recycling topping heat through the turbine, and no reactor manifolding need be added to extract turbine drive heat directly from the core, (2) engine start and shutdown transients are smoothed and assolated by the large, available heat capacity of the high surface area recuperator, (3) the steel heat exchanger adds no weight to the engine, because its weight is determined by its other duties as the forward closure of the reactor vessel. An aft core support structure was selected, because it has been shown by test that CIS fuel assembly life is superior when held in compression. A single DeLaval nozzle is selected that is internally cooled with hydrogen; no hydrogen bleed is necessary, because our formed platelet nozzle operates with low internal wall temperatures at high heat fluxes. A 40 Kbt nozzle of similar design, material and coolant is now in test at NASA. The nozzle is small, because of the engine’s high operating pressure, and we use a low weight, carbon-carbon nozzle extension. Its surface may be converted to ZrC to improve its life in hydrogen environment, using near term technology processes similar to those in work at Aeroljet, however this is probably unnecessary, because total surface recession in 4.5 hours of operation is expected to be less than 0.025 in. (0.64 mm). A borated ZrH and LiH neutron shield is located within the reactor vessel, between the core and recuperator/gamma shield. It is cooled by propellant flow in steel waters located between its many transverse layers.

Design Rationale for NTRE With CIS Reactor Is Clear

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 H₂ Mixed Mean Outlet Temperature (2,900K)</td>
<td>Expected 4.5 Hours Fuel Life (Demoed &gt; 1 Hour at 3000K)</td>
</tr>
<tr>
<td>2 Pc (2,000 psia)</td>
<td>Best Mars Mission Performance With Reusable Engines</td>
</tr>
<tr>
<td>3 Ae/Al (300)</td>
<td></td>
</tr>
<tr>
<td>4 Power Cycle (Recuperated)</td>
<td>· Enable High Pressure With Simple Reactor · Enhances Transient Operation · No Weight Penalty (γ Shield)</td>
</tr>
<tr>
<td>5 Core Support (aft)</td>
<td>Optimum With CIS FAs (Test Data)</td>
</tr>
<tr>
<td>6 Nozzle (Single DeLaval) (H₂ Cooled Without Bleed Flow) (C-C Extension)</td>
<td>Near Term Technology Use (Formed Cu Platelet)</td>
</tr>
<tr>
<td>7 Neutron Shield (Internal)</td>
<td>Lowest Weight and Risk</td>
</tr>
</tbody>
</table>

GenCorp Aeroljet
- Energopool - Babcock & Wilcox

NTP: System Concepts 322
Reactor gas outlet temperature for our CIS engine was selected by analyzing fuel assembly in-reactor test data. Fuel assembly tests demonstrated lifetimes of 4000 hours at gas outlet temperatures averaging 2000 K and lifetimes of 4000 seconds at gas outlet temperatures between 3000 K and 3100 K. An Arrhenius law study was applied to the data to predict lifetimes at other outlet temperatures. This work showed that fuel assembly lifetimes of 4.5 hours had been demonstrated at mean outlet gas temperatures of about 2800 K. In-reactor tests did not terminate with destroyed fuel assemblies, however, and Russian scientists have estimated the lifetime demonstrable with a three to five year fuel assembly development program to be about 2.8 hours with 3000 K outlet gas temperature. Arrhenius analysis shows this corresponds to a 4.5 hour life at gas temperatures above 2900 K. Thus, 2900 K nozzle inlet temperature was selected to provide the greatest mission benefit within current NASA life requirements.

### CIS Fuel Life is Expected to Be 4.5 Hours at 2900°K

<table>
<thead>
<tr>
<th>Tc in °K</th>
<th>Minimum Achieved Life (Hours)</th>
<th>Maximum Achieved Life (Hours)</th>
<th>Life Expected in 3-5 Years (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3200</td>
<td>0.400</td>
<td>0.700</td>
<td>1.000</td>
</tr>
<tr>
<td>3100</td>
<td>0.655</td>
<td>1.111</td>
<td>1.637</td>
</tr>
<tr>
<td>3000</td>
<td>1.111</td>
<td>1.820</td>
<td>2.778</td>
</tr>
<tr>
<td>2900</td>
<td>1.954</td>
<td>3.100</td>
<td>4.855</td>
</tr>
<tr>
<td>2800</td>
<td>3.579</td>
<td>5.470</td>
<td>8.348</td>
</tr>
<tr>
<td>2700</td>
<td>6.856</td>
<td>10.05</td>
<td>17.14</td>
</tr>
<tr>
<td>2600</td>
<td>13.80</td>
<td>19.45</td>
<td>34.50</td>
</tr>
<tr>
<td>2500</td>
<td>19.40</td>
<td>39.57</td>
<td>73.56</td>
</tr>
<tr>
<td>2400</td>
<td>66.67</td>
<td>35.40</td>
<td>166.7</td>
</tr>
<tr>
<td>2300</td>
<td>162.4</td>
<td>197.1</td>
<td>406.0</td>
</tr>
<tr>
<td>2200</td>
<td>428.7</td>
<td>480.7</td>
<td>1072</td>
</tr>
<tr>
<td>2100</td>
<td>1.242</td>
<td>1.333</td>
<td>3.105</td>
</tr>
<tr>
<td>2000</td>
<td>4.000</td>
<td>4.000</td>
<td>10.000</td>
</tr>
</tbody>
</table>

*Life = Ke^{Tc/Tc0} (Arrhenius Law)*

[Image of table with data]
The CIS engine's turbopump is powered by a topping cycle so that no specific impulse is lost through turbine exhaust overboard bleed flows. In this power cycle reactor heat that is deposited in engine components (and must be removed continuously) is removed by the hydrogen propellant, heating pump discharge flow to energy levels high enough to drive the turbines. About 9% of the reactor heat is removed, directly or indirectly, from the engine's nozzle, moderator, reflector, pressure vessel, and radiation shields. However, about 12% of the reactor heat is needed to drive the engine to a nozzle inlet pressure of 2000 psia with adequate (10%) power control margin and reasonable operating conditions for all engine components.

The power cycle requires a liquid hydrogen pump discharge pressure of 4950 psia. We have elected to use two 15,000 horsepower turbopumps in parallel. About 1/6 of the total flow (13 lb/sec) cools the copper nozzle to area ratio 10. The balance of the hydrogen is heated to turbine inlet conditions in the high pressure side of the recuperator (heat exchanger). The turbine inlet temperature is about 850 R (470 K), and the turbine pressure ratio is less than 1.6. Turbine exhaust flow internally cools the walls of the reactor vessel and joins with the nozzle coolant flow at the end of the reactor core. Here, the 775 R (430 K) flows join and cool the moderator rods and side wall neutron reflector with parallel flows, exiting at about 150 R (40 K). These gases rejoin and 100% of the propellant flows through the low pressure side of the recuperator. There it loses over 670 R (370 K) temperature to the high pressure flow for turbine drive power. The cool, recuperator outlet gas is distributed to the 102 fuel assembly inlets via the internal neutron shield. Fuel assemblies provide about 93% of the reactor's 1650 MW(e) power to the propellant, so that its maximum exit temperature is 5220 R (2900 K) at a pressure of 2000 psia. This gas flows through the DeLaval rocket nozzle to space.

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**CIS TOC Recuperated Topping Cycle Flow Schematic**

![Flow Schematic Image](image-url)

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GenCorp Energopool Babcock Wilcox

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The CIS engine flow scheme begins with two parallel turbopumps. Pump discharge flow splits into two streams; the smaller one cools the copper nozzle through internal passages as in a regeneratively cooled nozzle for bipropellant rocket engines. The nozzle support is cooled by a small portion of this flow. The larger pump discharge flow enters the center of the recuperator/gamma shield located at the forward end of the reactor vessel, distributes to thousands of parallel flow, high pressure passages, and flows radially outward to a peripheral manifold. This heated hydrogen gas flows to and through the turbopump’s turbine, the exhaust being routed to an inlet manifold on the aft section of the reactor vessel wall. This flow cools the wall internally as it moves aft to join the nozzle coolant at the aft core support structure. 100% of the propellant flows through this structure, cooling it and the aft peripheries of the 102 fuel assemblies. Propellant is metered forward from the support structure through the reactor’s moderator and reflector sections in parallel, collecting in a plenum at the forward end of the core. Here, gas flows radially outward to cooling channels in the forward section of the reactor vessel wall. Propellant flows forward to the periphery of the recuperator, where it enters low pressure, radial inflow heat exchanger passages. Cooled hydrogen leaves the aft face of the recuperator’s center and distributes axially through the two layers of the plate-type neutron shields. Propellant flows radially outward through these shields inside of metallic platelets to discharge at the inside wall of the reactor vessel. Hydrogen flows to the fuel assembly inlet plenum and into the 102 inlets, where it is heated to maximum temperature and flows aft into the rocket nozzle inlet and through the nozzle to space.
CIS Engine Layout

Thrust, lbf
Chamber Pressure, psia
Nozzle Area Ratio, Aa/A
Engine Specific Impulse, sec
Mars Mission Specific Impulse, sec
Engine Total Weight, lbm
Thrust/Weight
Engines per Vehicle
Payload Returned to Earth, lbm

Engine Weight Breakdown

Component
Uncooled Nozzle
Cooled Nozzle
Pressure Vessel, Reactor Manifolds & CSS
Reactor, Reactor I&C
Turbopump Assemblies (2)
Recuperator / Shield
Secondary Shield
Plumbing/Valves
Controls and Shielding

NTRE w/ Stage Power/Heat Removal
Stage Power & Heat Removal Sys W, lbm
Engine with Power Sys W, lbm
Mars Mission Specific Impulse, sec
Payload Returned to Earth, lbm

Component
Weight, lbm
232
965
2536
6613
410
2435
642
1320
758
2000
17900
942
52929

GenCorp
Aerojet
Energopool
Babcock & Wilcox
CIS Reactor Design

Richard Rochow

Reactor Design Summary

- Heterogeneity of the Core
- Average Specific Power Density in FE - 20 MW/1
- Fuel-Elements Twisted Rods on the Base of Solid U-Zr-Nb Carbide Solutions
- Neutron Moderator - Zirconium Hydride Rods
- Controls - 18 Drums in Reflector and 1 Rod in Core
- 7 Safety Rods in Core Against Water Filling Accident
- Reflectors - Be
- Internal Shielding - ZrH(B); LiH, Recuperator Steel

NIP: System Concepts
Main Characteristics of NRE Reactor

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Power, MW</td>
<td>1650</td>
</tr>
<tr>
<td>Neutron Spectrum</td>
<td>Thermal</td>
</tr>
<tr>
<td>Average Exit Temperature of Propellant, K</td>
<td>2900</td>
</tr>
<tr>
<td>Propellant Pressure in Nozzle Chamber, bar</td>
<td>136</td>
</tr>
<tr>
<td>Propellant Flow Rate, kg/s</td>
<td>35.4</td>
</tr>
<tr>
<td>Reactor Dimensions, mm:</td>
<td></td>
</tr>
<tr>
<td>- Diameter</td>
<td>1050</td>
</tr>
<tr>
<td>- Height (including inner shielding)</td>
<td>2100</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>5800</td>
</tr>
</tbody>
</table>

NRE Reactor Components Mass (kg)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core:</td>
<td></td>
</tr>
<tr>
<td>- FAs</td>
<td>1250</td>
</tr>
<tr>
<td>- Moderator</td>
<td>710</td>
</tr>
<tr>
<td>Reflector</td>
<td>600</td>
</tr>
<tr>
<td>Inner Shielding:</td>
<td></td>
</tr>
<tr>
<td>- Zirconium Hydride</td>
<td>430</td>
</tr>
<tr>
<td>- Lithium Hydride</td>
<td>120</td>
</tr>
<tr>
<td>- Recuperator Material (Steel)</td>
<td>1100</td>
</tr>
<tr>
<td>Rotating Drum Drives (18)</td>
<td>360</td>
</tr>
<tr>
<td>Safety Rod Drives (7)</td>
<td>80</td>
</tr>
<tr>
<td>Supporting Structure</td>
<td>300</td>
</tr>
<tr>
<td>Pressure Vessel</td>
<td>850</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5800</strong></td>
</tr>
</tbody>
</table>

CIS/NTRE Cross Section

*GenCorp, Energopool, Babcock & Wilcox*
**Main Core Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U Loading, kg</td>
<td>14.1 kg</td>
</tr>
<tr>
<td>$^{235}$U Enrichment, %</td>
<td>90%</td>
</tr>
<tr>
<td>Average Specific Power Density in FE, MW/liter</td>
<td>20</td>
</tr>
<tr>
<td>Non-Uniformity Power Release</td>
<td></td>
</tr>
<tr>
<td>- With the Core Radius</td>
<td>1.2</td>
</tr>
<tr>
<td>- With the Core Height</td>
<td>1.2</td>
</tr>
<tr>
<td>Thermal Neutron Flux Density, cm$^{-2}$S$^{-1}$</td>
<td>$1.5 \times 10^{15}$</td>
</tr>
<tr>
<td>Core Dimensions, mm</td>
<td></td>
</tr>
<tr>
<td>- Diameter/Height</td>
<td>750/1000</td>
</tr>
</tbody>
</table>

**CIS/NTRE Reactor Cross Section**

- **Central Drum**: Central Drum (CD)
- **Fissile Material**: Fissile Material (FM)
- **Moderator**: Moderator (MD)
- **Pile**: Pile (PL)
- **Safety Rod**: Safety Rod (SR)
- **Side Reflector**: Side Reflector (SR)
- **Fuel Assembly**: Fuel Assembly (FA)
- **Fissile Fissile Material (FFM)**

*GenCorp - Energopool - Babcock & Wilcox*

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NTP: System Concepts

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Fuel Assembly Description

Max. FA Thermal Power: Up to 22 MW
FE per FA: 356
Pressure Drop: 40 bar
Max. Mass Flow Rate: 0.42 kg/s

FA Dimensions, mm:
- Fuel Bundle Length: 100
- Fueled Length: 1000
- Bundle Diameter: 45
- Overall Length: 1500
- Overall Diameter: 55
Mass: 12 kg

Fuel Assembly Performance Exceeds Engine Requirements

<table>
<thead>
<tr>
<th>Fuel Element</th>
</tr>
</thead>
</table>

Required Performance Parameters

<table>
<thead>
<tr>
<th></th>
<th>T10, °K</th>
<th>ts</th>
<th>ΔT/Δt</th>
<th>qv (MW/L)</th>
<th>Propellant</th>
<th>No. (Start)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerojet Engine</td>
<td>2900-3000</td>
<td>1000</td>
<td>25</td>
<td>H2</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>In-Pile Tests</td>
<td>3000-3150</td>
<td>1500</td>
<td>-400</td>
<td>25</td>
<td>H2</td>
<td>3</td>
</tr>
<tr>
<td>Max. Parameter Values (in-Reactor)</td>
<td>3100</td>
<td>4000</td>
<td>Up to 1000</td>
<td>35</td>
<td>H2</td>
<td>12</td>
</tr>
</tbody>
</table>

IVG-1 Performance Parameters

<table>
<thead>
<tr>
<th>Start-up</th>
<th>T25, °K</th>
<th>ts</th>
<th>ΔT/Δt</th>
<th>qv (MW/L)</th>
<th>Propellant</th>
<th>Power, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3170</td>
<td>-500</td>
<td>100...150</td>
<td>-22.5</td>
<td>H2</td>
<td>4.74</td>
</tr>
<tr>
<td>2</td>
<td>3110</td>
<td>-500</td>
<td>100...150</td>
<td>-22.5</td>
<td>H2</td>
<td>4.81</td>
</tr>
<tr>
<td>3</td>
<td>3030</td>
<td>-500</td>
<td>100...150</td>
<td>-22.5</td>
<td>H2</td>
<td>4.05</td>
</tr>
</tbody>
</table>

No Fuel Technology Improvements Required
Fuel Element Description

<table>
<thead>
<tr>
<th>Composition</th>
<th>UC + ZrC + NbC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Fuel Loading of U</td>
<td>Up to 20%</td>
</tr>
<tr>
<td>Enrichment</td>
<td>90%</td>
</tr>
<tr>
<td>Max. Design Temperature (at Hot End)</td>
<td>3500 K</td>
</tr>
<tr>
<td>Operational Temperature (at Hot End)</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>2950 K</td>
</tr>
<tr>
<td>- Maximum</td>
<td>3100 K</td>
</tr>
<tr>
<td>Average Power Density</td>
<td></td>
</tr>
<tr>
<td>- In FE</td>
<td>20 kW/cm³</td>
</tr>
<tr>
<td>- In FA</td>
<td>12 kW/cm³</td>
</tr>
<tr>
<td>Amount FA Tested at H₂ Above 2,900 K</td>
<td>More than 10,000</td>
</tr>
</tbody>
</table>

Fuel Element Heating Bundle From IVG Reactor
Reactivity and Control Characteristics

1. Maximum Reactivity Margin, % $\Delta K$  
   4.2

2. Reactivity Effects, %  
   - Doppler Effect and Effect of Moderator Temperature $-1.0$  
   - Hydrogen Filling Effect $+0.6$  
   - Fuel Burn Up Effect (Compensated by Burning Poisons) $-0.4$  
   - Water Filling Effect $+7.4$

3. Control System Efficiency, %  
   - 18 Drums 3.0  
   - 7 Safety Rods in “dry” Reactor 18.7  
   - 7 Safety Rods in “wet” Reactor 8.3  
   - Central Rod (in function of regulator) 2.7

4. Poisoning Material of Controls $B_4C$

AEROJET/ENERGOPOOL/B&W NTRE  
NASA LeRC Final Report

Prepared by R.F. Rochow  
Babcock & Wilcox, ASE  
Oct 23, 1992
CIS CAPABILITIES

NUCLEAR REACTORS

- IVG-1 3100K, 240 MW
- IRGIT 2650K, 60 MW
- IGR 3100K, 35 MW
- Critical Reactors
- Shielding Test Reactors
- Materials Test Reactors

NUCLEAR REACTORS

DESIGN

- 250,000 Man-years of NRE Design/Test
- 30 Years Experience

MANUFACTURING

- Fuel Line 2 Cores/yr
- Insulating Mat's ZrC,NbC
- Bulk Fabrication ZrH, LiH
- Single Crystal Technology

TEST FACILITIES

- Baikal-1 IVG-1, IRGIT
- Plasmotron 100 MW
- Creep Test Rig 200 kW
- Corrosion Tester 250 kW
- Failure Mode Rig 100 kW

CIS REACTOR DESIGN PHILOSOPHY

- Heterogeneous Core
- Solid Carbide Solution "twisted ribbon" Fuel Elements
- Zirconium Hydride Moderator Rods
- ZrH(B) and LiH Internal Shielding
- Core Support at Hot End
- 12 MW/l Ave. Fuel Bundle Power Density
The CIS Reactor Utilizes Demonstrated Hardware

**REACTOR SUMMARY: KEY SPECS**

- Reactor Size: 1.00 GW
- Thrust (204 Lmoz): 25,000 lb
- Gas Outlet Temp (maximum): 2900 K (4200 °F)
- Propellant Flow Rate: 28 lb/sec
- Specific Impulse: 9500 seconds
- Fuel Composition: U,Nb,Zr6
- Fuel Form: "Twisted Ribbon"
- Fuel Burnup: Power Density: 12 MW/l
- Core Power Density: 4.7 MW/l
- Fuel Volume: 16 liters
- Number of Assemblies of Elements: 102
- Safety Shell: 6 Safety Rods
- Vessel Diameter: 1.05 meters
- Reactor Fueled Length: 100 cm
- Reactor Mass (without propellant): 4150 kg (9180 lb)

**GENCORP**

**Energopool**

**Babcock & Wilcox**

**AERODYN**

**Original page is of poor quality**
FUEL ELEMENT DESIGN HAS BEEN REFINED

**Numerous Materials and Fuel Forms Tested**
- Carbides
- Carbonitrides
- W, Mo, Re
- Graphite Carbides
- Particles (1-8 mm Dia.

**More Than 10,000 "Twisted Ribbons" Tested Above 2700 K**

5000 K for thousands of seconds in H2: Demonstrated

**Fuel Element Specifications**
- **Composition**: (U,Zr,Nb)C
- **Max. Uranium Loading**: 20%
- **Enrichment**: 90%
- **Max. Design Temp.**: 3,500 K
- **Max. Operating Temp.**: 3,100 K
- **Power Density**: in Fuel Element 20 MW/I
  in Fueled Volume 12 MW/I

FUEL ASSEMBLY DESIGN HAS BEEN REFINED

**Fuel Assembly Specifications**
- **Max. Thermal Power**: 22 MW
- **Pressure Drop Nom**: 40 bars
- **Mass Flow (max.)**: 0.42 kg/s
- **Mass**: 12 kg
- **Dimensions**:
  - Fueled Length: 1.0 m
  - Fueled Diameter (round): 48 mm
  - Overall Length: 1.5 m
  - Overall Diameter: 55 mm
REACTOR RADIAL CROSS-SECTION

REACTOR LONGITUDINAL CROSS-SECTION
CORE SUPPORT STRUCTURE

INTERNAL SHIELD CONFIGURATION

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ORIGITAL PAGE IS OF POOR QUALITY
Energopool companies have tested NTRE fuel assemblies in reactors with hydrogen outlet temperatures as high as 3100 K. At the highest temperature the assemblies have been tested successfully for 4000 seconds including 12 starts or thermal transients. Thermal transient rates of about 400 K/sec have been used, but a single start-up rate as high as 1000 K/sec was observed without incident. Fuel assemblies have been shown to resist long duration vibration and high impact loads without critical damage. Fuel power density has been demonstrated to 25 Watt/liter, or about 15 Watt/liter of fuel bundle volume.

Based on results to date, Russian scientists estimate that their fuel assemblies will be able to demonstrate better performance and life within a 3 to 5 year demonstration program. Such improvements can lead to higher performance, lower weight, longer life, rocket engines.

Russia Has Fuel Elements and Fuel Assemblies for NRE Reactor and Plans to Improve Them

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NERVA Nerva Reactor</th>
<th>Achieved</th>
<th>Expected in 3-5 Years</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Temperature, °K</td>
<td>2550</td>
<td>3000</td>
<td>&gt; 3,200</td>
<td></td>
</tr>
<tr>
<td>Specific Impulse, S</td>
<td>850</td>
<td>975</td>
<td>&gt; 1000</td>
<td></td>
</tr>
<tr>
<td>Life-Time, Seconds</td>
<td>3600</td>
<td>4000 s in Hydrogen at T = 3000 K</td>
<td>~10,000 s in Hydrogen at T = 3000 K</td>
<td>~30,000 s in Hydrogen at T ≥ 2800 K</td>
</tr>
<tr>
<td>Power Density, Mw/Litre</td>
<td>2.5</td>
<td>25</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>H₂ Temperature Transient, °K/sec</td>
<td></td>
<td>400</td>
<td></td>
<td>~1,000</td>
</tr>
<tr>
<td>Number of Starts-Ups</td>
<td>12</td>
<td>12</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Vibro-Strength g/Frequency (Hz)</td>
<td>16/ Up to 3 KHz/50 hrs</td>
<td>300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Russians have developed several families of high temperature nuclear fuel and have tested them in many ways in material laboratories, nuclear reactors, and in hot cells for post-irradiation properties. Carbide fuels have demonstrated the highest temperature capabilities with good material properties. U, Zr, Nb tricarbide alloys are selected for NTRE fuel, the exact composition depending on core location. Low uranium concentration is used in the highest temperature, all fuel bundles, and in the center of the core to flatten the radial power distribution profile. The favored geometry of individual fuel elements is that of thin, twisted strips. Coatings of carbides, nitrides, carbonitrildes and pyrocarbon mixtures of tungsten, molybdenum, and rhenium have been developed and tested for corrosion resistance and thermal strength characteristics.
Engeropool fuel assemblies for NTRE are about a meter long and 30 to 45 mm in diameter. The forward, inlet end runs cooler than the rest of the assembly, and it contains an adjustable flow metering orifice, neutron reflector, and thermal expansion compliance (bellows). The center of the fuel assembly contains several bundles of fuel elements placed in series, flow passing through each sequentially, so that the hottest gas exits the aft end of the last bundle. A grid plate holds the fuel element bundles in place and allows the hot gas to pass through to the outlet plenum of the fuel assembly. Each grid plate resembles fuel bundles, except that the carbide elements are fused together and contain no uranium. The outlet plenum delivers gas to either a DeLaval rocket nozzle or to a subsonic diffuser (selected for our Mars engines). The outer envelope is metallic and hydrogen cooled within the reactor, and it is insulated internally with several layers of graphitic material.

Each Fuel Assembly Is a Fully Integrated Unit

![Diagram of fuel assembly](image)

Types and Parameters of Fuel Elements

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat</td>
<td>D = 1.6, B = 0.1</td>
</tr>
<tr>
<td>2</td>
<td>Round</td>
<td>D = 2.5, B = 0.1</td>
</tr>
<tr>
<td>3</td>
<td>Square</td>
<td>D = 3.0, B = 0.1</td>
</tr>
</tbody>
</table>

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NTP: System Concepts

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Fuel assemblies have been tested in the steady state nuclear reactor, IVG-1, both singly and in clusters of seven in hydrogen, and under high temperature and pressure at thermal neutron fluxes above $10^{15}$ neutrons/cm²-sec.

**Typical Test Arrangements of Fuel Assemblies in IVG-1 Reactor**

 Obtained Conditions of Tests

1. Power of 1 FA ≤ 11 MW
2. Temperature of $H_2 ≈ 3100K$
3. Power Density $q_{\text{max}}^\text{max} ≈ 35$ MW
4. Heat Flux $q_{\text{max}}^\text{max} ≈ 13$ MW/m²
5. $H_2$ Temperature Transient 150°K/s
6. Reactor Start Per Month, 2
7. Thermal Neutron Flux = $2\times10^{15}$ neutrons/cm²-sec

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NTP: System Concepts
Many reactor materials have been fabricated and tested by Energopool in laboratories, in reactors, and in post-irradiation hot cells. Structural, neutron moderating, neutron reflecting, and neutron absorbing materials have been tested to high fluxes, fluences, temperatures, and immersion times in hydrogen and other media.

### Materials Testing Results

<table>
<thead>
<tr>
<th>Materials</th>
<th>Test Parameters</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel and Its Alloys (18 Types)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be, Be-Al, Be with Coatings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZrH, ZrH + B, LiH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorbing Elements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutrons cm²/s</th>
<th>Neutrons cm²</th>
<th>T, °K</th>
<th>Life-Time, Hours</th>
<th>Medium</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10¹³</td>
<td>up to 3 x 10²⁰</td>
<td>77...1100</td>
<td>500 - 12,000</td>
<td>H₂, He</td>
<td></td>
</tr>
<tr>
<td>10¹⁴</td>
<td>up to 2 x 10²¹</td>
<td>77...1200</td>
<td>500 - 2,400</td>
<td>H₂, He</td>
<td>H₂O Vacuum</td>
</tr>
<tr>
<td>10²⁻¹⁰³</td>
<td>up to 2 x 10²¹</td>
<td>400...1,000</td>
<td>500 - 12,000</td>
<td>H₂O, He</td>
<td></td>
</tr>
<tr>
<td>10²⁻¹⁰⁴</td>
<td>up to 2 x 10²¹</td>
<td>600...1,300</td>
<td>500 - 10,000</td>
<td>H₂, He</td>
<td></td>
</tr>
<tr>
<td>4 x 10⁻¹⁹</td>
<td>up to 2 x 10²¹</td>
<td>400...1,000</td>
<td>500 - 12,000</td>
<td>H₂O, He</td>
<td></td>
</tr>
</tbody>
</table>

During Some Experiments T = 20°K
qᵥ = 150 W/cm³
qₚₑₓₘₐₓ = 700 W/cm³
The experimental capability of Engeropool is rather complete. Between six companies they have experienced analysis, design, manufacturing, and test personnel. Energopool has facilities that cover the range of critical assemblies, shielding investigation, material and equipment manufacturing, reactor safety analysis, and many testing laboratories. These laboratories include facilities for material investigation in pre, in-pile, and post-irradiation environments, hot cells, and a variety of research reactors for fuels investigation.

**Experimental Capabilities of CIS Test Facilities for Validation of NRE Reactor Development (Carried Out Tests)**

- **EWG-1 Reactor**
  - J E SIA "Luch"
  - 300 FAc Tested
  - $T = 2500 \text{ to } 3500 \text{ K}$
  - $t = 4000 \text{ sec}$
  - Multiple Cycles
  - Failures Not Observed

- **IGR Reactor**
  - J E SIA "Luch"
  - $U = 600 \text{ K/s}$
  - $P = 35 \text{ MW/t}$
  - $T = 3100 \text{ K}$

- **IGT Reactor**
  - $T = 2500 \text{ K}$
  - $N = 60 \text{ MW}$

- **IA Reactor**
  - J E SIA "Luch"
  - $T = 2300 \text{ K}$
  - Inert Media
  - $t = 8000 \text{ hr}$

- **Electricity Thermal Benchmarks**
  - SIA "Luch"
  - $T = 3400 \text{ K}$
  - $H_2$, Vacuum

- **IVV-2M Reactor**
  - SIA "Luch"
  - $U = 70 \text{ to } 1000 \text{ K}$, $\varphi = 10^{17} \text{ cm}^{-2} \text{s}^{-1}$
  - Moderator and Structural Materials
  - Absorbing Materials: $T = 1500 \text{ K}$, $\varphi = 10^{12} \text{ cm}^{-2} \text{s}^{-1}$
  - $H_2$ Media

**Design and Manufacturing**

- **Design**
  - 250,000 Man Years
  - To Date
  - 30 Years Experience

- **Manufacturing**
  - SIA "Luch"
  - 1 Core/Year
  - Reactor Components
    - (Including Shielding)
  - Plant
  - SB RDIPE
  - 90% Complete (Full Set of Equipment)
  - 1 Set/Year

- **NRE Reactor for Mars Mission**

- **RI-50 Reactor**
  - RDIPE
  - VVR Reactor
  - SC "Kurchatov Institute"
  - Shielding Investigation

- **Critical Assemblies**
  - SC "Kurchatov Institute" and RDIPE

**NTP. System Concepts**

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Our Integrated Engines Provide

Safety and Reliability  •  Simple Thermodynamic Cycle
  •  Integrated Auxiliaries Simplify Propulsion
    – Start System
    – RCS (No Igniters, O2, Combustion)
    – Electric Power and H2 Refrigeration
    – Four Core Cooling Systems
  •  Improved Engine Start (Preheat)
    – No Thermal Shocks
    – Enhances Multiple Engine Safety
    – No LH2 In Core (Reduced Reactivity Insertion)
    – Thermal and Acoustic Damping
    – Assured Restart
  •  High Margins – Long Life
    – Low Fuel Temp and Stress (4600°F)
    – Low Turbine Temperature (400°F)
    – Low Nozzle Temperature (600°F)
    – Low Moderator Temperature (400°F)
    – No Deep Thermal Cycles
Our Integrated Engines Provide

**Mission Benefits**
- Improved Mission Average Isp
  - Heterogeneous Reactor
  - Greatly Reduced After Cool Loss, Save > 100 K lb LH2
  - LH2 Refrigeration Option
  - OMS Thrust at > 700 sec Isp (w/o Pump Start)
  - ACS Thrust at > 500 sec Isp
- Improved Engine Thrust/Weight
  - High Power Density Reactor
  - High Pc (Reduces Shield and Nozzle Size and Weight)
- Operational Benefits
  - Deep Throttling (Enables Multiple Burn TMI)
  - ~ 100 kWe Electric Power/Engine
  - Rapid Restart

**Our Integrated Engines Provide**

**Low Life Cycle Cost**
- TRL 4 to 6 for Major Components
  - CIS Fuel Developed
- Smaller, Lower Cost Components
  - High Pc
  - Nozzle
  - Pressure Vessel
  - Shield
- High Pc Enables Small ETF
  - High Pressure Storage
  - High AP Scrubbers
- Reduced ETO Cost
  - Reduced IMLEO
  - Smaller Payload Bay
- Design Flexibility and Growth Potential
  - Reduces Cost
  - Recuperated Cycle
  - Electrical Power System