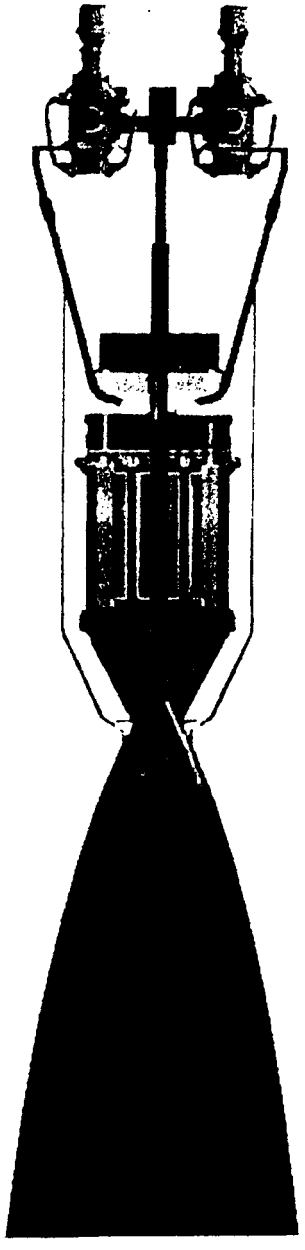
N93-26921

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

Aerojet Propulsion Division
Sacramento, California

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Lynchburg, Virginia

Energopool – Moscow, Russia

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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)

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The NASA LeRC TOC Addresses the Emerging NTRE Requirements

Thrust	25K, 40K, 75K
Thrust/Wt (With Internal Shield)	> 4
Isp	> 850 sec
Length	30 Meters
Diameter	10 Meters
Throttling	25%
Restarts	> 10
Single Burn Duration	60 Min (Max)
Life	> 270 Min at Rated Thrust
Reliability	Manned

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NASA LeRC TOC Final Report Agenda

• Introduction	Wayne Dahl
• Technical Overview	Mel Bulman
• Concept Definition	Don Culver
• Engine Design	Roy Squires
• Integrated Engine	Mel Bulman
• Engine Reliability and Safety	Mel Bulman
• PBR Engine Sensitivity Study	Mel Bulman
• PBR Reactor System	Richard Rochow
• CIS Engine	Don Culver
• CIS Reactor System	Richard Rochow
• Technology Road Maps	Mel Bulman
• Summary	Mel Bulman

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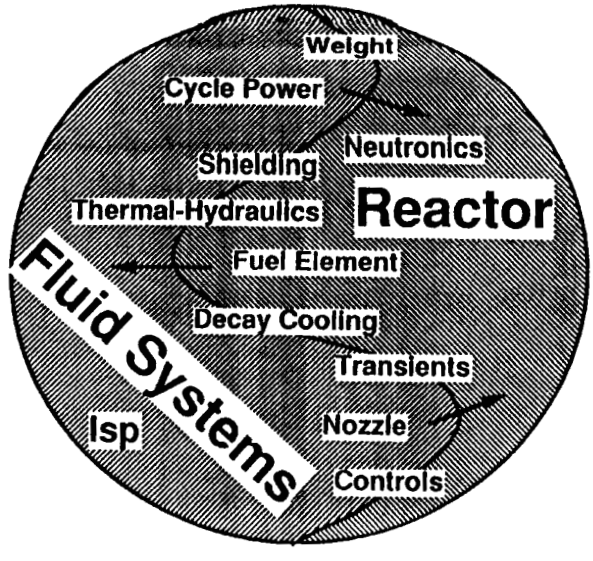
The NTRE is a highly integrated machine. As we will show, interactions between reactor and engine level operations are significant. Our systems approach to NTRE design reveals exciting new possibilities for improving the reliability and performance of spacecraft.

The NTR Engine Is a Highly Integrated Machine (Not Just a Reactor Between a Pump and Nozzle)



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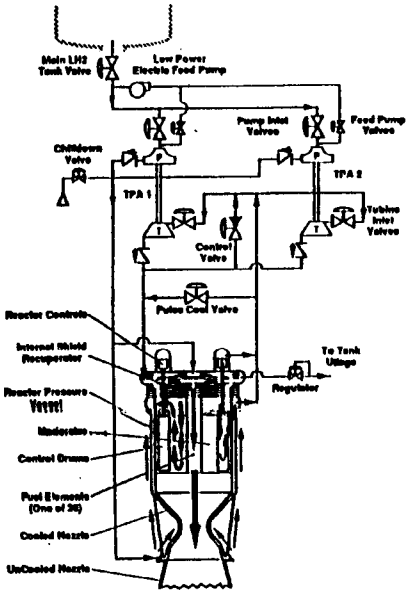
Our basic NTREs meet all current NASA requirements.

The thrust to weight ratio of the PBR engine is 6.3. The CIS engine is somewhat heavier with a F/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.

Our Basic Engine Meets All Current NASA Requirements With a Recuperated Topping Cycle



	Requirement	PBR Value	CIS Value
Thrust	75 Klbf	75 Klbf	75 Klbf
Thrust/Weight With Shield	> 4	6.3	4.6
Isp	≥ 850	915	959
Length	≤ 30M	7.7M	8.1M
Diameter	≤ 10M	2.2M	2.2M
Throttling	≥ 4:1	20:1	20:1
Reuse	≥ 10 Restarts	> 10	> 10
Single Burn	60 min	> 60 min	> 60 min
Engine Life	> 270 min	> 270 min	> 270 min
Reliability	Manned Stage →		

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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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There are several ways in which heterogeneous fission 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 if formed 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. Primarily, 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 hexagonal blocks of beryllium containing cavities filled with LiH that surround each fuel bed, while the CIS moderator is ZrH2 rods close-packed between the fuel assemblies.

For Mars mission NTRE 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 life 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 leads 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.

Heterogeneous Reactors Superior to Homogeneous Types (NERVA)

Features

- Fuel Separated from Moderator

Benefits

- Moderator Cooling Powers Turbine and Enables Closed Loop Cooling (Reliability and Weight)

	PBR	CIS
• Fuel More Efficient	Spheres	Twisted Ribbon
• Moderator More Efficient	Be Hex with ZrH_2 Cavities	ZrH_2 Rods

- Higher Gas Outlet Temperature (High Isp)
- Lower Fissile Inventory (Safety and Weight)

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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 heterogenously 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

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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

Requirements

- Safety
  - Radiation Protection
  - Manrate, Verify, Automate
- Performance
  - 850 sec Isp
  - 4:1 Thrust Weight
  - Throttling @ Tmax
  - 15-75K lbf Thrust
- Operation
  - Reusable, Long Life
  - Bootstrap Start w/o Power
  - Degraded/Failed Tolerance

Goals

- Safety
  - Minimize Radioactive Materials Hazard Mitigation and Reliability
- Mission Benefit
  - IMLEO/Trip Time (Isp and F/W) Mission Commonality
  - 2006 Availability
  - Simplicity (Inherent Reliability)
- Technical Risk and Development Cost
  - Technology Readiness and Tests Needed
  - Propulsion System Integration
  - Facility Requirements

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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	Criticality Trades (B&W)
– Non Nuclear	Feed System Reliability
• Performance and Mission Benefit	
– Mission Payload	Versus Cycle Type, Pc, Nozzle Design
– Power Cycle	Definition (Shield Integration)
– Control System	Architecture Study
• Operation and Technical Risk	
– System Operation	Modes and Procedures Identified
– Propulsion System Integration	Shield, Decay Heat, Deep Throttling
– Technology Readiness	Major Component Status

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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

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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 H_2 Losses

- Engine Isp = f (Tout)$^{1/2}$
  - Theoretical Isp (Tout and ε)
  - Tout max – Tout Mixed Mean
  - Nozzle Losses (Cooling, Divergence)
  - Power Cycle Bleed Losses
- Operational H_2 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

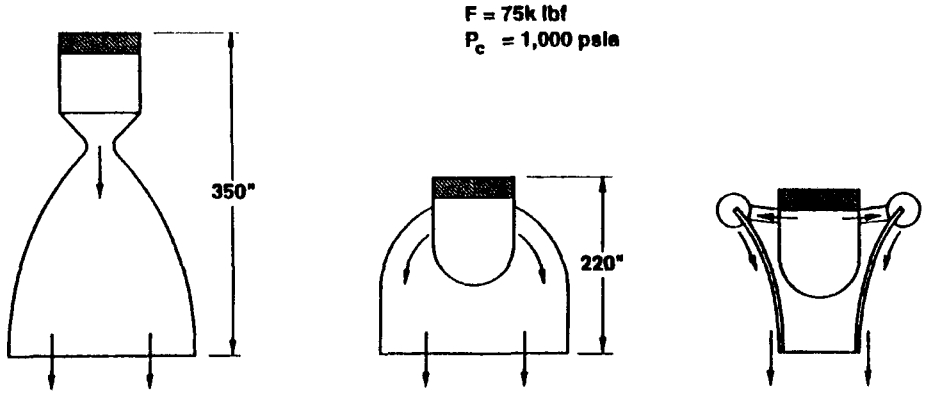
The E-D nozzled engine appears to have the best mission performance potential, but it needs further study, and at this time it is recommended for a second-generation engine. However, we recommend this concept be studied in more detail soon, because it is rapidly developing into a more practical concept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

F = 75k lbf
P_c = 1,000 psia



DeLaval	E/D	Plug
• Low Losses	• Good Integration	• Highest Nozzle Heat Flux and Losses
• Long and Heavy	• Short and Lightweight	• Short

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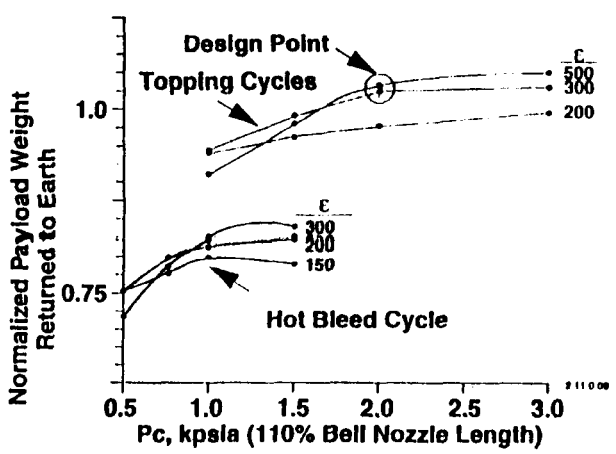
A trade study evaluated both engine weight and specific impulse by estimating the Mars mission payload delivery capability of identical vehicles powered by similar engines of conventional geometry having different power cycles, operating pressures, and nozzle area ratios. Both hot bleed cycle engines 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

Study Results



Engine Selection

- Topping Cycle
- Pc = 2,000 psia
- ε = 300 (De = 92 in.)
- Lnoz = 110% Bell (210)
- Tc = 2,700K

* 4 Burn, All-Up, Manned Mars Mission With $C_3 \cong 16$ km^2/s^2 and 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

Turbine Exhaust Destination	Heat Sources for Turbine		
	Reactor Core	System (Expander)	
		Recuperated	Not Recuperated
Overboard = Bleed Cycles	Hot Bleed	Recup. Bleed	Cold Bleed
• Isp Loss • Partial Admission • Large Turbine	• Hot Turbine • Nozzle Port • Mixer Fatigue • ≈20% P/L Loss	Similar to Cold Bleed	• Larger Toploss or • Hot Turbine • ≥14% P/L Loss
Reactor = Topping Cycles	Augmented	Recuperated	Expander
• More Valves	• Core Complexity • Reactor Size and Weight	• Recuperators Typically Large and Heavy • Max. P/L	• Limited Power • Restart Heat? • 7% P/L Loss

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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.

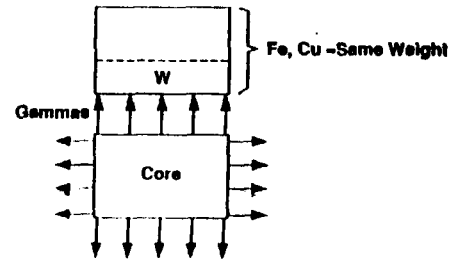
(3) Low density material, such as steel may be used efficiently for a gamma shadow shield, because it is located close to the large diameter reactor, and the radiation tends to be planar to all surfaces, because of the self shielding provided at all other angles.

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



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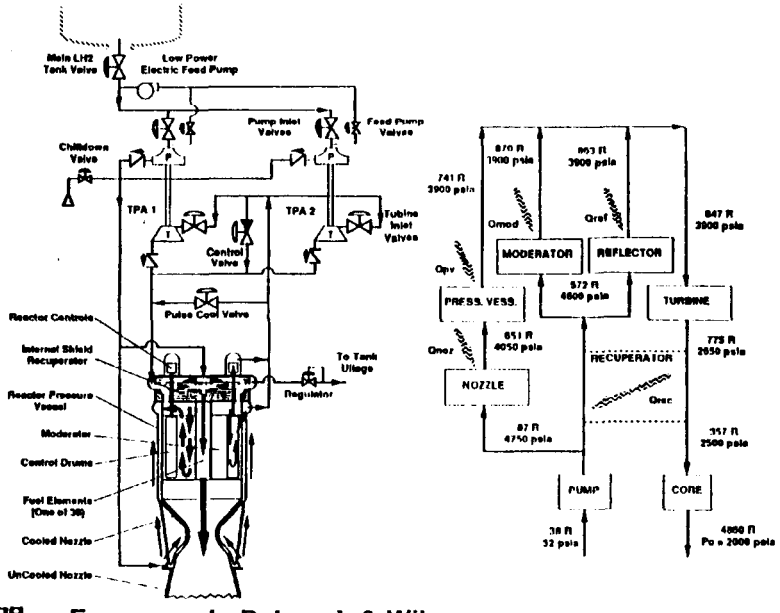
The power cycle we have selected for both engines uses a recuperator to transfer heat from turbine exhaust to pump discharge, and each cool the nozzle with a small side stream of liquid hydrogen from the pump. The PBR cycle variation is shown here; it requires a pump discharge pressure of 4750 psia to deliver an engine Pc of 2,000 psia. It does this with a low turbine inlet temperature of 847 R (470 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 Btu/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



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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 GH_2 is vented overboard as required. However, much of the GH_2 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 valve 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 GH_2
- **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

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Engine Design

Roy Squires

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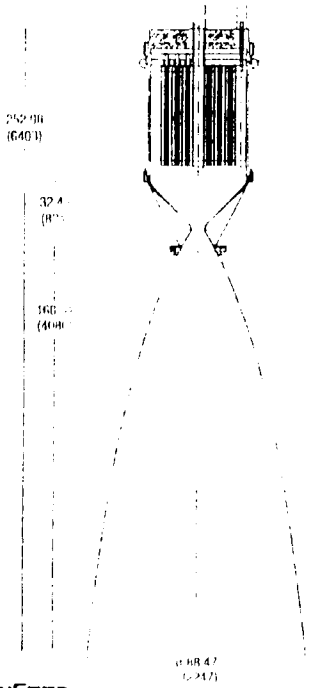
Aerojet NTRE Is Small and Lightweight



	PBR
Thrust, lbf	75000
Chamber Pressure, psia	2000
Nozzle Area Ratio, Ae/At	100
Engine Specific Impulse, sec	915
Mars Mission Specific Impulse, sec	887
Engine Total Weight, lbm	11879
Thrust/Weight	6.3
Engines per Vehicle	2
Payload Returned to Earth, lbm	44900

Engine Weight Breakdown

Component	
Uncooled Nozzle	240
Cooled Nozzle	1000
Pressure Vessel, Reactor Manifolds & CSS	1501
Reactor, Reactor I&C	3982
Turbopump Assemblies (2)	410
Recuperator / Shield	2168
Secondary Shield	521
Plumbing/Valves	1320
Controls and Shielding	737

NTRE w/ Stage Power/Heat Removal

Stage Power & Heat Removal Sys Wt, lbm	2000
Engine with Power Sys Wt, lbm	13879
Mars Mission Specific Impulse, sec	905
Payload Returned to Earth, lbm	50220

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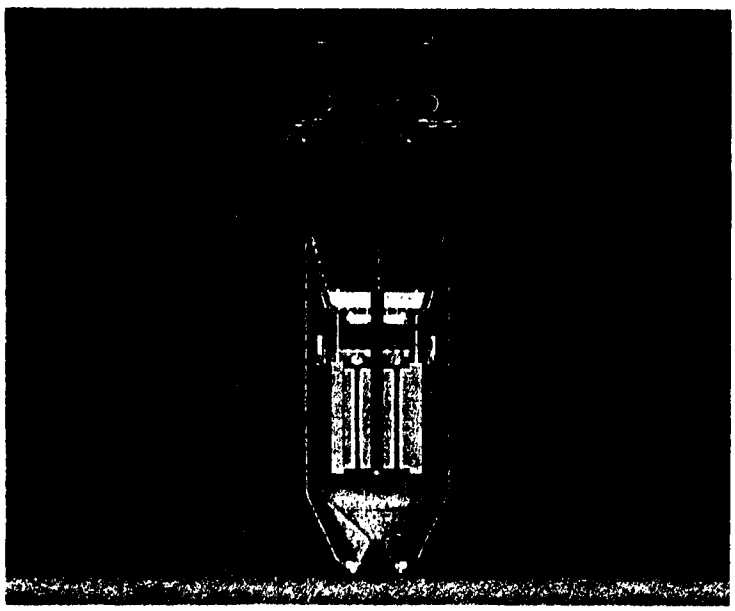
Aerojet NTRE



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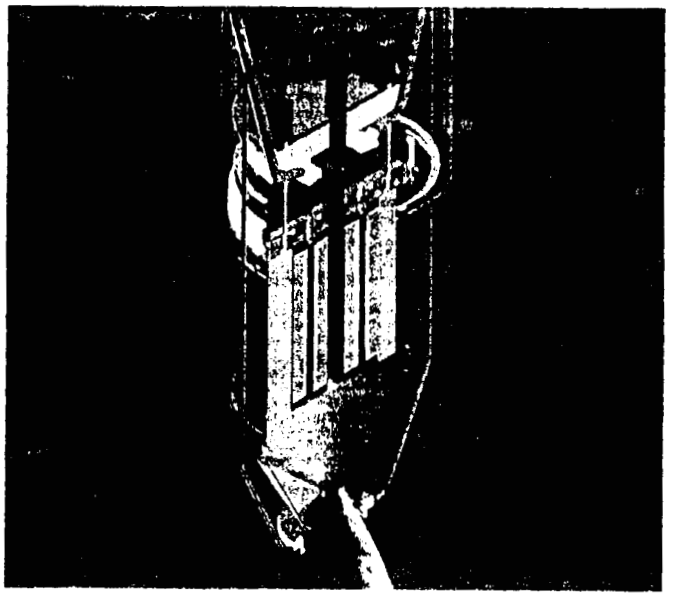
Aerojet NTRE



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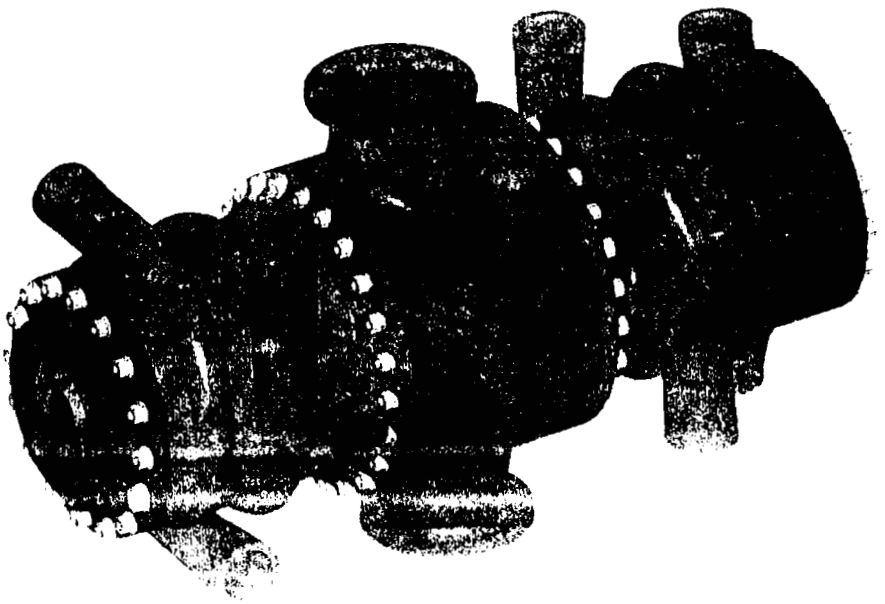
CAD TPA Dual Spool 3-D Color Exterior View



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XLR-134 LH_2 TPA

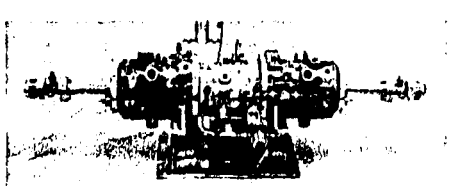
The XLR-134 program addressed the need for a relatively low thrust engine to move large fragile structures from low earth orbit into higher orbits. It was an Air Force program originating from the Phillips Lab at Edwards Air Force Base and spanned 1986 through 1990.

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/LH_2 single expander cycle engine (gaseous hydrogen turbine drive). The turbopumps for both the LOX and LH_2 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 LH_2 TPA with appropriate material and tolerance changes.

The LH_2 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 LH_2 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	Benefits
• Dual Spool	• High Turbine Efficiency • Low Weight • Commonality of Parts
– Short Shafts With 3 Rotors per	• Subcritical Shaft Speed Operation for Deep Throttling
• Operate Below Design Speed	• Increased Life and Reliability
• Hydrostatic Bearings	• Increased Life



XLR-134 Fuel TPA

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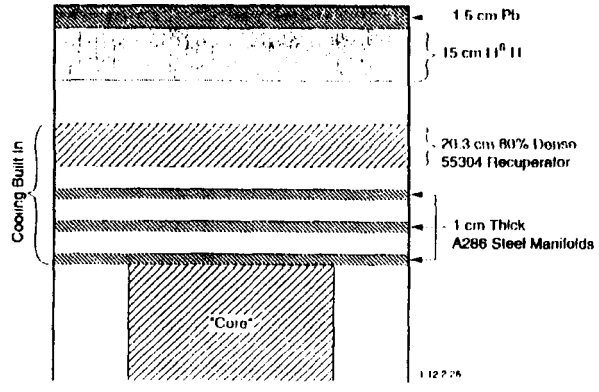
Radiation transmission through manifolds includes 36 2.5 cm holes for gas flow. Shield penetrations for drum control rods and the central "poison" rod were ignored.

Heating in the Li_6H/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



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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

Components	Gamma Factor	Fast Neutron Factor	Mass (Kg)	Comments
Gas Manifolds and Recuperator	101	21	1178	Dual Function: Cools and Shields
Dedicated Shield	4.4	80	236	Additional Shield Necessary to Meet NASA Spec
Distributed Electronics and Controls Shield	6.3×10^4	1.75×10^3	130	Required Beyond NASA Spec for 3.5 Hours at Full Power

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C-4

Recuperator

Function

- Internal gamma shield cooled by LH_2
- Provides thermal energy for starting and operating TPA
- Enables high chamber pressure for lightweight, compact NTRE

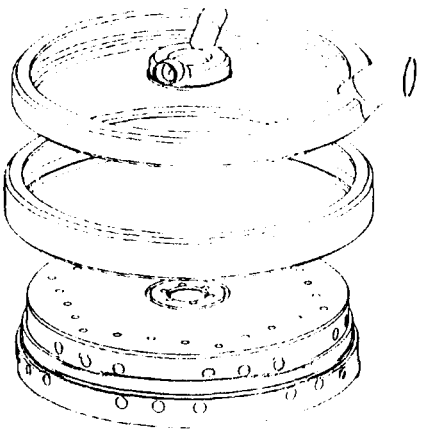
Design and Performance Parameters

Propellant	H_2
Cold-Side Inlet Pressure	4750 psia
Cold-Side Inlet Temperature	87°R
Cold-Side Flow Rate	68 lbm/sec
Cold-Side Pressure Drop	150 psid
Hot-Side Inlet Pressure	2650 psia
Hot-Side Inlet Temperature	775°R
Hot-Side Pressure Drop	150 psid
Thermal Load	126,000 Btu/sec
Envelope	40 in. dia x 7 in. height
Weight	2500 lbm
Material	CRES SS (A-286)

Characteristics

The 300 series stainless steel, platelet design, counterflow HEX accepts 83% of the LH_2 flow from the TPAs and heats the hydrogen to 572°R gas in the high pressure circuit of the HEX. The outflow cools the reflector and moderator, ensuring that LH_2 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°R 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

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Cooled Nozzle

Function

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

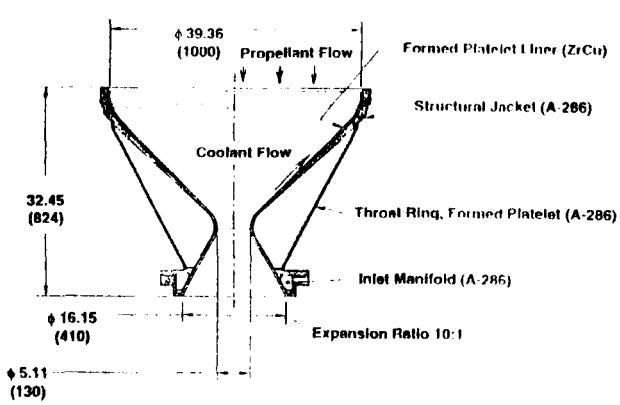
Design and Performance Parameters

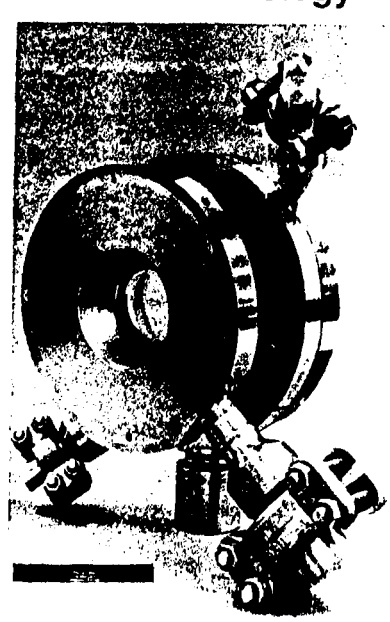
Propellant	H_2
Coolant Inlet Temperature	87°R
Coolant Inlet Pressure	4750 psia
Coolant Flow Rate	14 lbm/sec
Coolant Pressure Drop	700 psia
Throat Diameter	5.121 in.
Exit Area Ratio	10:1
Chamber Pressure	2000 psia
Gas Temperature	4860°R
Flowrate	82 lbm/sec
Material	ZrCu Liner/A286 SS Structure
Envelope	40 in. dia x 32 in. long
Weight	1000 lbm
Cylindrical Length	5.00 in.
Wall Temperature	600 F

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 40Klbf Chamber

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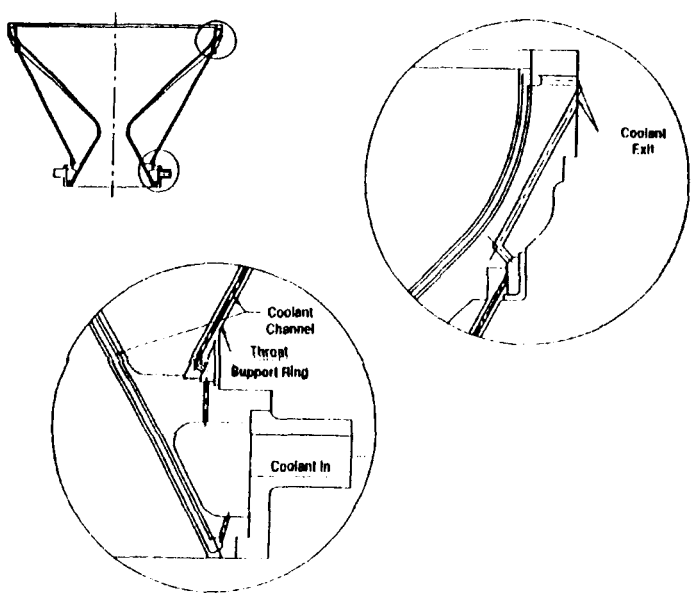
Cooled Nozzle Concept

- 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



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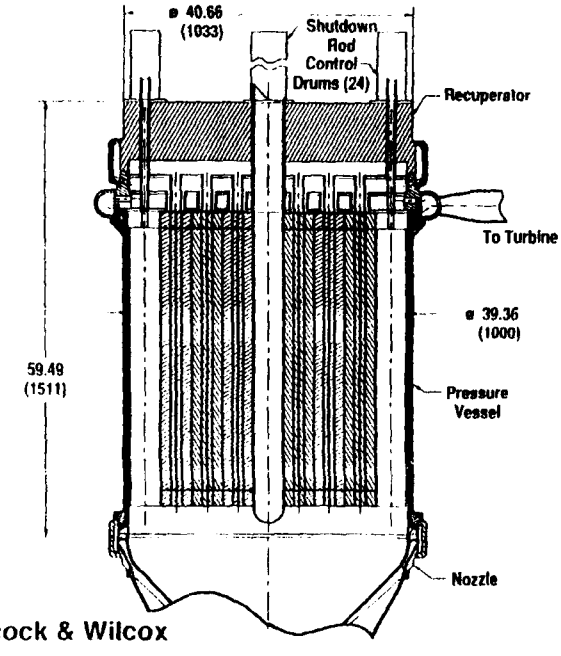
Pressure Vessel Function / Concept

- 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



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Pressure Vessel (PV)

Function

- Contains pressure and supports reactor
- Provides manifolding for GH_2
  - 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

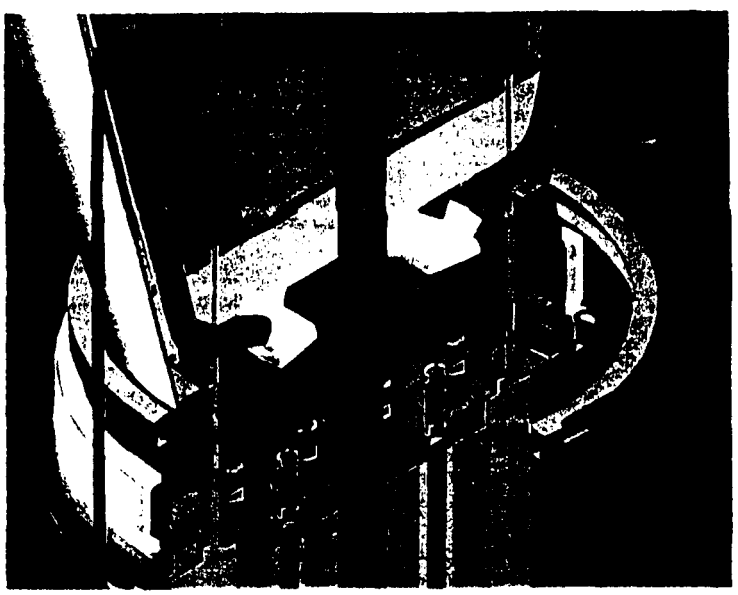
Propellant	H_2	Moderator Coolant Temperature	572°R
Coolant Inlet Temperature	651°R	Moderator Coolant Pressure	4600 psia
Coolant Inlet Pressure	4050 psia	Moderator Coolant Flowrate	53.5 lbm/sec
Coolant Outlet Temperature	847°R	Reflector Coolant Temperature	572°R
Coolant Flowrate	14 lbm/sec	Reflector Coolant Pressure	4600 psia
Coolant Pressure Drop	150 psid	Reflector Coolant Flowrate	14.5 lbm/sec
Core Propellant Temperature	357°R	Envelope	40 in. dia x 53 in. long
Core Propellant Pressure	2500 psia	Weight	2610 lbm
Core Propellant Flowrate	82 lbm/sec	Material	A286 SS

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



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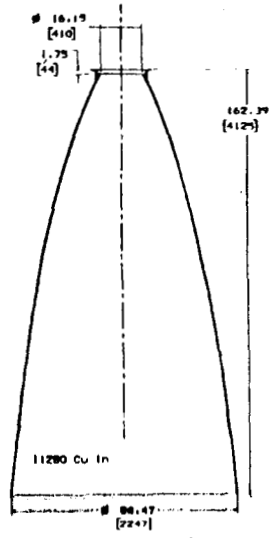
A carbon-carbon nozzle extension for NTRE is a cost effective, low weight component. Carbon-carbon has good mechanical properties for temperatures in excess of 5000°F and will only suffer a total recession of less than 0.005 inch due to hydrogen chemical attack (assuming a temperature of 2500°F, pressure 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.

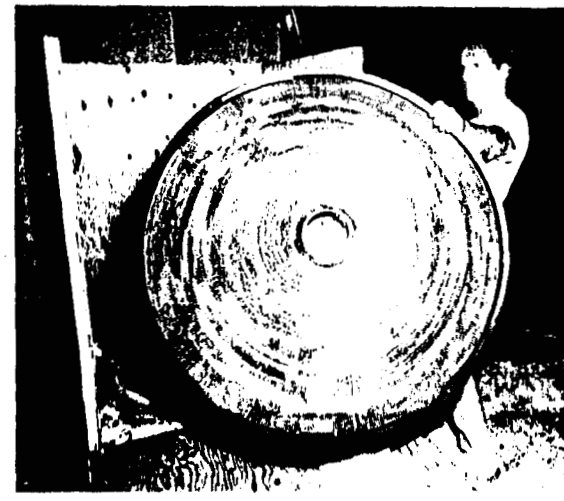
Carbon-carbon structures can be fabricated in many different ways, but only several are appropriate for thin wall nozzle extensions. Involute, 3-D cylindrical, braided, and Novoltex™ preforming are the four most realistic techniques to provide carbon-carbon nozzle extensions. None of these techniques 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 nozzles 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	10:1
Exit Area Ratio	200:1
Nozzle Shape	110% Bell
Material	Carbon/Carbon
Envelope	88.7 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

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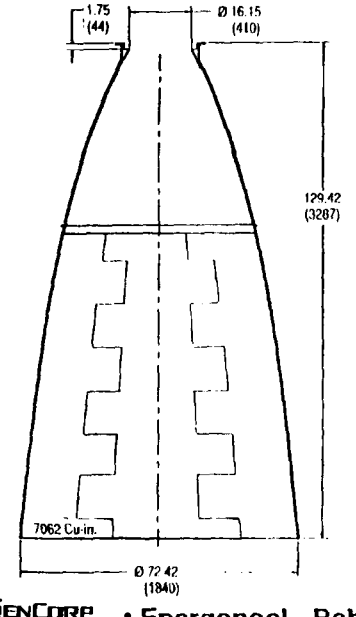
Instead of fabricating a one-piece carbon-carbon nozzle extension, fabricating carbon-carbon segments is an option which will not require facilitization nor extensive validation. A defect in a large one-piece carbon-carbon nozzle would cause the rejection of the whole nozzle or acceptance of materials 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

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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, turbopump ramp up, and power ramp up. The engine controller actively controls engine steady state operation to maximize engine Isp. Engine power down and post firing cool down is actively controlled to minimize propellant usage and maximize total engine Isp. 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 I80960 microprocessor provides the processing power for the engine controller. The I80960 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.

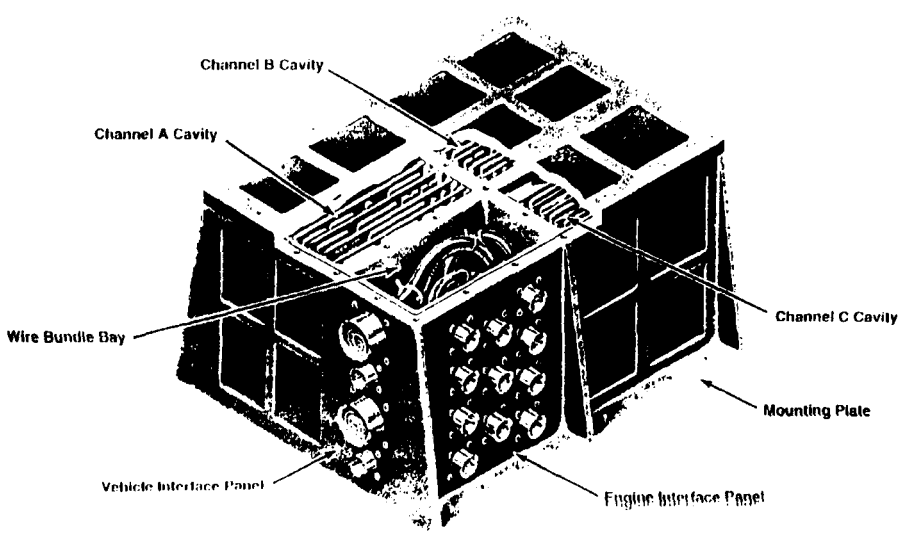
INTERFACES: 4 MIL-STD-1553B Vehicle Command Channels 4 MIL-STD-1553B Vehicle Data Channels, 4 MIL-STD-1553B Effector Command Channels, 4 Vehicle Power Buses, Solenoid Interfaces

SIZE: 8 in. x 16 in. x 10 in.

WEIGHT: 59 lbs (46 lbs Electronics + 13 lbs Shield)

TOTAL DOSE: 100 K RADs (Si)

Advanced Fault Tolerant Controller Improves Mission Reliability



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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)

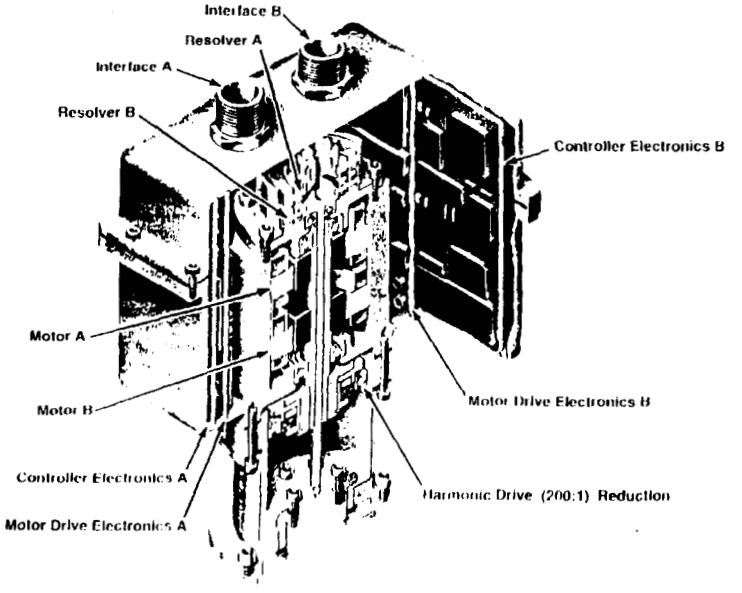
TOTAL DOSE: 100K RADs(Si)

TORQUE: 600 in.-lb

SLEW RATE: 360 deg/sec

POSITIONAL ACCURACY/REPEATABILITY: ± 0.5 deg

Advanced Electro-Mechanical Actuator Combines High Torque and Small Size



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COMPONENT: Quad Channel Control System

FUNCTION: Provide full Fail Op/Fail 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 1553B implementation. This provides a total of four data paths to each actuator thus providing full Fail Op/Fail 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

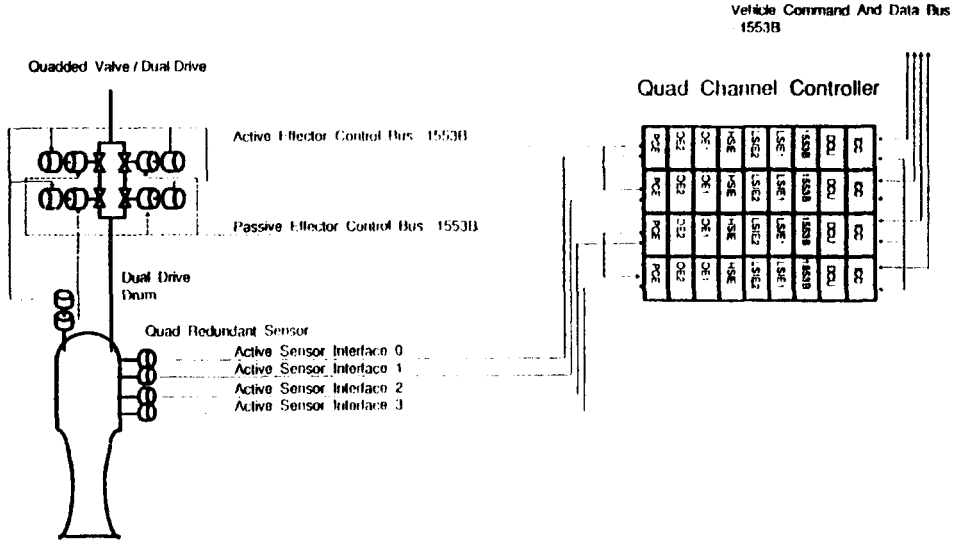
SIZE: 8 in. x 16 in. x 10 in.

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



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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.

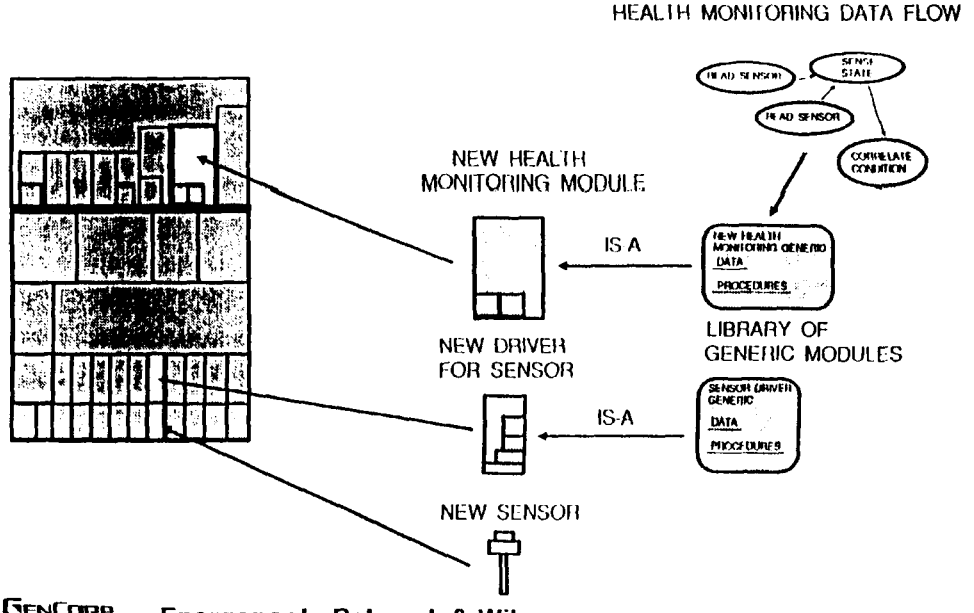
The OFP implements the required vehicle communications protocols and validates commands. Additionally status and data packets are sent back to the vehicle.

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/IO Devices

Plug In Software Modules Improves Controller Development



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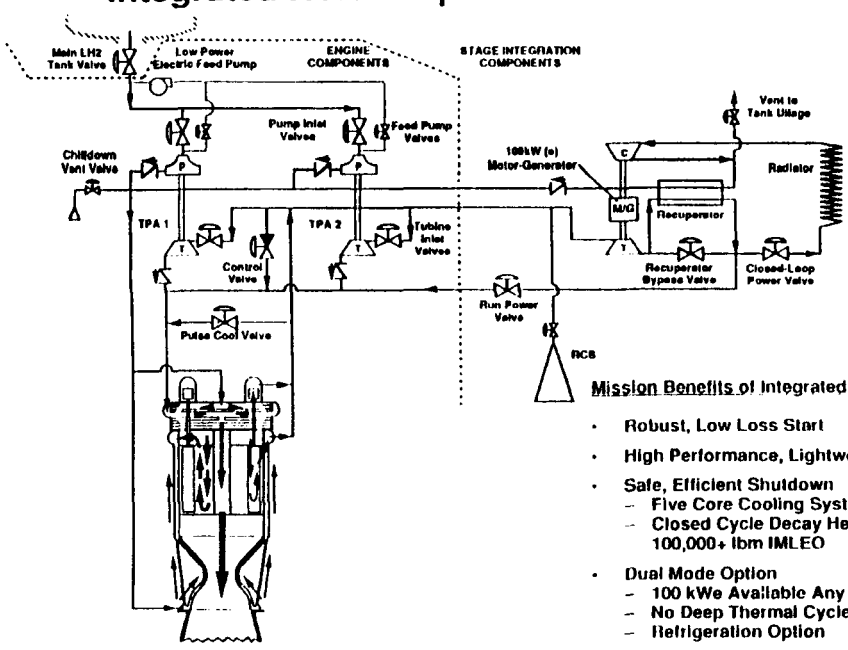
Integrated Engine

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.

Integrated NTRE Improves Mission Performance



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 kWe 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

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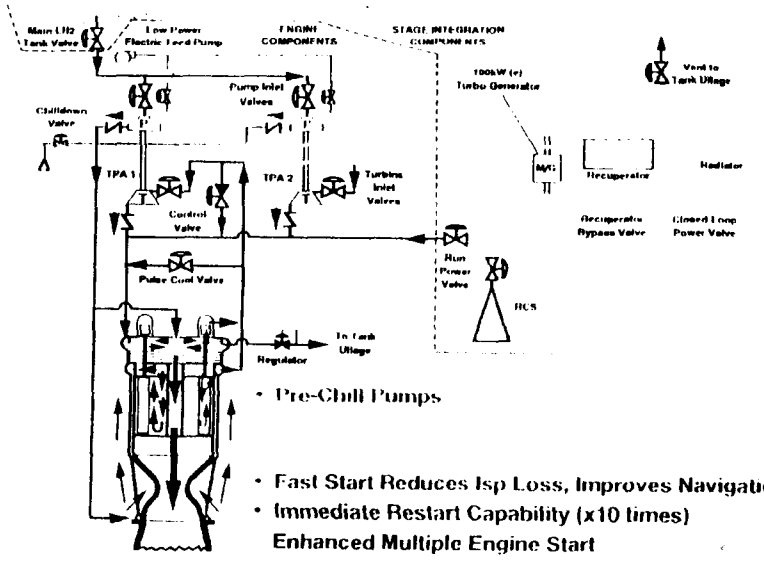
Integrated NTRE Start Sequence

- Engine Prestart Conditioning
  - Pump Chill In
  - Moderator Loop Pressurization With TPA Chill H_2 (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 H_2 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

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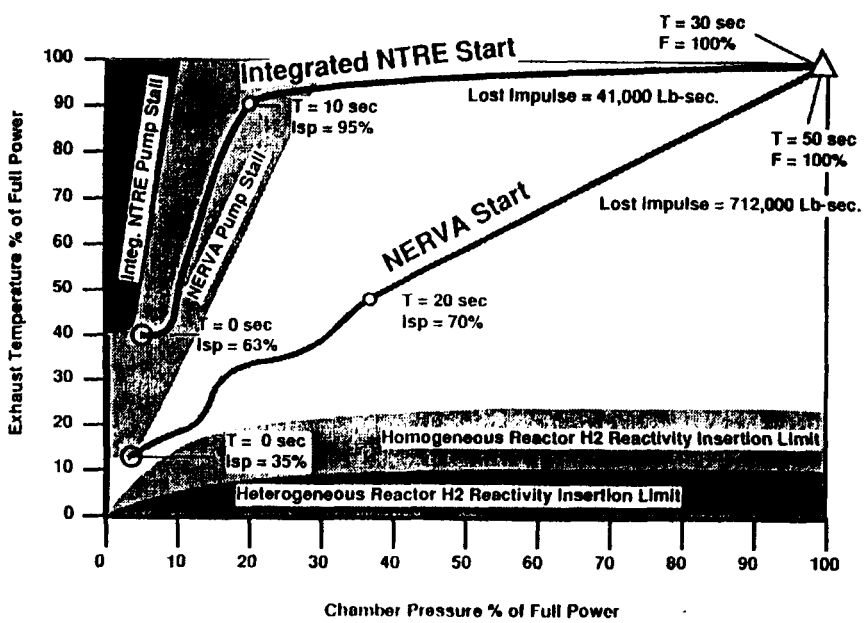
Our Propellant Feed System Dynamics Are Efficiently Controlled

- 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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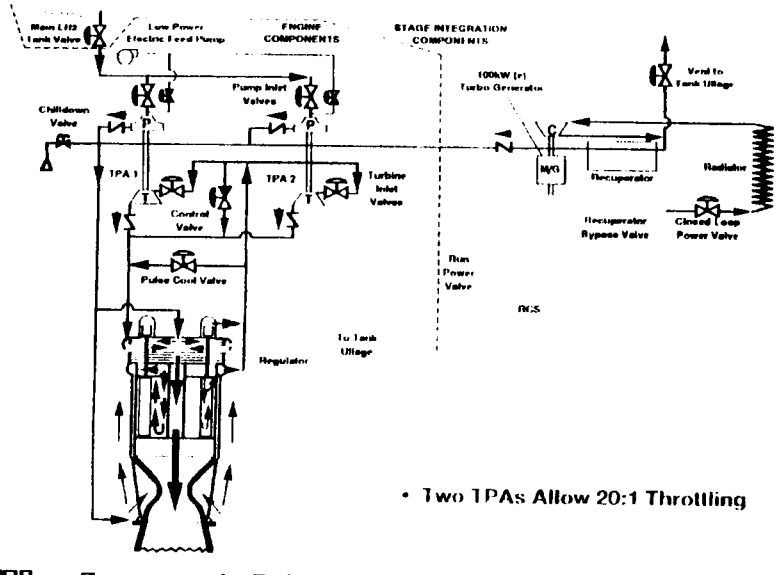
Tapping into the hot H_2 in the moderator loop of our integrated NTRE during operation allows us to generate up to 100 kW(e), attitude control impulse, and tank pressurization at lower cost than if provided by separate systems.

Integrated Engine Provides RCS and Tank Pressurization During "Burns"



• Two TPAs Allow 20:1 Throttling

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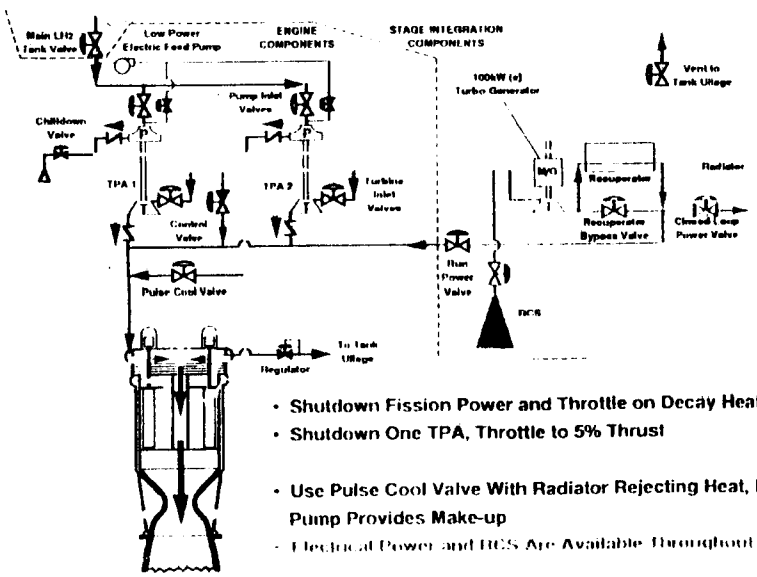
The decay heat build up in the engine during the main burn must be removed from the reactor or it will over heat. Decay heat persists for days even after a short fifteen minute burn. Our integrated engine can reject a significant portion of the heat through its radiators, greatly reducing the expenditure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

Integrated Engine Saves Over 100,000 lbm LH_2



- Shutdown Fission Power and Throttle on Decay Heat
- Shutdown One TPA, Throttle to 5% Thrust
- Use Pulse Cool Valve With Radiator Rejecting Heat, Feed Pump Provides Make-up
- Electrical Power and RCS Are Available Throughout Cooldown

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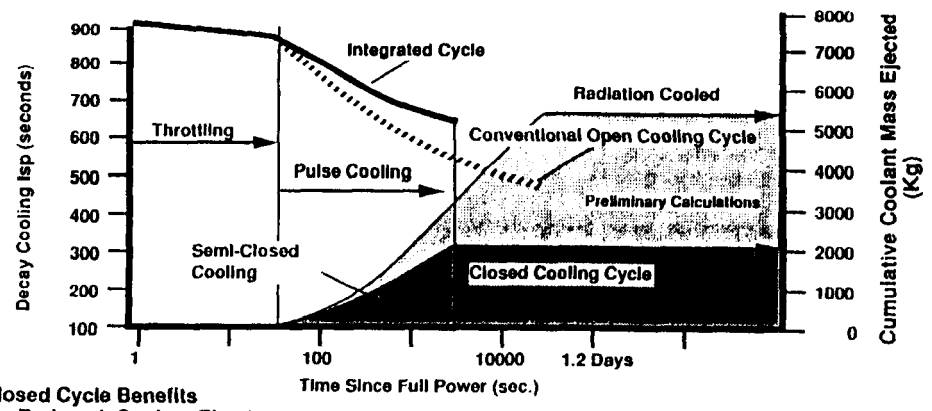
Our Closed Cycle Cooling System Saves Over 7500 lbm During Perigee Pulsing

Conventional Cooling System	Pluse 1	Cool 1	Pluse 2	Cool 2	Pluse 3	Cool 3
Initial Mass (Lbm)	1000000	850842	840942	695357	684665	542970
Burn Time (Sec)	981	174 Min	958	1006 Min	932	Days
Propellant Consumed (Lbm)	149158	9900	145586	10692	141694	10692
Effective Isp (Sec)	915	640	915	600	915	600
Final Mass (Lbm)	850842	840942	695357	684665	542970	532278
ΔV (ft/sec.)	4755	241	5596	299	6825	384
Mission Velocity (Ft/Sec.)	4755	4996	10591	10890	17716	18100
Mission Effective Isp (Sec)		896	906	894	902	892
Closed Cycle Cooling System	**Pluse 1**	**Cool 1**	**Pluse 2**	**Cool 2**	**Pluse 3**	**Cool 3**
Initial Mass (Lbm)	1000000	845720	843520	692280	690080	541986
Burn Time (Sec)	1015	174 Min	995	1006 Min	974	Days
Propellant Consumed (Lbm)	154280	2200	151240	2200	148094	2200
Effective Isp (Sec)	915	760	915	760	915	760
Final Mass (Lbm)	845720	843520	692280	690080	541986	539786
ΔV (ft/sec.)	4932	64	5816	78	7111	99
Mission Velocity (Ft/Sec.)	4932	4996	10812	10890	18001	18100
Mission Effective Isp (Sec)		913	914	913	914	913
Propellant savings (lbm)		2578		5415		7508

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 f(ΔIsp & ΔMass)
- Reduced g Loss (Cooldown Impulse Delivered Faster)
- Closed Cycle Has All Brayton Power Cycle Components (Except Generator)

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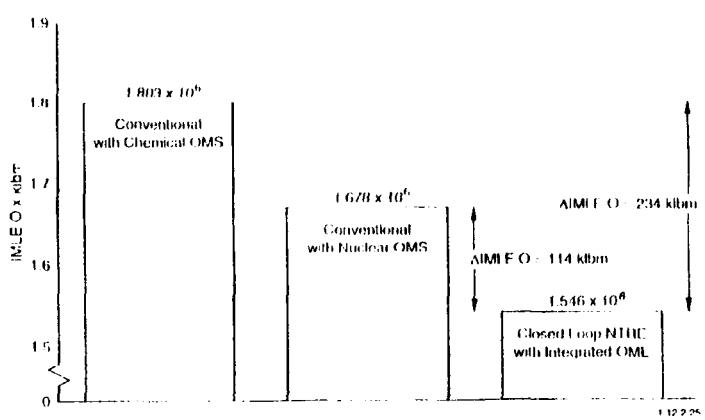
Our Integrated NTRE Can Reduce IMLEO 100-200+ Klbm

Conventional Cooling System (H2/O2 OME System)						
	Burn 1	OMS-1	Burn 2	Burn 3	OMS-2	Burn 4
Initial Mass (Lbm)	1803170	871599	813424	397457	243069	226845
Propellant Consumed (Lbm)	846882	58175	287242	140353	16224	106541
Effective Isp (Sec)	892	450	892	892	450	892
Final Mass (Lbm)	956288	813424	526182	257104	226845	120304
ΔV (ft/sec.)	18200	1000	12500	12500	1000	18200
Mission Velocity (Ft/Sec.)	18200	19200	31700	44200	45200	63400
Δ IMLEO (Klbm/%) Over Integ. NTRE	257	16.64		Payload Returned		50000
Conventional Cooling System With Main Engine Restart for Plane Change Maneuver						
	Burn 1	OMS-1	Burn 2	Burn 3	OMS-2	Burn 4
Initial Mass (Lbm)	1678020	811106	775875	374494	229025	219077
Propellant Consumed (Lbm)	788104	35231	273983	132244	9948	102893
Effective Isp (Sec)	892	700	892	892	700	892
Final Mass (Lbm)	889916	775875	501892	242250	219077	116185
ΔV (ft/sec.)	18200	1000	12500	12500	1000	18200
Mission Velocity (Ft/Sec.)	18200	19200	31700	44200	45200	63400
Δ IMLEO (Klbm/%) Over Integ. NTRE	132	8.55		Payload Returned		50000
Integrated NTRE Closed Cycle Cooling System + Nuclear OMS (without restart)						
	Burn 1	OMS-1	Burn 2	Burn 3	OMS-2	Burn 4
Initial Mass (Lbm)	1545880	760485	727453	350094	216612	207203
Propellant Consumed (Lbm)	713995	33032	252145	121347	9409	95701
Effective Isp (Sec)	913	700	913	913	700	913
Final Mass (Lbm)	831885	727453	475308	228746	207203	111502
ΔV (ft/sec.)	18200	1000	12500	12500	1000	18200
Mission Velocity (Ft/Sec.)	18200	19200	31700	44200	45200	63400
				Payload Returned		50000
				100 Klbm Drop @ Mars, 10% Tank fraction		
				Tanks droped after burns		

10/18/92

Closed Cycle Cooling Can Reduce IMLEO Over 100K lb*



* Four Burn Full Up Mars Mission

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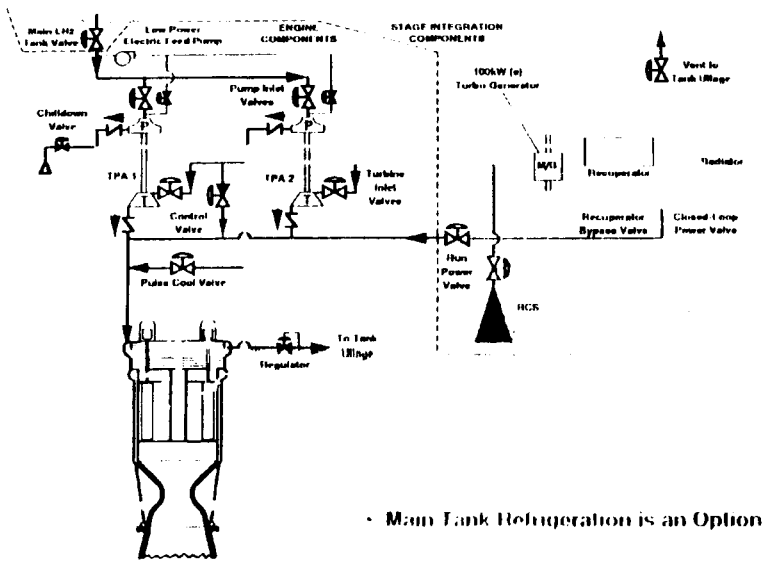
During coast, our integrated engine is kept warm while generating up to 100 kW(e). The mean electrical power will be less than 100 kW(e). At 20 kW(e) the Brayton cycle efficiency is approximately 30% requiring a thermal power of approximately 60 kW(t), which causes only a small additional burn up of the reactor fuel.

Integrated Engine Eliminates Additional Stage Components and Improves Stage Performance



• Main Tank Refrigeration is an Option

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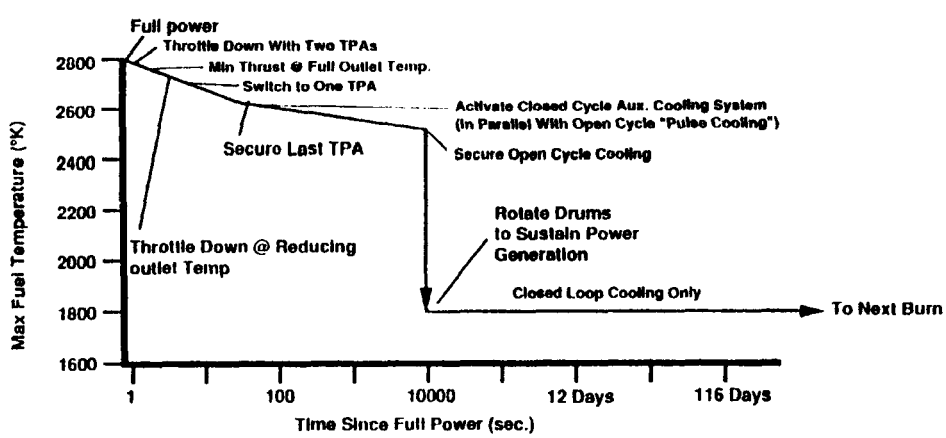
The integrated engine adds life to the fuel, because it allows fuel to be kept warm during coast (~1800 K). Therefore, the fuel will see only ~1000K ΔT's during startup and shutdown. 1800K was chosen to balance the effects of vaporization rate, thermal cycling, and power cycle efficiency.

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

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Reliability and Safety

Mel Bulman

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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

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Dual Spool TPA Provides High Margin for NTRE

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

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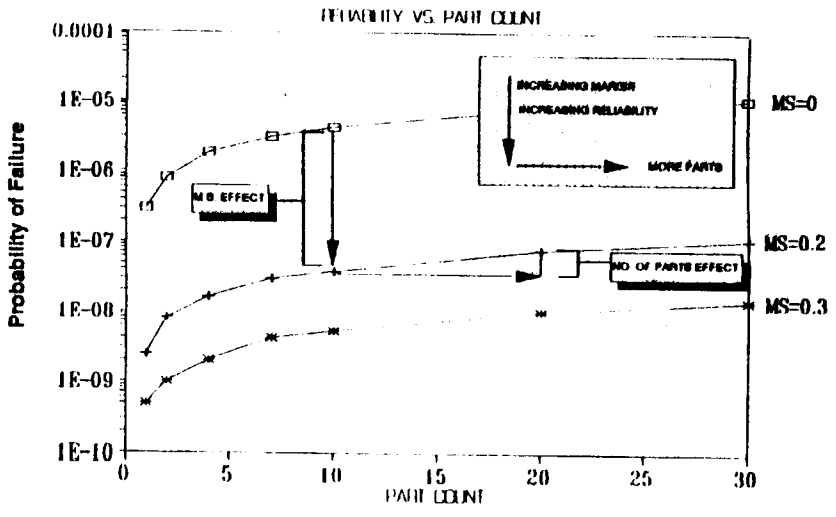
Reliability Increased With Lower Stressed Parts



Margin A Stronger Influence On Reliability Than Parts Count

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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

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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.

NTRE – Concept Design

Reliability

Methodology to Evaluate the Effect of Redundant Components on the System

- 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

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NTRE Design Criteria

- Safety Factors

  Pressure Loads

Yield Safety Factors	FSy	=	1.25
Ultimate Safety Factor	FSu	=	1.50

  Thermal Loads

Yield Safety Factor	FSy	=	1.00
Ultimate Safety Factor	FSu	=	1.00

- Margin of Safety

  MS = (Allowable Stress) (FS * Applied Stress) – 1.0

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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

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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

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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

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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

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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

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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

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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

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PBR Engine Sensitivity Studies

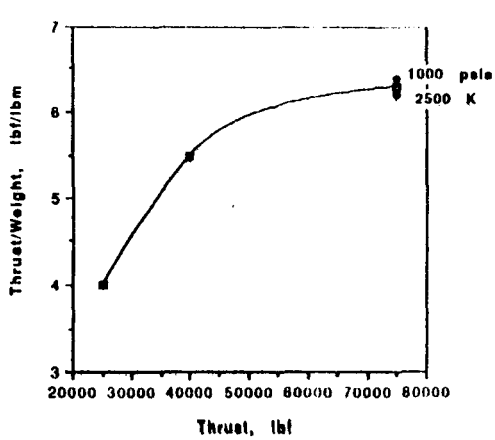
Mel Bulman

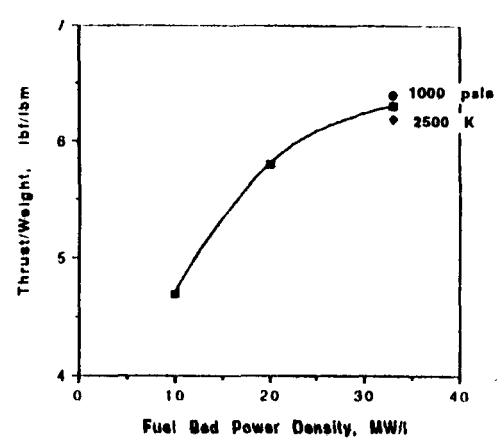
GenCorp Aerojet • Energopool • Babcock & Wilcox

	CIS*	PBR	40k PBR	25k PBR	2500K PBR	10MW/l	20MW/l	1000 psia
Thrust, lbf	75000	75000	40000	25000	75000	75000	75000	75000
Chamber Pressure, psia	2000	2000	2000	2000	2000	2000	2000	1000
Nozzle Area Ratio, Ae/At	300	300	300	300	300	300	300	200
Engine Specific Impulse, sec	959	915	915	915	880	915	915	910
Mars Mission Specific Impulse, sec	930	887	887	887	853	887	887	883
Engine Total Weight, lbm	15900	11879	7278	6193	12027	15901	13032	11687
Thrust/Weight	4.7	6.3	5.5	4.0	6.2	4.7	5.8	6.4
Engines per Vehicle	2	2	4	6	2	2	2	2
Payload Returned to Earth, lbm	47067	44900	37947	26897	34682	34242	42201	44222
Engine Weight Breakdown								
Component	Weight, lbm							
Uncooled Nozzle	232	240	175	139	249	240	240	212
Cooled Nozzle	965	1000	730	577	1039	1000	1000	1414
Pressure Vessel, Reactor Manifolds & CSS	2536	1501	701	613	1503	2168	1894	1042
Reactor, Reactor I&C	6613	3982	2244	2019	3982	6219	4803	3957
Turbopump Assemblies (2)	410	410	236	152	440	410	410	300
Recuperator / Shield	2425	2168	1111	727	2179	2916	2395	2412
Secondary Shield	642	521	572	753	523	704	576	565
Plumbing/Valves	1320	1320	964	762	1372	1320	1320	1048
Controls and Shielding	758	737	544	451	740	928	794	737
NTRE w/ Stage Power/Heat Removal								
Stage Power & Heat Removal Sys Wt, lbm	2000	2000	1285	939	2000	2000	2000	2000
Engine with Power Sys Wt, lbm	17900	13879	8563	7132	14027	17901	15032	13687
Mars Mission Specific Impulse, sec	949	905	905	905	871	906	905	901
Payload Returned to Earth, lbm	52929	50226	43249	32161	39768	39531	47518	49523

* 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.

High Thrust and Power Density Increase Engine Thrust-to-Weight





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PBR Design

Richard Rochow

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 Klbf 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 Li_6H 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

Design Parameter	Rationale
1 H_2 Mixed Mean Outlet Temperature (2,700K)	Expected 4.5 Hours Fuel Life
2 Pc (2,000 psia) 3 Ae/At (300)	Best Mars Mission Performance With Reusable Engines
4 Power Cycle (Recuperated)	• Enable High Pressure With Simple Reactor • Enhances Transient Operation • No Weight Penalty (γ Shield)
5 Core Support (forward)	U.S. Experience Base
6 Nozzle (Single DeLaval) (H_2 Cooled Without Bleed Flow) (C-C Extension)	Near Term Technology Use (Formed Cu Platelet)
7 Neutron Shield (External)	Simplifies Core Support

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AEROJET/B&W PBR NTRE

NASA LeRC Final Report

Prepared by R.E. Rochow
Babcock & Wilcox, ASE
Oct 23, 1992

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-RATED 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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PBR PROVIDES A COMPACT HIGH POWER ENGINE

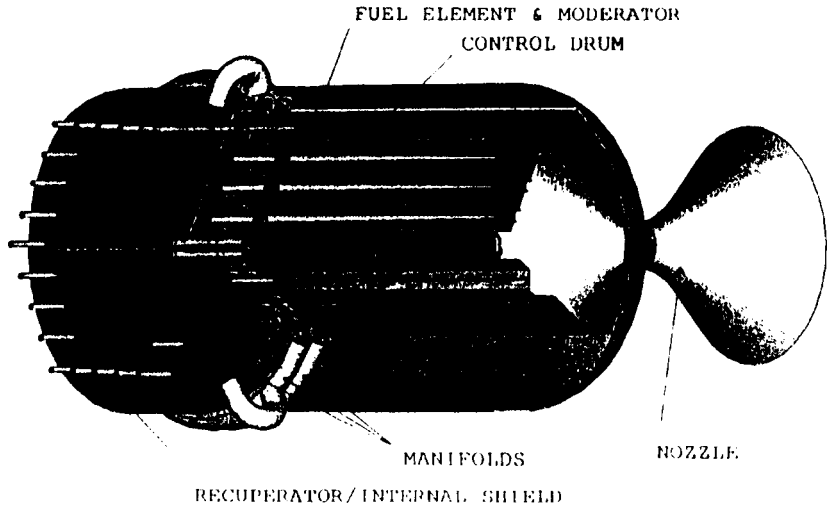
THE PBR IS A PARTICULARLY ATTRACTIVE CONCEPT DUE TO THE HIGH SURFACE AREA OF THE PARTICLE FUEL FORM. THE HEAT TRANSFER CAPABILITY IS UNSURPASSED. SMALL PARTICLES, BY DEFINITION, ALSO LIMIT THE THERMAL STRESSES WITHIN THE PARTICLES DUE TO THE SHORT CONDUCTION PATH LENGTH. THESE FEATURES ALLOW THE PBR TO OPERATE AT HIGH POWER DENSITY AND THEREFORE REQUIRE LESS CORE VOLUME. SMALLER CORE VOLUME TRANSLATES 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 11 CM. THE SUPPORT FOR THE CORE IS ACCOMMODATED BY THE MANIFOLD STRUCTURE. THE CORE IS "HUNG" FROM THE TOP WHERE COOL GAS KEEPS THE STRUCTURE WITHIN ITS ALLOWABLE TEMPERATURE REGIME. BERYLLIUM 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_4C) 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_4C) 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 "RECYCLES" 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



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RECUPERATED CYCLE PROVIDES SUPERIOR ENGINE OPERATION

THE RECUPERATED CYCLE BENEFITS THE ENGINE IN MANY WAYS. THE RECUPERATOR CONTRIBUTES TO THE SHIELDING REQUIREMENTS (PARTICULARLY GAMMA). IT ENABLES HIGH CHAMBER PRESSURE BY SATISFYING THE POWER BALANCE OF THE SYSTEM. IT ALSO HOLDS A LARGE AMOUNT OF THERMAL ENERGY. THERE IS SUFFICIENT THERMAL ENERGY WITHIN THE RECUPERATOR FOR SEVERAL RESTARTS. FROM THE REACTOR STANDPOINT, PERHAPS THE MOST IMPORTANT BENEFIT OF THE RECUPERATED CYCLE IS THAT IT PREVENTS LIQUID HYDROGEN FROM ENTERING THE CORE. THIS ELIMINATES THE POSSIBILITY OF HIGH EXCESSIVE REACTIVITY DUE TO VERY DENSE HYDROGEN IN THE CORE. IN ADDITION, THE RECUPERATOR DAMPS HYDRAULIC OSCILLATIONS THROUGH THE USE OF SMALL PASSAGES AND FLOW DIRECTION CHANGES. IT INSURES THE DELIVERY OF UNIFORM, STEADY FLOW TO THE FUEL ELEMENTS WITHOUT SHARP PRESSURE PULSES.

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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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 90 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 (IE. MELT 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 ZrC.

REACTOR SUMMARY: *KEY SPECS*

⊙ Reactor Power	1.56 GW
⊙ Thrust (200:1 nozzle)	75,000 Lb
⊙ Gas Outlet Temp (mixed mean)	2,700 K (4,400F)
⊙ Propellant Flow Rate	82 Lb/sec
⊙ Fuel Form	Binary (Zr,U)C/NbC
⊙ Particle Diameter	500 Micron (20 mils)
⊙ Bed 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	1.03 meters
⊙ Reactor Fueled Length	92.5 cm
⊙ Reactor Mass (no recup/ shielding)	5,340 Lb (2,420Kg)

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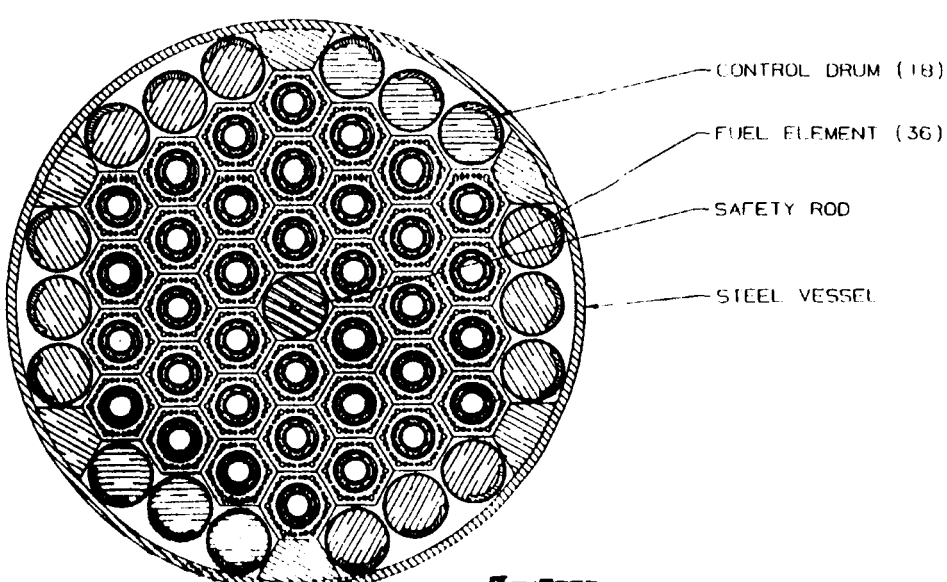
REACTOR FEATURES EFFICIENT INTEGRATION OF COMPONENTS

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 (IE 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 B_4C. 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.

keactor Features Efficient Integration of Components



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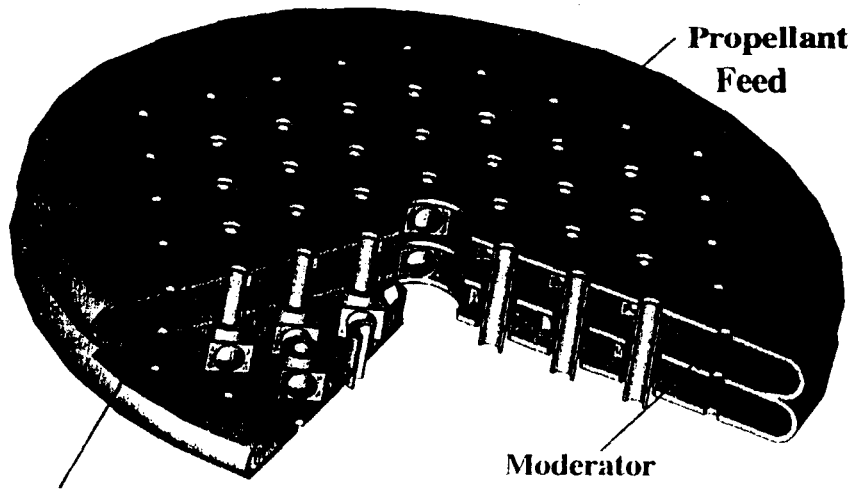
MANIFOLDS PROVIDE CORE SUPPORT

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 IT 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.

MANIFOLDS PROVIDE CORE SUPPORT



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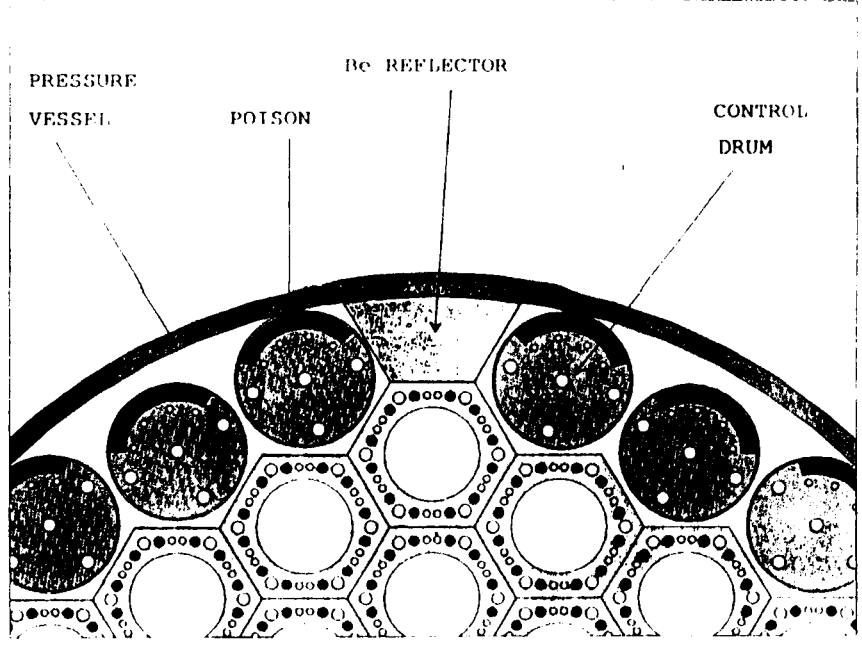
CONTROL DRUMS POSITIONED FOR MAXIMUM WORTH

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_4C 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 WORTHS 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.

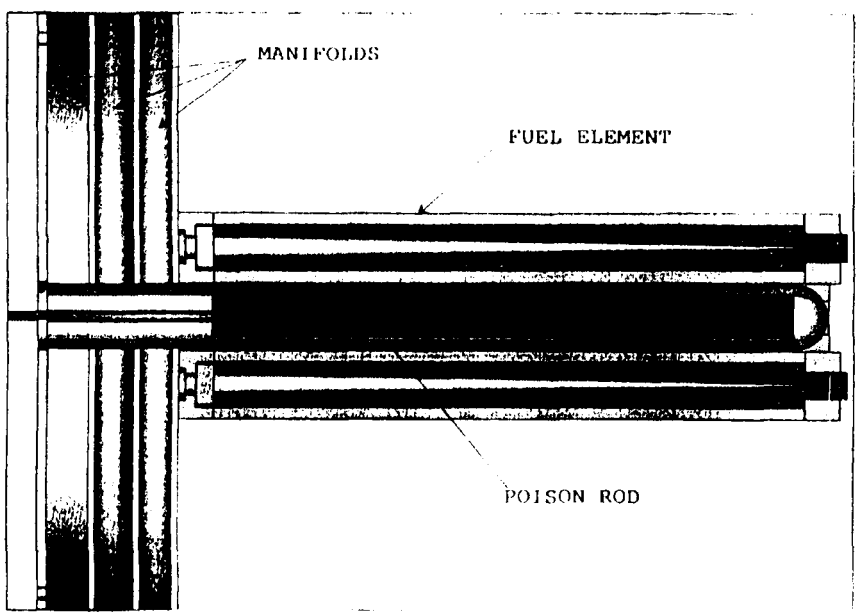
CONTROL DRUMS POSITIONED FOR MAXIMUM WORTH



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_4C IN A CYLINDRICAL SHAPE WITH OUTSIDE DIAMETER OF ALMOST 11 CM. A BeO 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 BE 0.01 DELTA-K/K SHUTDOWN EVEN IN THE MOST REACTIVE CONTROL POSITIONS

SAFETY ROD LOCATED FOR MAXIMUM WORTH



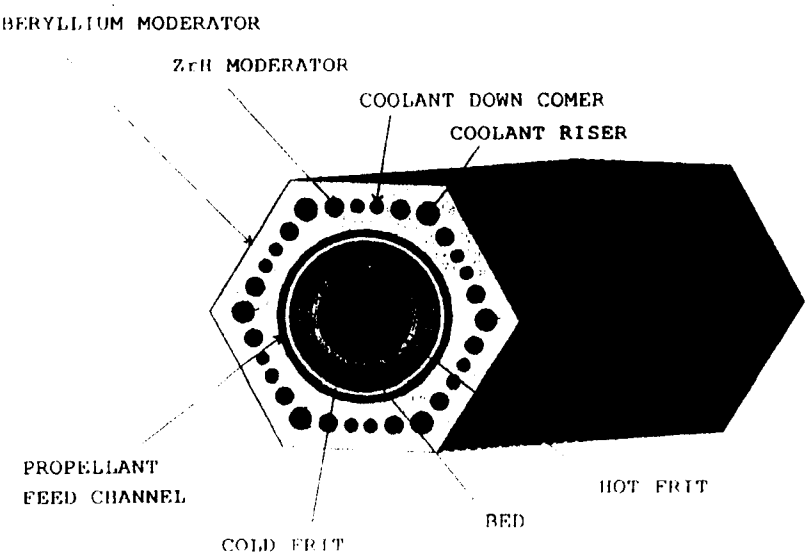
FUEL ELEMENT INTEGRATED EFFICIENTLY

THE PBR CORE IS HETEROGENEOUS WITH A COOLED MODERATOR JACKET SURROUNDING THE COLD FRIT, FUEL AND HOT FRIT. THE MODERATOR CONSISTS OF MACHINED BLOCKS OF BERYLLIUM JOINED TOGETHER TO FORM A RIGID JACKET NEARLY 1 METER IN LENGTH. THE BLOCKS ARE PRE-DRILLED WITH CARFULLY 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_2. 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 CORE. FURTHER OPTIMIZATION CAN SIGNIFICANTLY ENHANCE THE PERFORMANCE OF THE MODERATOR AND REACTOR.

THE COLD FRIT DISTRIBUTES THE FLOW TO THE FUEL BED IN PROPORTION TO THE LOCAL HEAT GENERATION. COOLANT FLOW IS DIRECTED RADIALLY 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 PLATELET 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 0.25 TO AVOID COMPRESSIBILITY EFFECTS.

FUEL ELEMENT INTEGRATED EFFICIENTLY



FUEL ELEMENT FLOW IS SELF CONTAINED

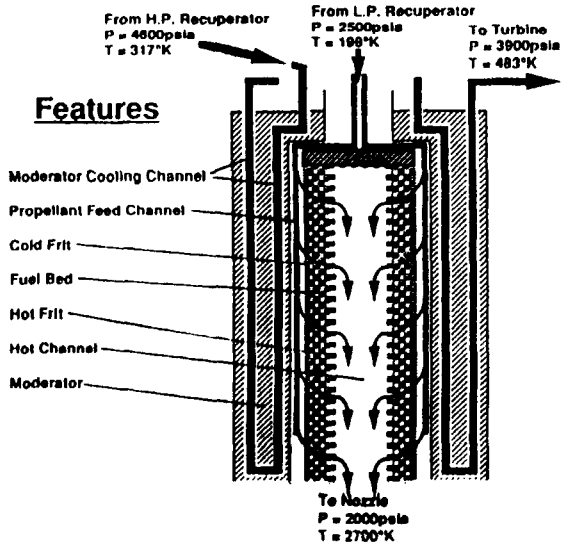
THE FUEL ELEMENT WAS ANALYZED USING FOTVE, A 1-D B&W PROPRIETARY COMPUTER CODE WHICH PREDICTS PRESSURE LOSSES IN THE DIFFERENT COMPONENTS OF AN ELEMENT, AS WELL AS TEMPERATURES OF THE PROPELLANT AND FUEL. EACH FUEL ELEMENT WAS INITIALLY ALLOTTED A PRESSURE DROP OF 500 PSID. RESULTS FROM FOTVE INDICATE 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 FOTVE 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 B&W 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

Fuel Element Cross-Section
(with Afterburner)



FUEL PARTICLE PROVIDES HIGH POWER DENSITY & TEMP

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 PBR'S, EACH CAPABLE OF MEETING DIFFERENT SETS OF MISSION REQUIREMENTS.

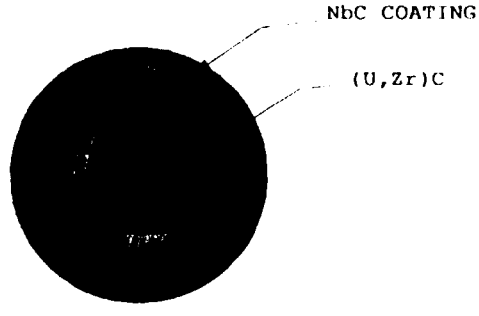
1. THE EARLIEST PARTICLE B&W DEVELOPED WAS THE SO-CALLED BASELINE PARTICLE. IT WAS BASED ON THE TRISO PARTICLE DEVELOPED FOR GAS-COOLED POWER REACTORS. IT CONSISTS OF A URANIUM CARBIDE KERNEL SURROUNDED BY TWO LAYERS OF CARBON (BUFFER, FOR CTE MISMATCH AND SEALANT) AND AN OUTER SHELL OF ZrC OR NbC. THIS PARTICLE IS CAPABLE OF OPERATING FOR 10'S TO 100'S OF SECONDS IN THE RANGE OF 2500-2800K 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 2700K FOR SEI APPLICATIONS.

2. WE ARE PRESENTLY DEVELOPING MIXED CARBIDE PARTICLES WHICH ARE DESIGNED TO REACH MAX. FUEL TEMPERATURES OF 3200-3400K. THEY ARE DESIGNED TO OPERATE FOR 100'S TO 1000'S OF SECONDS. MIXED CARBIDES SUCH AS (U,Zr)C AND (U,Nb)C WITH NbC 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 UO_2 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 700 K, AND HAVE VERY GOOD FISSION PRODUCT RETENTION BUT BE LIMITED TO A MAXIMUM TEMPERATURE OF ABOUT 3000-3100K.

4. IN THE EARLY STAGES OF LAB DEVELOPMENT ARE ADDITIONAL ADVANCED PARTICLE CONCEPTS WHICH ARE THEORETICALLY CAPABLE OF OPERATING FOR 1000'S SECONDS AT 3400K 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



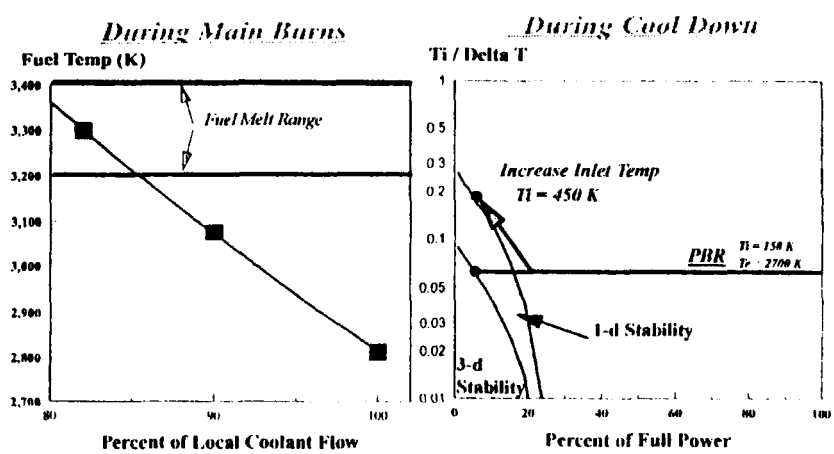
- **48 Liters of Fuel**
- **33 MW/l (ave)**
- **500 Micron Dia.**
- **Loading:**
  - 127 kg Uranium
  - 21 kg Carbon
  - 57 kg Zirconium
  - 60 kg Niobium
  - **265 kg Total Bed**
- **73% Enrichment**
- **3,300+ K Melt Approx.**

THE PBR NTRE IS THERMALLY STABLE

THE PBR IS THERMALLY STABLE. THE FUEL TEMPERATURE OPERATES AT ABOUT 2800K 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



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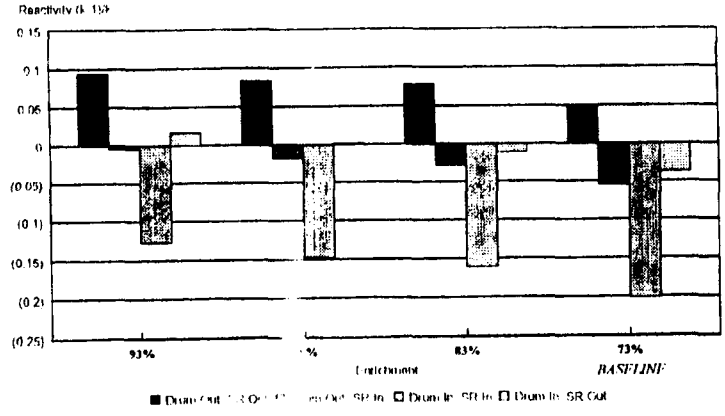
FUEL DESIGN BALANCES REACTIVITY AND CONTROL

THE REACTOR AND FUEL DESIGN IS FLEXIBILE. THE 48 LITER FUEL VOLUME WAS BASED ON 33 MW/LITER POWER DENSITY AND 1566 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 KERNAL SURROUNDED BY 30% NBC COATING, BY VOLUME, AND THE KERNAL CONTAINS 50% UC, FOR AVERAGE BED URANIUM DENSITY OF 2.7 G/CC. IT IS EXPECTED THE URANUIM 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 U^{235} ENRICHMENT WAS ALSO REDUCED, INCREASING THE NEGATIVE PROMPT TEMPERATURE FEEDBACK OF THE FUEL DUE TO THE DOPPLER COEFFICIENT OF THE LARGER FRACTION OF U^{238}. 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 0.12 DELTA K/K IS SOMEWHAT HIGHER THAN THE CONTROL DRUMS WORTH OF 0.10 DELTA-K/K.

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 (K-EFFECTIVE = 0.82); THE REACTIVITY PRIOR TO IMMERSION IS ABOUT -0.32. FOR THE UNCHANGED BASELINE DESIGN, THE REACTIVITY AFTER IMMERSION WAS 0.07 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 FUEL BED 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 (ie. no LH2)
- **THERMAL PROTECTION**
  - -Five Systems to Cool the Reactor
    - Twin Turbopumps (70 % full flow capacity ea.)
    - 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

• Bed Power Density	33	20	10	MW/l
• Reactor Power	1,560	1,560	1,560	MW
• Thrust	75,000	75,000	75,000	lb
• Reactor Mass	2,420	2,779	3,687	Kg
• T/W (reactor mass only)	14	12	9	
• Outlet Gas Temp	2,700	2,700	2,700	K
• Fuel Volume	48	79	157	Liters
• Propellant Flow Rate	37	37	37	Kg/s
• Number of Fuel Elements	36	60	60	
• Vessel Diameter	100	106	119	cm
• Reactor Fueled Length	92	92+	92+	cm

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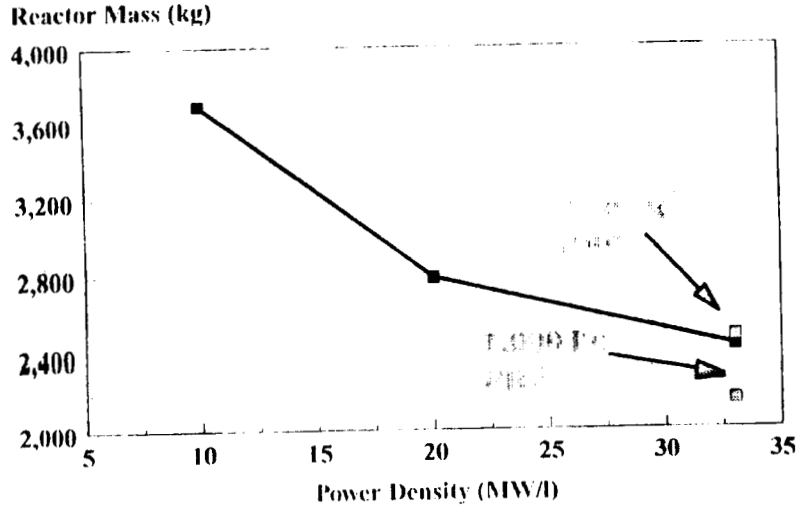
The PBR is Scalable in Power Density



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THE PBR IS SCALABLE WITH THRUST

SCALABILITY -

Thrust	75,000	40,000	25,000	lb
Reactor Power	1,560	832	520	MW
Reactor Mass	2,420	1,301	1,160	Kg
T/W (reactor mass only)	14	14	10	
Outlet Gas Temp	2,700	2,700	2,700	K
Fuel Volume	48	25	20	Liters
Propellant Flow Rate	37	20	12	Kg/s
Number of Fuel Elements	36	18	18	
Vessel Diameter	100	78	76	cm
Reactor Fueled Length	92	66	66	cm

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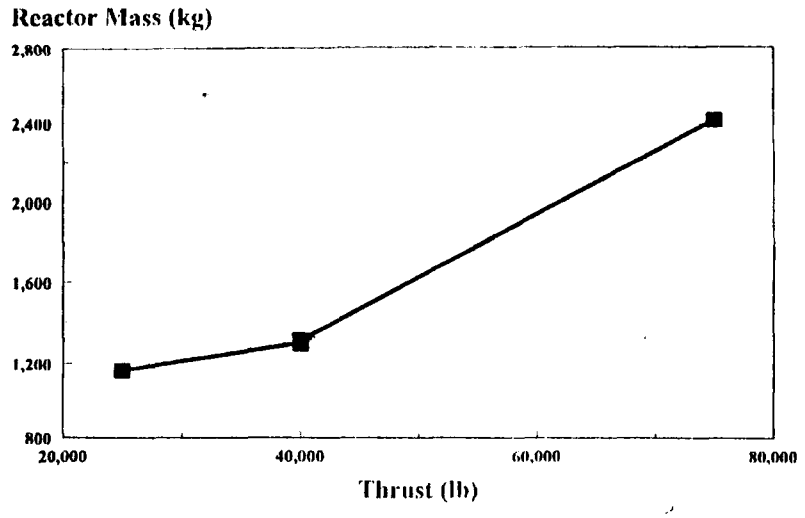
The PBR is Scalable with Thrust



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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.

THE PHYSICAL ARRANGEMENT OF THE FUEL BED IS BENEFICIAL IN TERMS OF FISSION PRODUCT RETENTION. THE OUTSIDE SURFACE OF EACH FUEL BED WILL OPERATE AT MUCH HIGHER POWER DENSITY THAN THE INSIDE SURFACE OF THE BED. THE FISSION EFFICIENCY OF THE INNERMOST PARTICLES IS NOT AS HIGH BECAUSE THE THERMAL NEUTRONS (WHICH WERE THERMALIZED BY THE MODERATOR) DO NOT PENETRATE FAR INTO THE BED. TO INCREASE THE EFFICIENCY OF THE BED AND REDUCE THE "BLACK-NESS", THE BEDS ARE MADE AS THIN (RADIALLY) AS POSSIBLE. IN FACT, THIS SO-CALLED SELF-SHIELDING IS TO A LARGE DEGREE WHAT DETERMINES THE NUMBER OF FUEL ELEMENTS IN THE PBR REACTOR. SINCE THE OUTER PARTICLES ARE PRODUCING THE MOST POWER THEY ALSO PRODUCE THE MOST FISSION PRODUCTS. THE BENEFIT OF THE PBR IS THAT THESE OUTER, HIGH POWER PARTICLES ARE ALSO THE COOLEST SINCE THE COLD GAS COOLS THEM FIRST AS IT MOVES RADIALLY THROUGH THE BED. THE HIGH DIFFUSION RATES TYPICAL AT HIGH TEMPERATURES WILL BE, TO A GREAT EXTENT, HALTED BY THE RELATIVELY COOL PARTICLES. ADDITIONAL FISSION PRODUCT RETENTION CAN EASILY BE DESIGNED INTO THE PARTICLE IN THE FORM OF BUFFER LAYERS OF OTHER COATINGS. THE TRADE IS THE FISSION PRODUCT RETENTION CAPABILITY VS THE URANIUM LOADING OF THE PARTICLE.
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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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

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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 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 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 Klbf 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 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 wafers located between its many transverse layers.

Design Rationale for NTRE With CIS Reactor Is Clear

Design Parameter	Rationale
1 H_2 Mixed Mean Outlet Temperature (2,900K)	Expected 4.5 Hours Fuel Life (Demoed > 1 Hour at 3000K)
2 Pc (2,000 psia) 3 Ae/At (300)	Best Mars Mission Performance With Reusable Engines
4 Power Cycle (Recuperated)	• Enable High Pressure With Simple Reactor • Enhances Transient Operation • No Weight Penalty (γ Shield)
5 Core Support (aft))	Optimum With CIS FAs (Test Data)
6 Nozzle (Single DeLaval) (H_2 Cooled Without Bleed Flow) (C-C Extension)	Near Term Technology Use (Formed Cu Platelet)
7 Neutron Shield (Internal)	Lowest Weight and Risk

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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

H_2 Gas Tc, °K	Minimum Achieved Life (Hours)	Maximum Achieved Life (Hours)	Life Expected in 3-5 Years (Hours)
3200	0.400	0.700	1.000
3100	0.655	1.111	1.637
3000	1.111	1.820	2.778
2900	1.954	3.100	4.855
2800	3.579	5.470	8.948
2700	6.856	10.08	17.14
2600	13.80	19.45	34.50
2500	19.40	39.57	73.56
2400	66.67	35.40	166.7
2300	162.4	197.1	406.0
2200	428.7	490.7	1,072
2100	1,242	1,333	3,105
2000	4,000	4,000	10,000
Tc at 4.5 Hours, °K	2,764	2,830	2,914
K	$8,574 \times 10^{-8}$	$3,789 \times 10^{-7}$	$8,574 \times 10^{-8}$
λ	49,132	46,160	49,132

Life = $Ke^{(\lambda/TC)}$ (Arrhenius Law)

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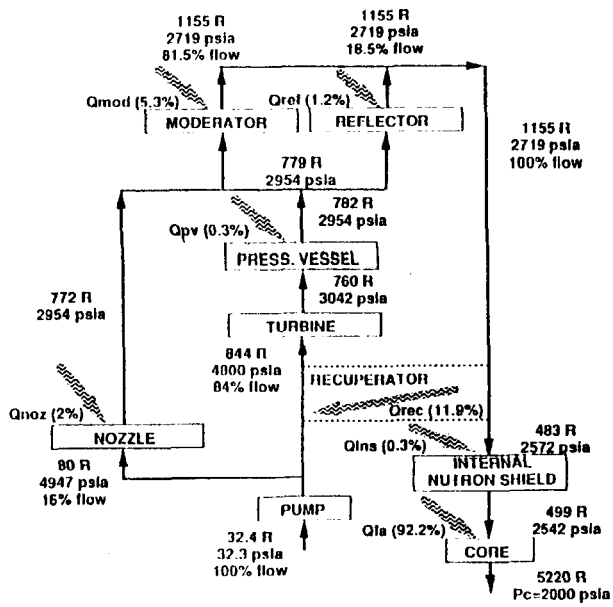
The CIS engine's turbopump is powered by a topping cycle so that no specific impulse is lost through turbine exhaust overboard bleed flows. In this power cycle reactor heat that is deposited in engine components (and must be removed continuously) is removed by the hydrogen propellant, heating pump discharge 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 aft 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 1150 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(t) 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.

CIS TOC Recuperated Topping Cycle Flow Schematic



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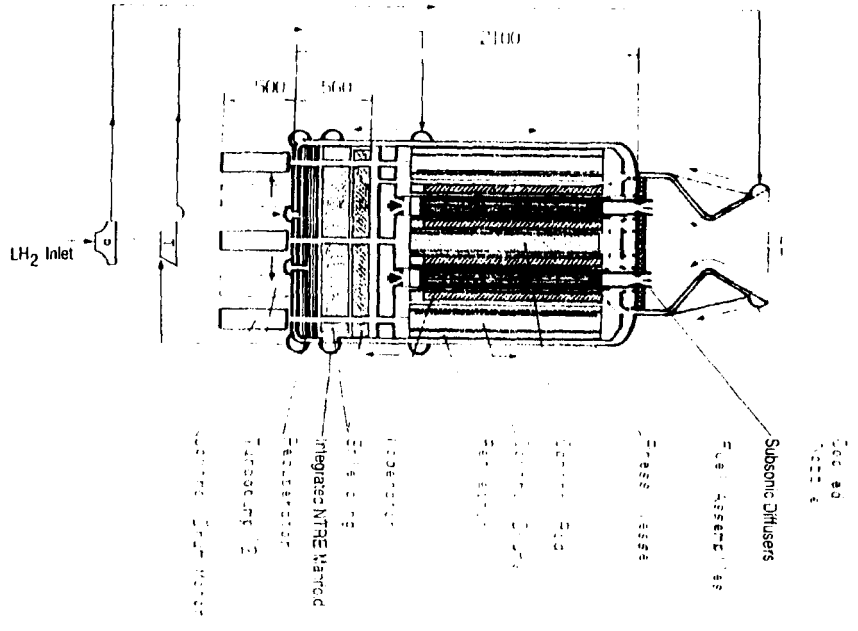
The CIS engine flow scheme begins with two parallel turbopumps. Pump discharge flow splits into two streams; the smaller one cools the copper nozzle through internal passages as in a regeneratively cooled nozzle for bipropellant rocket engines. The nozzle support is cooled by a small portion of this 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.

NTRE Flow Scheme With CIS Reactor



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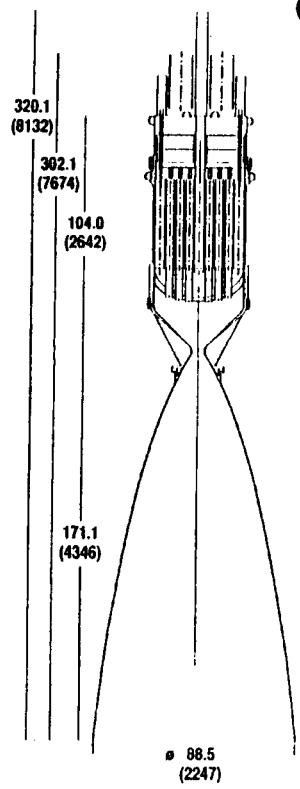
CIS Engine Layout



Thrust, lbf	75000
Chamber Pressure, psia	2000
Nozzle Area Ratio, Ae/At	300
Engine Specific Impulse, sec	959
Mars Mission Specific Impulse, sec	930
Engine Total Weight, lbm	15900
Thrust/Weight	4.7
Engines per Vehicle	2
Payload Returned to Earth, lbm	47067

Engine Weight Breakdown

Component	Weight, lbm
Uncooled Nozzle	232
Cooled Nozzle	965
Pressure Vessel, Reactor Manifolds & CSS	2536
Reactor, Reactor I&C	6613
Turbopump Assemblies (2)	410
Recuperator / Shield	2425
Secondary Shield	642
Plumbing/Valves	1320
Controls and Shielding	758

NTRE w/ Stage Power/Heat Removal

Stage Power & Heat Removal Sys Wt, lbm	2000
Engine with Power Sys Wt, lbm	17900
Mars Mission Specific Impulse, sec	949
Payload Returned to Earth, lbm	52929

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17.69 5/01/93

CIS Reactor Design

Richard Rochow

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17 89 Sch/44

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
- Reflector – Be
- Internal Shielding – ZrH(B); LiH, Recuperator Steel

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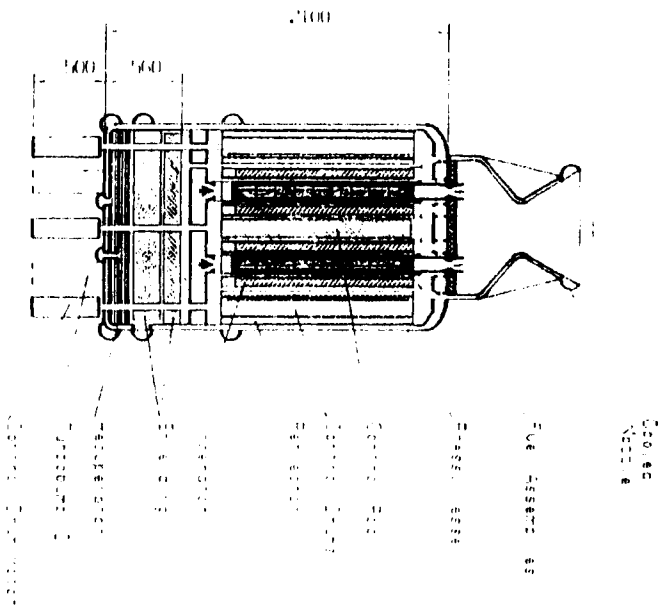
Main Characteristics of NRE Reactor	
Thermal Power, MW	1650
Neutron Spectrum	Thermal
Average Exit Temperature of Propellant, K	2900
Propellant Pressure in Nozzle Chamber, bar	136
Propellant Flow Rate, kg/s	35.4
Reactor Dimensions, mm:	
– Diameter	1050
– Height (including inner shielding)	2100
Mass, kg	5800

NRE Reactor Components Mass (kG)	
Core:	
– FAs	1250
– Moderator	710
Reflector	600
Inner Shielding	
– Zirconium Hydride	430
– Lithium Hydride	120
– Recuperator Material (Steel)	1100
Rotating Drum Drives (18)	360
Safety Rod Drives (7)	80
Supporting Structure	300
Pressure Vessel	850
Total	5800

CIS/NTRE Cross Section



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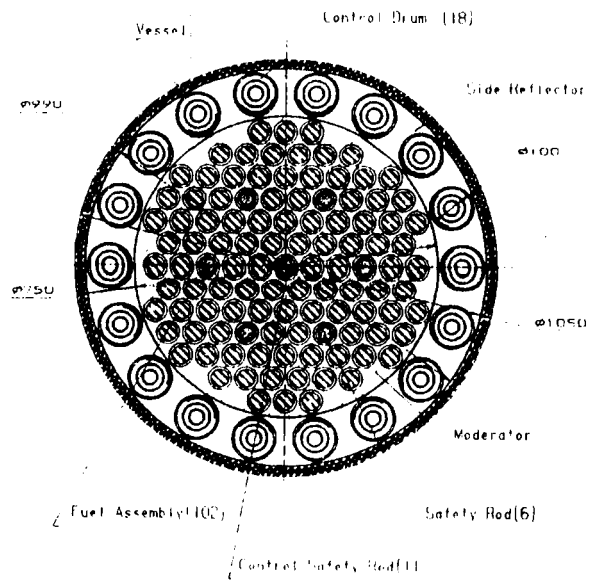
Main Core Parameters

^{235}U Loading, kg	14.1
^{235}U Enrichment, %	90
Average Specific Power Density in FE, MW/liter	20
Non-Uniformity Power Release	
– With the Core Radius	1.2
– With the Core Height	1.2
Thermal Neutron Flux Density, $cm^{-2}.S^{-1}$	1.6×10^{15}
Core Dimensions, mm	
– Diameter/Height	750/1000

CIS/NTRE Reactor Cross Section



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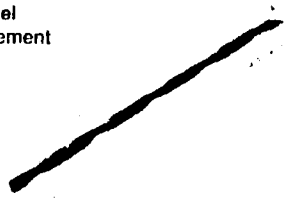
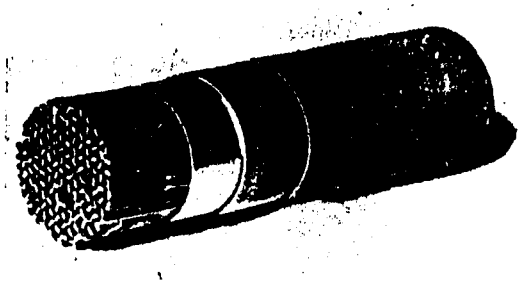
Fuel Assembly Description

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

Fuel Element





Required Performance Parameters

	T_{H_2}, °K	ts	δT/δt	qv MW/L	Pro-pellant	No. (Start)
Aerojet Engine	2900-3000	1000		25	H_2	1...2
In-Pile Tests	3000-3150	1500	~400	25	H_2	3
Max. Parameter Values (in-Reactor)	3100	4000	Up to 1000	35	H_2	12

IVG-1 Performance Parameters

Start-up	T_{H_2}, °K	ts	δT/δt	qv MW/L	Pro-pellant	Power, MW
1	3170	~500	100...150	~22.5	H_2	4.74
2	3110	~500	100...150	~22.5	H_2	4.81
3	3030	~500	100...150	~22.5	H_2	4.85

No Fuel Technology Improvements Required

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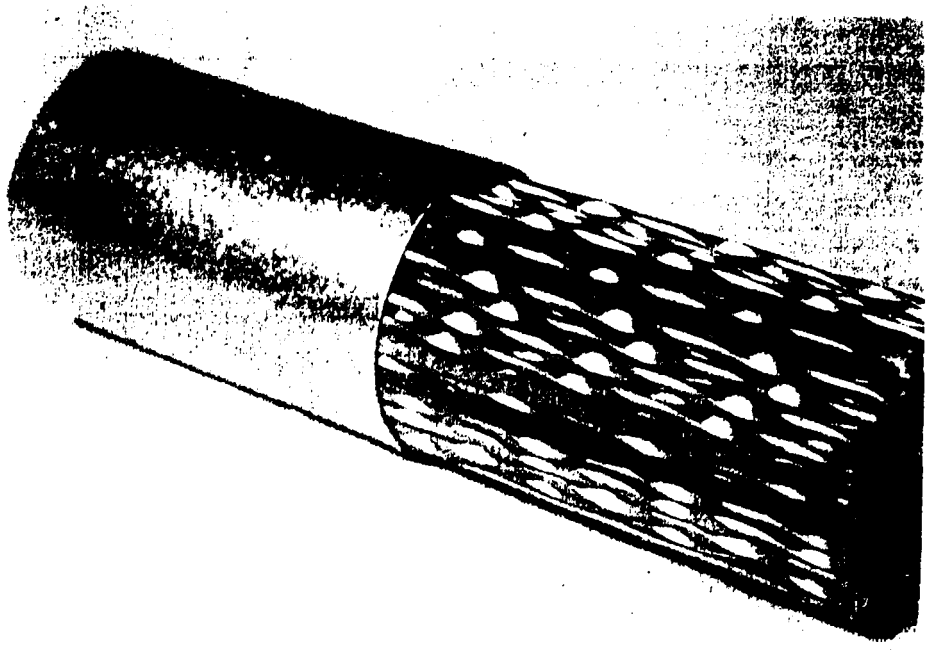
Fuel Element Description

Composition	UC + ZrC + NbC
Max. Fuel Loading of U	Up to 20%
Enrichment	90%
Max. Design Temperature (at Hot End)	3500 K
Operational Temperature (at Hot End)	
– Average	2950 K
– Maximum	3100 K
Average Power Density	
– in FE	20 kW/cm^3
– In FA	12 kW/cm^3
Amount FA Tested at H_2 Above 2,900 K	More than 10,000

Fuel Element Heating Bundle From IVG Reactor



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Reactivity and Control Characteristics

1. Maximum Reactivity Margin, % ΔK	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

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AEROJET/ENERGOPOOL/B&W NTRE

NASA LeRC Final Report

Prepared by R.F. Rochow
Babcock & Wilcox, ASE

Oct 23, 1992

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CIS CAPABILITIES

NUCLEAR REACTORS

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

DESIGN

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

NRE for Mars

MANUFACTURING

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

TEST FACILITIES

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

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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

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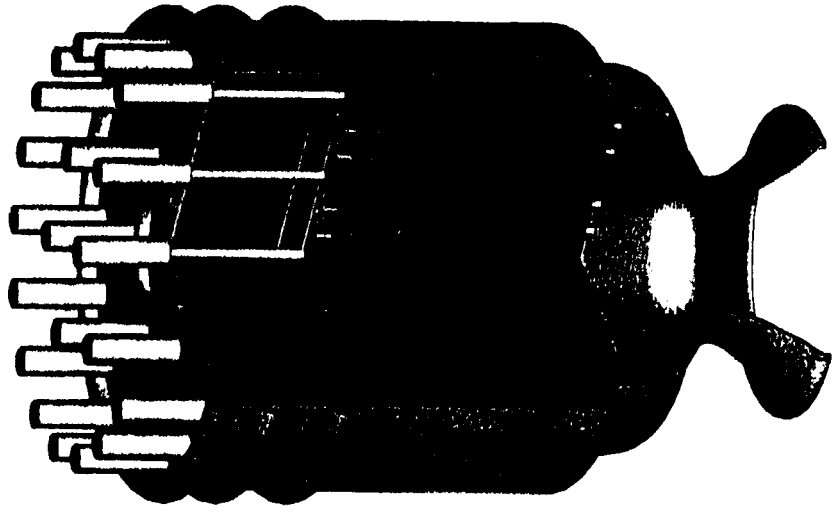
The CIS Reactor Utilizes Demonstrated Hardware



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REACTOR SUMMARY: *KEY SPECS*

• Reactor Power	1.65 GW
• Thrust (200:1 nozzle)	25,000 Lb
• Gas Outlet Temp (maximum)	2,900 K (4,240 F)
• Propellant Flow Rate	79 Lb/sec
• Specific Impulse	959 seconds
• Fuel Composition	(U,Nb,Zr)C
• Fuel Form ("Twisted Ribbon")	100x1.6x1.0 mm Approx
• Fuel Bundle Power Density (ave)	12 MW/l
• Core Power Density	3.7 MW/l
• Fuel Volume	162 liters
• Number of Assemblies (elements)	102
• Safety Shutdown	6 Safety Rods
• Vessel Diameter	1.05 meters
• Reactor Fueled Length	100 cm
• Reactor Mass (no recuperator/shielding)	4,150 kg (9,150 lb)

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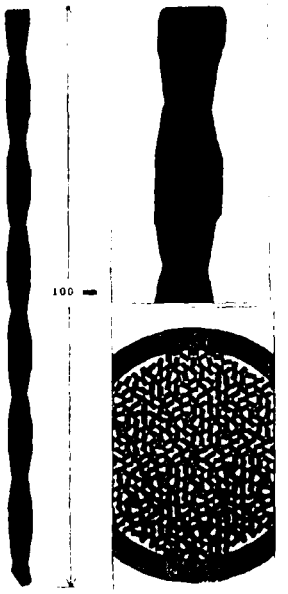
FUEL ELEMENT DESIGN HAS BEEN REFINED



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 2,900 K

3,000 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/l
in Fueled Volume	12 MW/l

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FUEL ASSEMBLY DESIGN HAS BEEN REFINED

FUEL COMPOSITION IS TAILORED
- *axially and radially*
- *for mechanical properties*

INSULATION HAS BEEN DEVELOPED
- *Monolitic NbC and ZrC tubes*
- *Temp capability up to 3,100 K*
- *greater than 50 % porosity*

HUNDREDS OF ASSEMBLIES TESTED

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 (outside)	45 mm
Overall Length	1.5 m
Overall Diameter	55 mm

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Advanced Concepts

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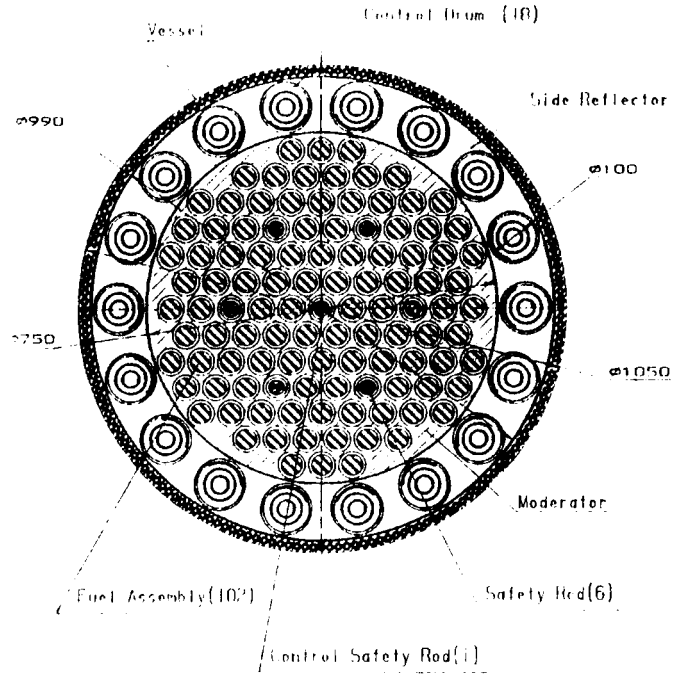
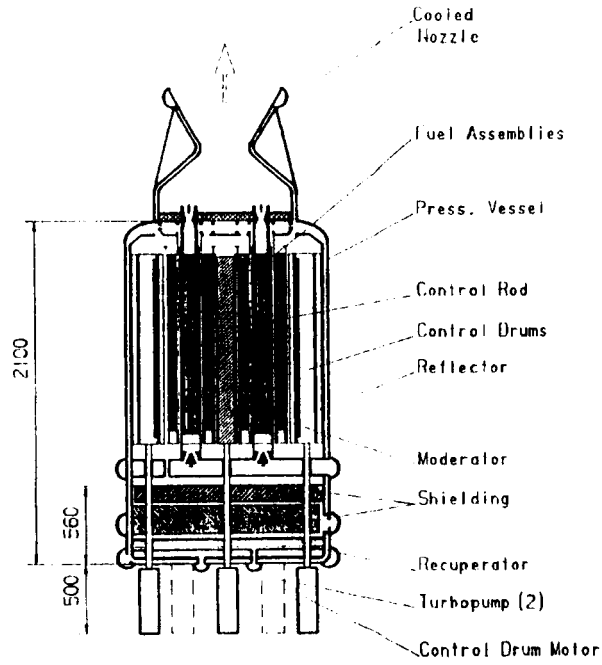


REACTOR RADIAL CROSS-SECTION



REACTOR LONGITUDINAL CROSS-SECTION

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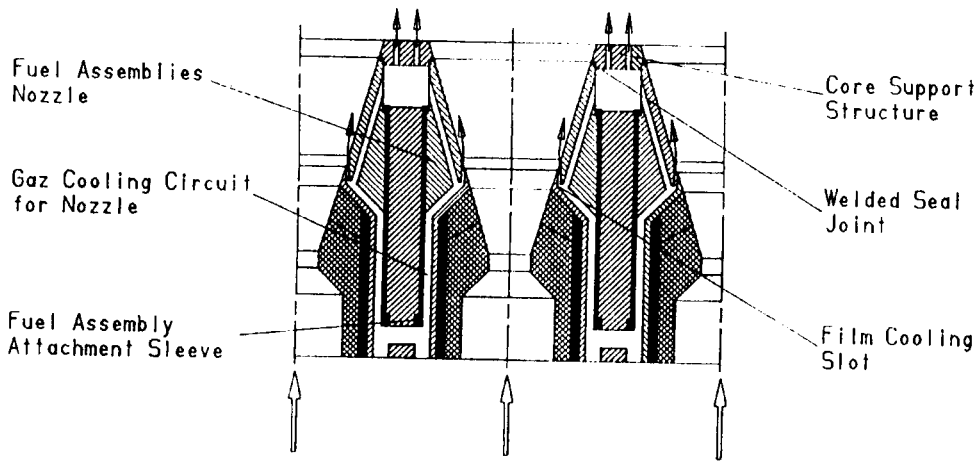
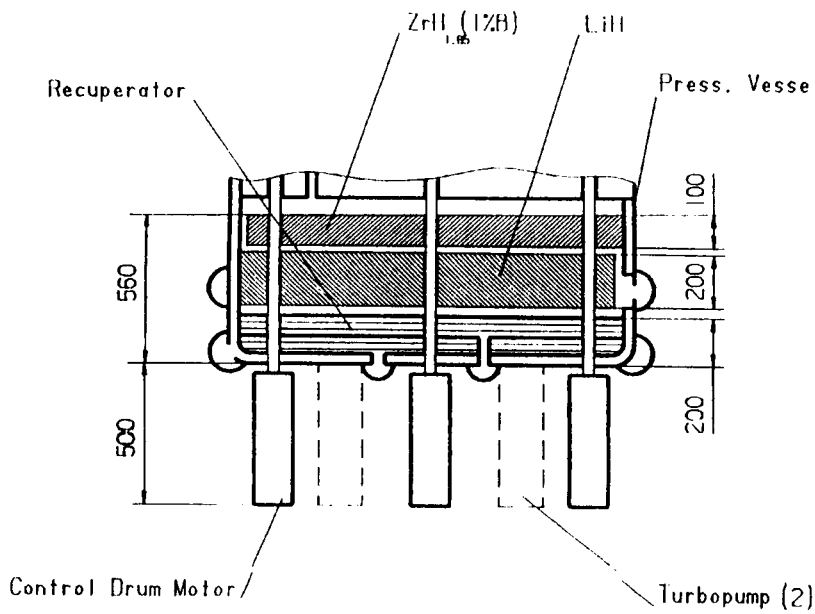


CORE SUPPORT STRUCTURE



INTERNAL SHIELD CONFIGURATION

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Technology Roadmap

- Demonstrated Reactor Technologies
- Technology Schedules

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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

Reactors / Parameters	NERVA	IGV-1 and IGR		
	Nerva Reactor	Achieved	Expected in 3-5 Years	Future
Hydrogen Temperature, °K	2550	3000	≥ 3,200	
Specific Impulse, S	850	975	> 1000	
Life-Time, Seconds	3600	4000 s in Hydrogen at T = 3000°K	~10,000 s in Hydrogen at T = 3000°K	~ 30,000 s in Hydrogen +SC at T ≥ 2800°K
Power Density, Mw/Litre	2.5	25	40	80
H_2 Temperature Transient, °K/sec		400		~ 1,000
Number of Starts-Ups	12	12	20	
Vibro-Strength g/Frequency (Hz)/ Testing Time (h)		15/ Up to 3 KHz/50 hrs		
Impacts, g		300		

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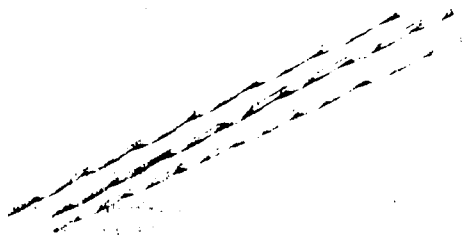
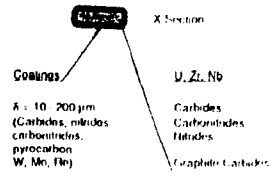
Russians have developed several families of high temperature nuclear fuel and have tested them in many ways in material laboratories, nuclear reactors, and in hot cells for post-irradiation properties. Carbide fuels have demonstrated the highest temperature capabilities with good material properties. 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, aft 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, carbonitrides and pyrocarbon mixtures of tungsten, molybdenum, and rhenium have been developed and tested for corrosion resistance and thermal strength characteristics.

Fuel Element Rods Have Been Tested Thoroughly

Rod Fuel Element





Test Conditions

Parameter			Before Reactor	In Reactor	Post-Reactor
Strength	Tension	Temperature, K	2100	T ≤ 3100 (+ 400 K)	10^{20} neut/cm² T ≤ 300K
	Bending		<3500		
	Torsion		2100		
Thermal Technology	Heat Conductivity		2300		
	Heat Capacity		2400		
	Thermal Expansion		2800		
	Plastic Deformation		<3500		
Evaporation of Material		Vacuum, He, H_2	< 3200		
Melting			3900		
Radiation Swelling				T ≤ 3200 (He, H_2, vac)	T ≤ 2500K
Output of Fission Products				T ≤ 3200	
Interaction with H_2, N_2 Additives of O_2, H_2O, CH_4			T ≤ 3500 P ≤ 20MPa τ ≤ 800s	T ≤ 3100 P ≤ 10MPa τ	
Surface Erosion neutrons/cm2			T ≤ 3000 10^2 - 2 10^5		
Heat Generation kW/cm³			90	30	

Operation Conditions

	Graphite Carbides	Carbo nitrides	Carbides
T, K	<2700	<3100	<3500
I, kW	<80	< 40	<40
τ, cm³			
τ, s	10^4	15000	$5x10^3$ - >7000
Coolant	H_2	N_2, H_2 + $8N_2$	H_2 H_2 + N_2

Coatings reduce relative fission products release by 30 - 200 times

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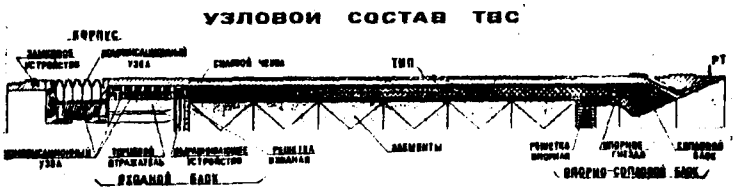
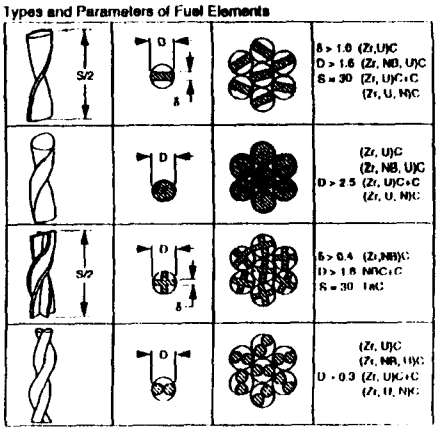
Engeropool fuel assemblies for NTRE are about a meter long and 30 to 45 mm in diameter. The forward, inlet end runs cooler than the rest of the assembly, and it contains an adjustable flow metering orifice, neutron reflector, and thermal expansion compliance (bellows). The center of the fuel assembly 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



Types and Parameters of Fuel Elements



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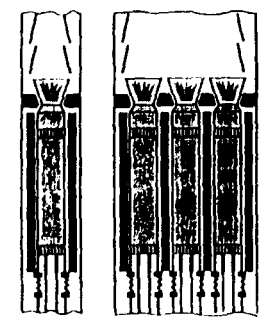
Fuel assemblies have been tested in the steady state nuclear reactor, IVG-1, both singly and in clusters of seven in hydrogen, and under high temperature and pressure at thermal neutron fluxes above 10^{15} neutrons/cm^2-sec.

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_v^{max} 35. MW
4. Heat Flux q_s^{max} 13 MW/m
5. H_2 Temperature Transient 150°K/s
6. Reactor Starts Per Month, 2
7. Thermal Neutron Flux ≈ $2 \cdot 10^{15}$ neutrons/cm^2 -s

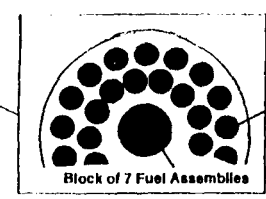


Tested Object: Module of Active Zone With 7 FA

H_2 Flow Rate: 1.6 kg/s
Pressure of H_2: 16 MPa

Tested Object: 1 FA

H_2 Flow Rate: 0.7 kg/s
Pressure of H_2: 14 MPa



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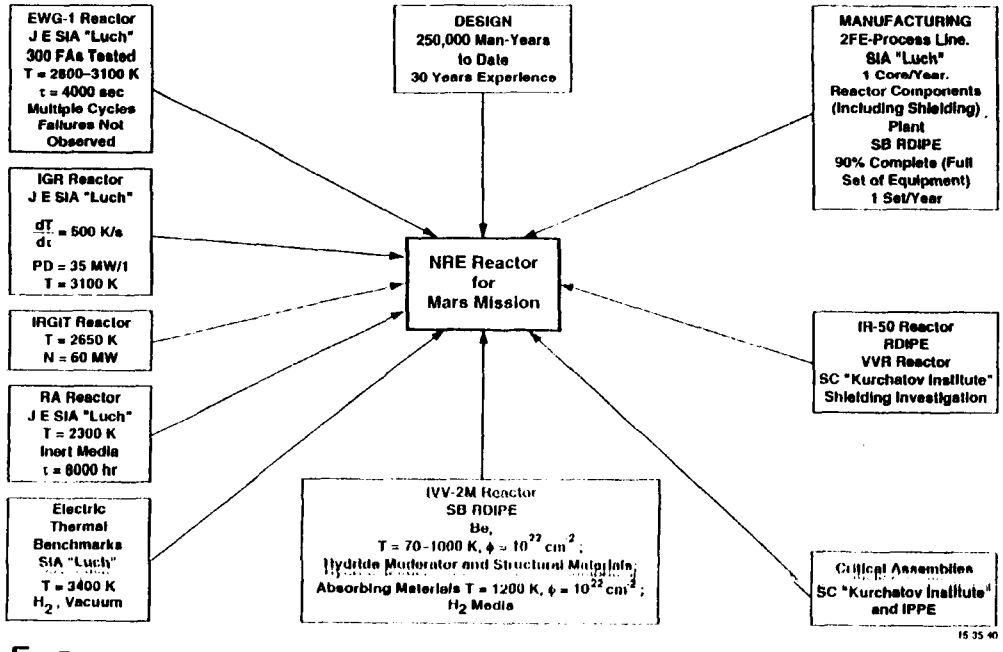
Many reactor materials have been fabricated and tested by Energopool in laboratories, in reactors, and in post-irradiation hot cells. Structural, neutron moderating, neutron reflecting, and neutron absorbing materials have been tested to high fluxes, fluences, temperatures, and immersion times in hydrogen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

Materials Testing Results

Materials	Test Parameters					Notes
	Neutrons cm^2/s	Neutrons cm^2	T, °K	Life-Time, Hours	Medium	
Steel and its Alloys (18 Types)	10^{13} 10^{14}	up to $3 \cdot 10^{20}$	77 . . . 1100	500 - 12,000	H_2, He Vacuum	
Be, Be-Al, Be with Coatings	10^{12} . . . 10^{14}	up to $2 \cdot 10^{21}$	77 . . . 1200	500 - 2,400	H_2, He H_2O Vacuum	During Some Experiments T = 20°K q_v = 150 W/cm^3
ZrH, ZrH + B, LIH	10^{12} . . . 10^{14}	$4 \cdot 10^{19}$ up to $2 \cdot 10^{21}$	400 . . 1,000	500 - 12,000	H_2 CO_2 He	
Absorbing Elements	10^{13} . . . 10^{14}	up to $2 \cdot 10^{21}$	600 . . 1,300	500 - 10,000	H_2, He Vacuum	q_v^{max} = 700 W/cm$_3$

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)



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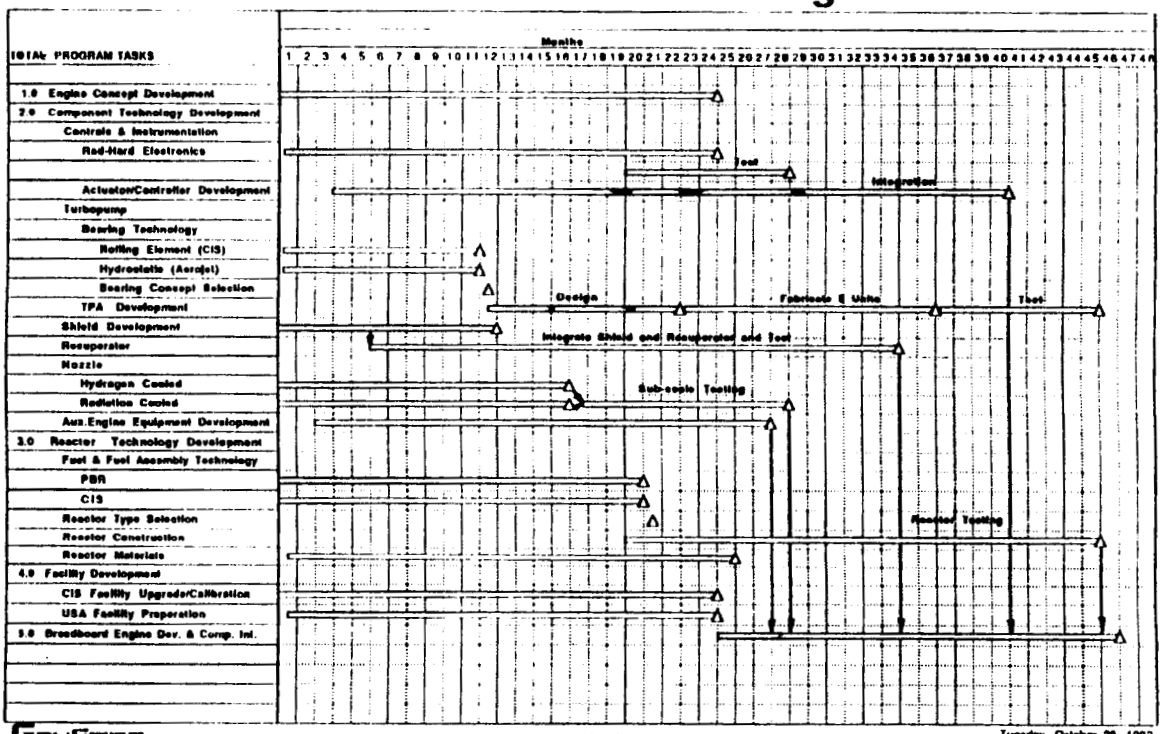
Parallel 4-Year Technology Development for an NTRE Breadboard Engine



Summary

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Our Integrated Engines Provide

Safety and Reliability

- Simple Thermodynamic Cycle
- Integrated Auxiliaries Simplify Propulsion
  - Start System
  - RCS (No Igniters, O_2, Combustion)
  - Electric Power and H_2 Refrigeration
  - Four Core Cooling Systems
- Improved Engine Start (Preheat)
  - No Thermal Shocks
  - Enhances Multiple Engine Safety
  - No LH_2 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

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Our Integrated Engines Provide

Mission Benefit

- Improved Mission Average Isp
  - Heterogeneous Reactor
  - Greatly Reduced After Cool Loss, Save > 100 K lb LH_2
  - LH_2 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

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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 ΔP Scrubbers
- Reduced ETO Cost
  - Reduced IMLEO
  - Smaller Payload Bay
- Design Flexibility and Growth Potential Reduces Cost
  - Recuperated Cycle
  - Electrical Power System

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