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NUCLEAR GAS CORE PROPULSION RESEARCH PROGRAM

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NUCLEAR GAS CORE PROPULSION RESEARCH PROGRAM

Advanced Nuclear Propulsion Studies

- To develop a hydrogen properties package at temperatures 10 - 10,000 K and pressures 0.1 - 200 atm.
- To develop a transient simulation program for parametric studies and design analysis of high temperature nuclear rockets

Nuclear Vapor Thermal Rocket (NVTR) Studies

- To conduct nuclear and thermal design optimization of the NVTR fuel, fuel elements and core geometry
- To develop a system and parametric analysis code for the NVTR

Ultrahigh Temperature Nuclear Fuels and Materials Studies

- Determine properties of UF_4 and UF_4 mixtures nuclear fuels at temperature - pressure ranges of interest to advanced nuclear propulsion systems
- Measure/model high temperature compatibility of UF_4 with refractory carbides.

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The objectives of these studies are to develop models and experiments, systems and fuel elements for advanced nuclear thermal propulsion rockets. The fuel elements under investigation are suitable for gas/vapor and multiphase fuel reactors.

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EVALUATION OF PARA- AND DISSOCIATED HYDROGEN PROPERTIES AT T = 10 - 10,000 K

- NASA/NIST Property Package
  (13.8 < T < 10,000 K and .1 < P < 160 bar)
  - Molecular Weight, Density
  - Enthalpy, Entropy
  - Specific Heats, Specific Heat Ratio
  - Thermal Conductivity, Viscosity
- Hydrogen Property Generator Code Features
  - Linear Interpolation
  - Natural Cubic Spline
  - Least Square Curve Fitting with Pentad Spline Joint Functions
- Graphical Representation of Properties

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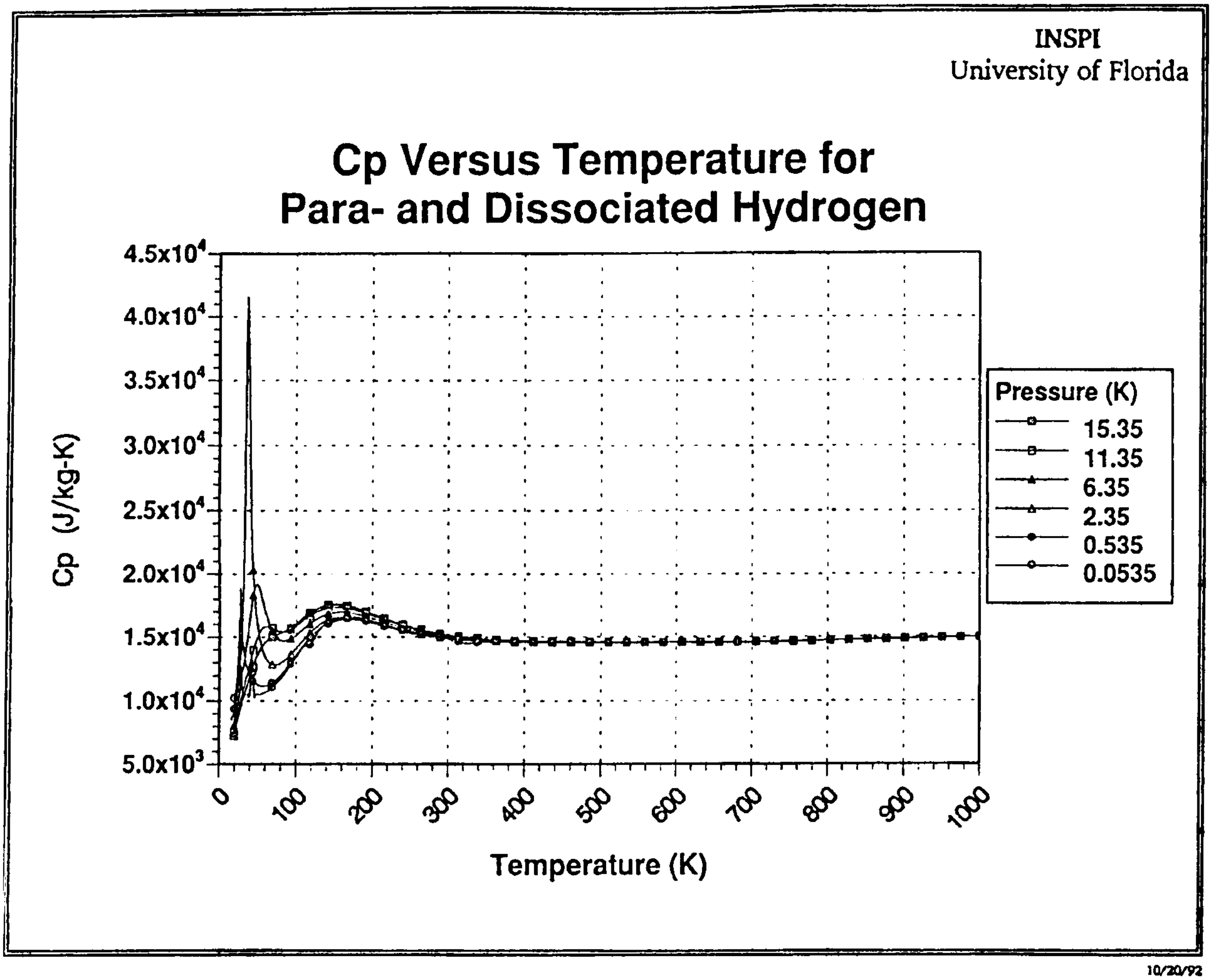
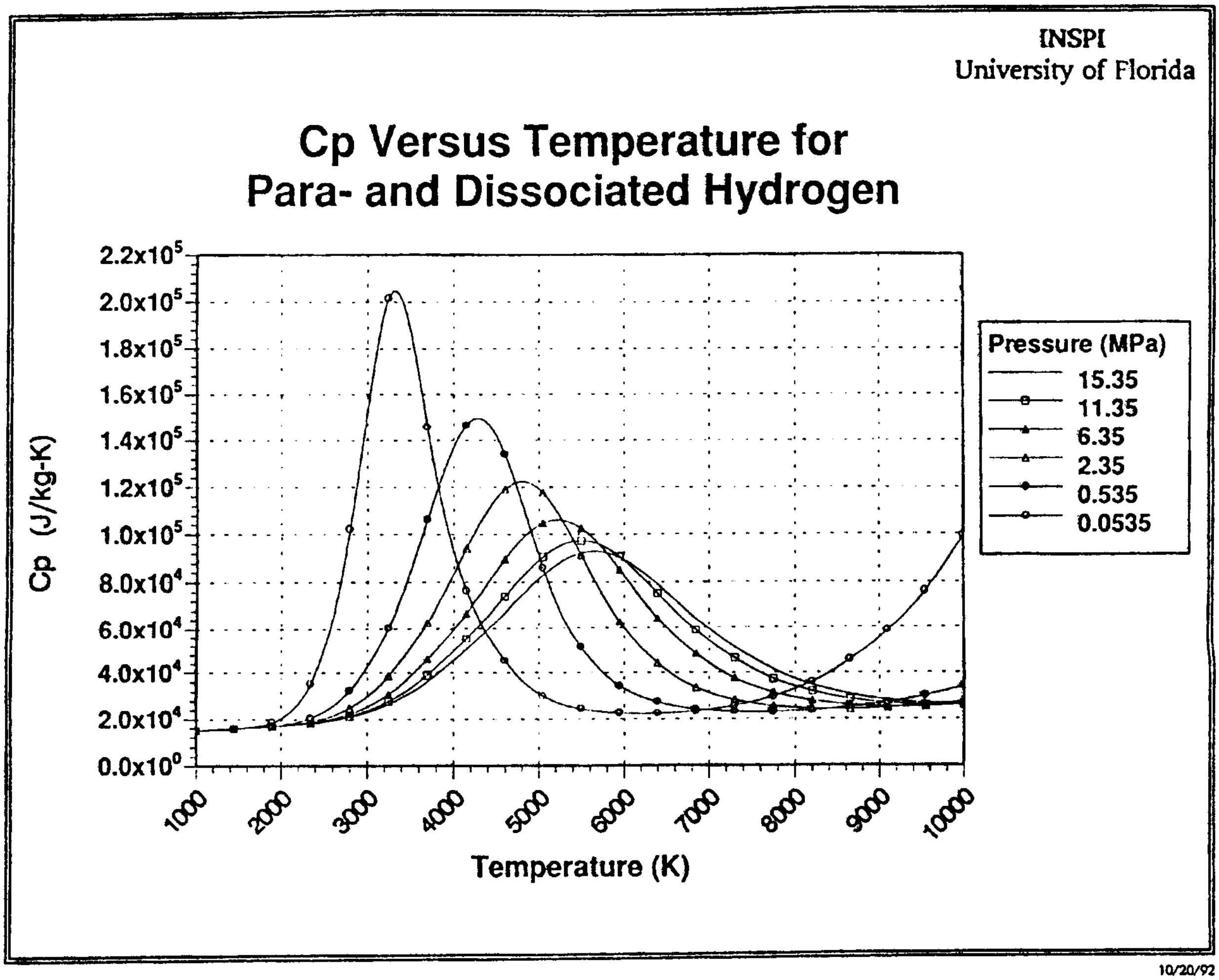
The hydrogen property generator utilizes two interpolation techniques and a least-square curve fitting routine with a pentad spline function which links least-square fitted pieces together. The property generator package is incorporated into the NTR simulation code and also into a system of CFD-HT codes.



Heat capacity of hydrogen near the critical point shows large gradient and oscillatory behavior. At p = 2.35 MPa the property package indicates a sharp peak for C_p.



At higher temperatures, the heat capacity data displays smooth behavior. The sharp increase in C_p value at temperatures above 2000 K is due to hydrogen dissociation.

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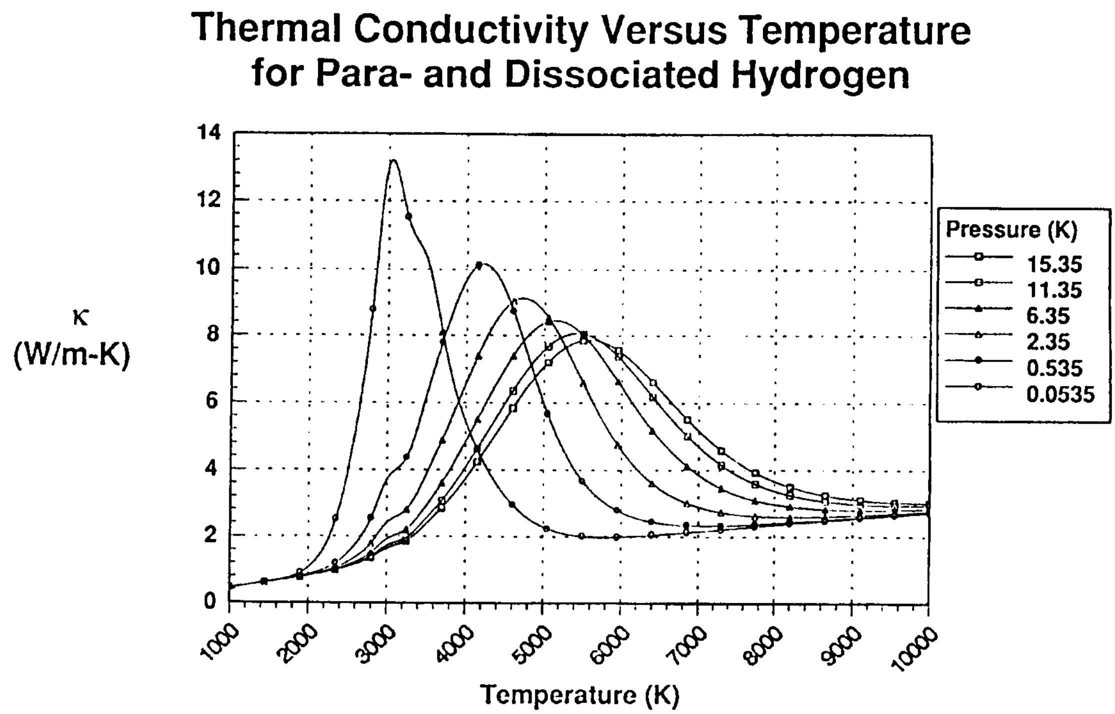

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The hydrogen property package is a combination of two subpackages covering the temperature ranges 10 - 3000 K and 3000 - 10,000 K, respectively. The large change of gradients in hydrogen viscosity at 3000 K indicates a non-physical flaw in the model.

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MODELING AND ENGINEERING SIMULATION OF NUCLEAR THERMAL ROCKET SYSTEMS

- Modular Thermal Fluid Solver with Neutronic Feedback
- Main Component Modules:
  - Pipes, Valves, Mixer
  - Nozzle Skirt
  - Pump, Turbine
  - Reflector, Reactor Core
- Hydrogen (Para- and Dissociated) Property Package
  - $10 \leq T \leq 10{,}000$ K
  - $.1 \leq P \leq 160$ bar
- Models Developed for NTVR, NERVA and XNR 2000
- CFD and Heat Transfer Models for Main NTR Components

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A detailed program for modeling of full system nuclear rocket engines is developed. At present time, the model features the expander cycle. Axial power distribution in the reactor core is calculated using 2- and 3-D neutronics computer codes. A complete hydrogen property model is developed and implemented. Three nuclear rocket systems are analyzed. These systems are: a 75,000 lbf NERVA class engine, a 25,000 lbf cermet fueled engine and INSPI's nuclear thermal vapor rocket.

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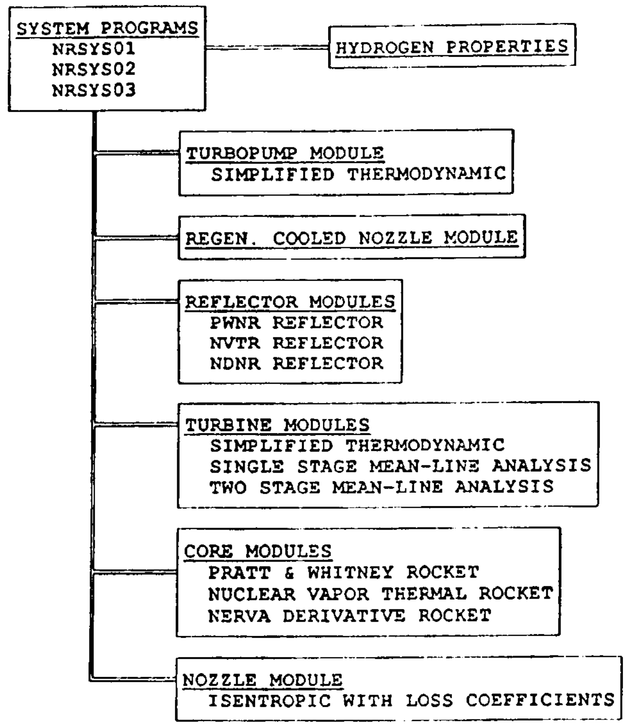
NUCLEAR THERMAL ROCKET SIMULATION SYSTEM



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The main program links all the component modules and iterates to arrive at the user specified thrust chamber pressure and temperature and thrust level. Reactor power and propellant flow rate are among outputs of the simulation program. Fuel elements in the core module are prismatic with variable flow area ratio. Each module divides the relative component into N segments.

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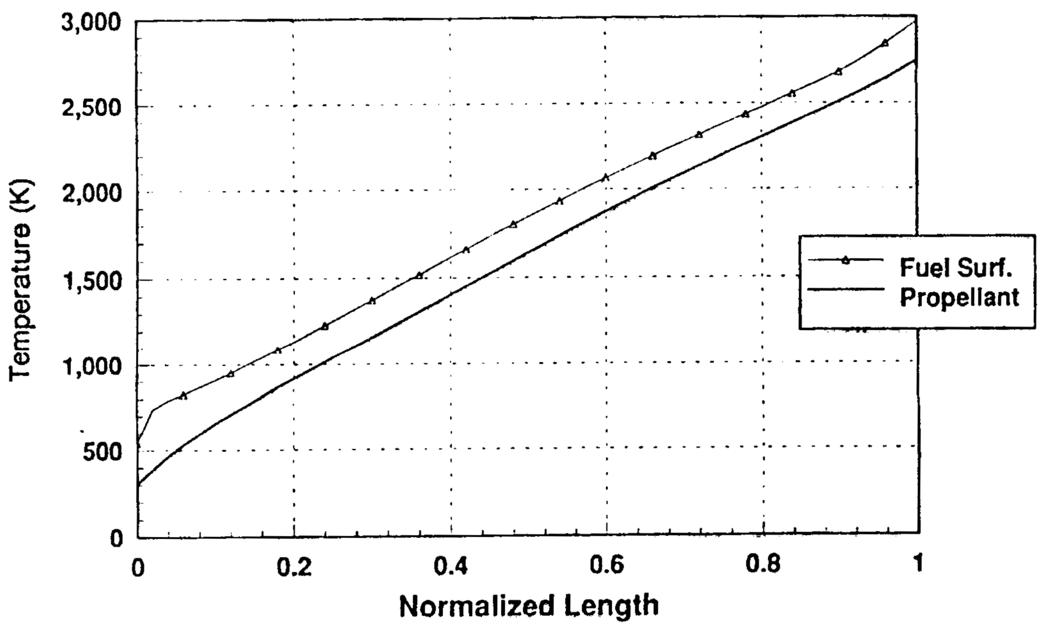
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



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Axial temperature distribution of NVTR fuel surface and propellant in an average power rod. Reactor power is adjusted to achieve the thrust chamber temperature and pressure of 2750 K and 750 psi, respectively.

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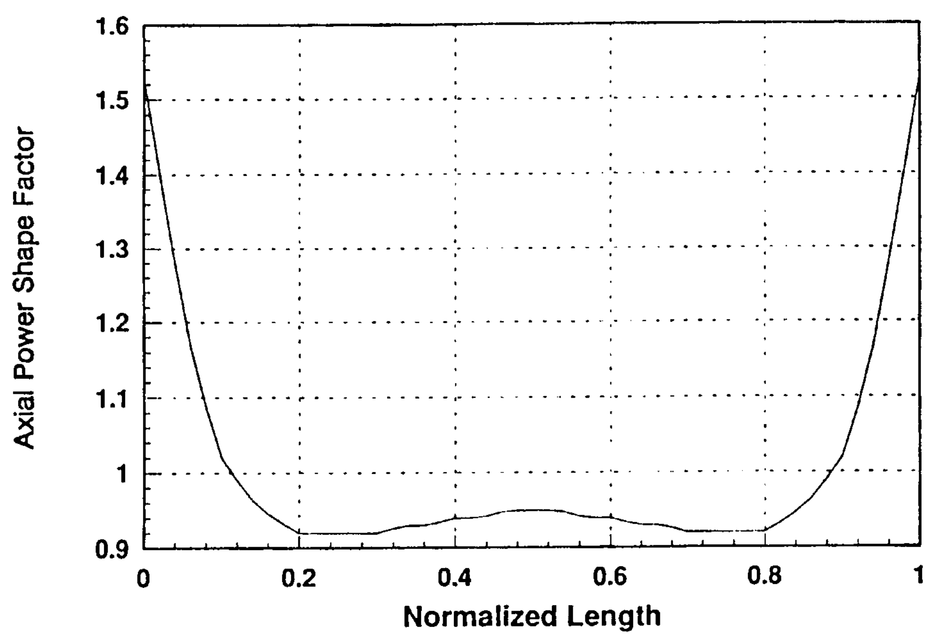
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



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Normalized axial power distribution in C-C composite fuel matrix NTVR, calculated by DOT-2 S_n code. The axial power shape factor is an input for the simulation code.

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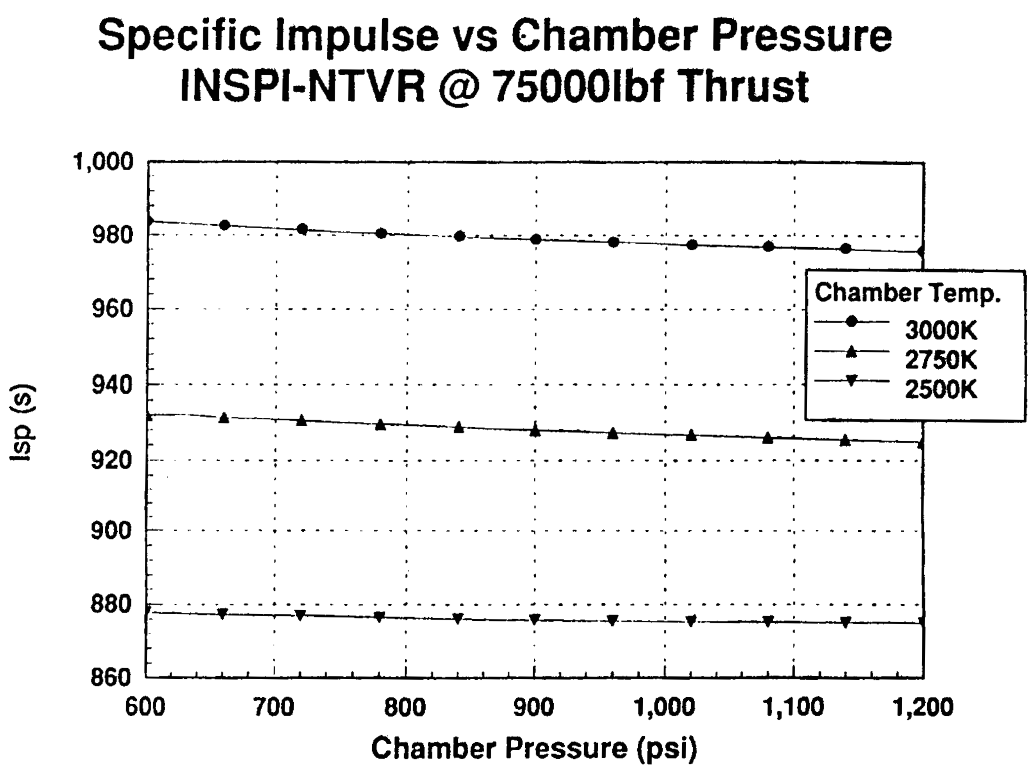

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Parametric study of thrust chamber pressure and temperature impact on Isp of NTVR. At higher pressures Isp is less sensitive to thrust chamber temperature.

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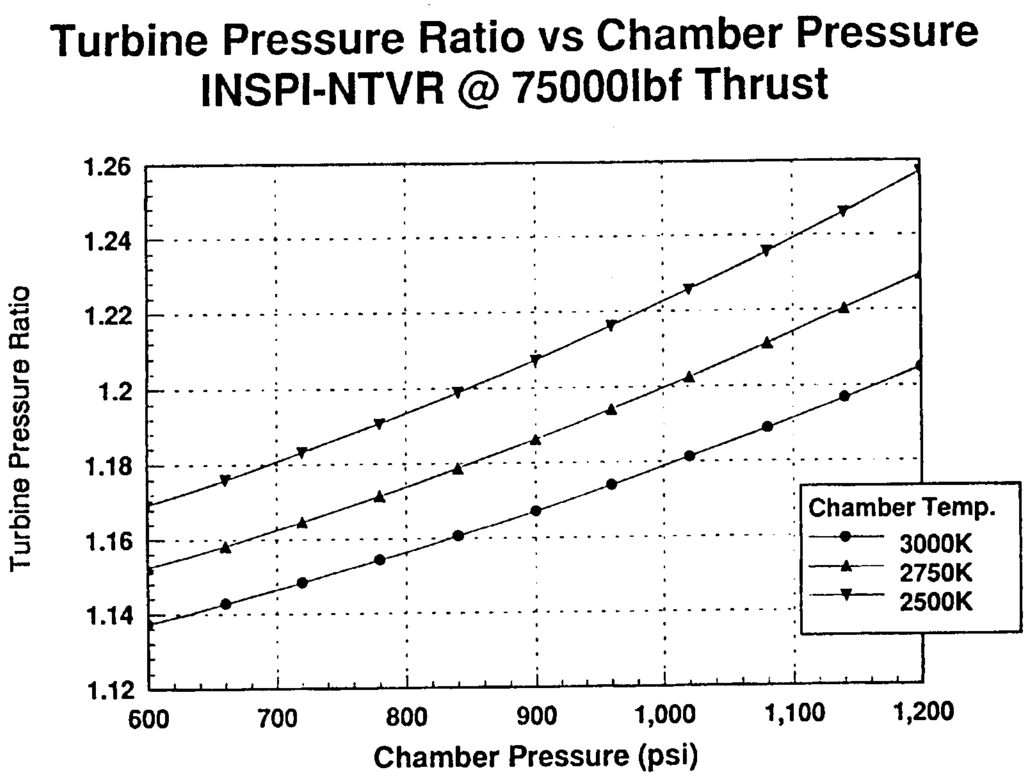

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Turbine pressure ratio is sensitive to both thrust chamber pressure and temperature. For thrust chamber pressure of 1200 psi and temperature of 3000 K, the turbine pressure ratio of 1.26 is well within the range of available technology.

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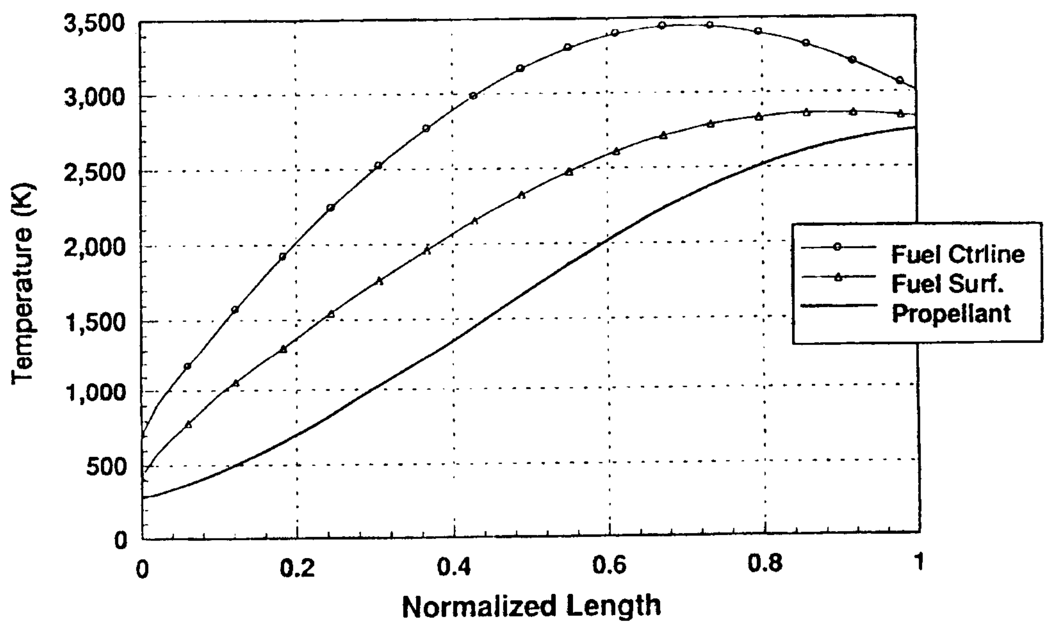
NERVA Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



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Axial temperature profiles for NERVA-75,000 lbf engine are presented. The maximum fuel temperature is 3490 K at .7 m from the core entrance.

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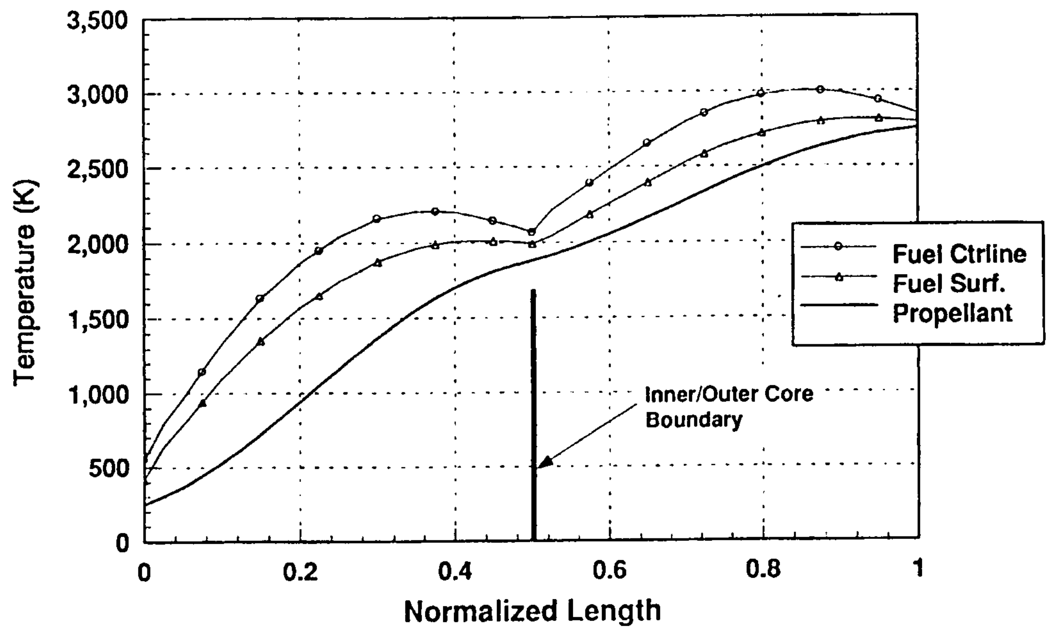
P&W XNR2000 Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=25000lbf



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Axial temperature distribution in XNR 2000 core is presented. XNR 2000 features a two path folded flow core fueled with CERMET. The maximum fuel temperature is 3000 K at about 85% from the entrance to the inner core region.

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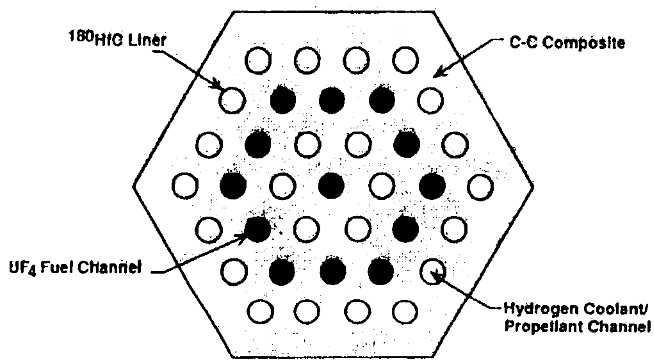
NUCLEAR VAPOR THERMAL ROCKET (NVTR)

NVTR PERFORMANCE

Thrust = 75,000 lbs
Isp = 1000 sec
H flow = 30 kg/sec
H TEMP = 3100 K
T/W = 5

CORE: 2000 fuel element
Radius = 0.5 m
Height = 1.5 m
Fuel channel/ele. = 24-32
H channel/ele. = 24-32
Critical mass = 20 kg
H pressure = 100 atm
UF_4 pressure = 100 atm
Fuel Center T = 4500 K

FWD Reflector (BeO) = 15 cm
Aft Reflector (C-C Composite) = 25 cm
Radial Reflector (BeO) = 15 cm



Schematic of NVTR Fuel Element

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The Nuclear Vapor Thermal Rocket (NVTR) is an advanced thermal propulsion engine, using vapor or multiphase nuclear fuel, with predicted performance at the upper limits of solid core reactors. The NVTR also serves as base technology development toward high performance Gas Core Reactors.

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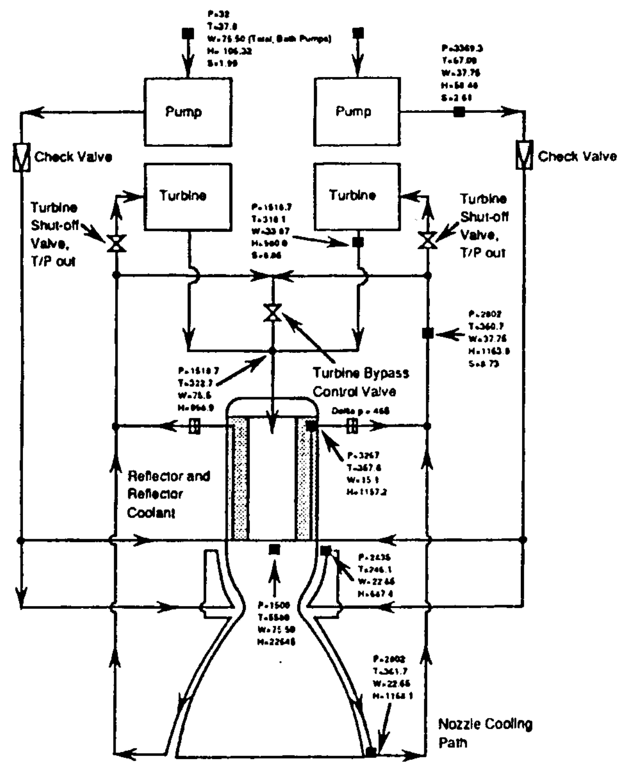
NUCLEAR VAPOR THERMAL ROCKET (NVTR)
75 K-lbf NVTR, Expander Cycle, Dual T/P



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Design Values

Pump Flowrate (Total)	75.50	lb_m/sec
Pump Discharge Pressure	3,369	psia
Number Of Pump Stages	2	
Pump Efficiency (%)	78.26	%
Turbopump Rpm	70,000	RPM
Turbopump Power (Each)	8,802	HP
Turbine Inlet Temp	361	deg-R
Number Of Turbine Stages	2	---
Turbine Efficiency	81.51	%
Turbine Pressure Ratio	1.85	---
Turbine Flow Rate (Each)	33.87	lb_m/sec
Reactor Thermal Power	1,759	MW
Fuel Element Transferred Power	1,724	MW
Nozzle Chamber Temperature	5,580	deg-R
Chamber Pressure (Nozzle Stagnation)	1,500	psia
Nozzle Expansion Area Ratio	500:1	---
Nozzle Percent Length	123	%
Vacuum Specific Impulse (Delivered)	993.3	sec

Heat loads are as follows:

Nozzle-con (total):	30.05	MW
Nozzle-div (total):	22.97	MW
Reflector (total):	35.00	MW

P = psia
T = deg-R
W = lb_m/sec
H = BTU/lb_m
S = BTU/lb_m-R

Note: Flows indicated are for one-half of system

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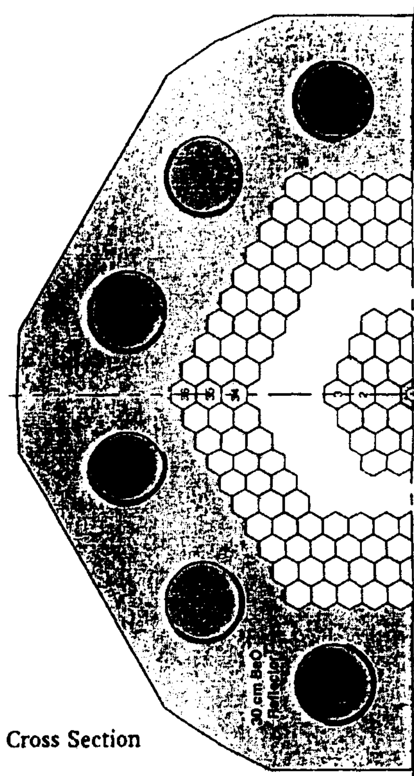
NUCLEAR VAPOR THERMAL ROCKET PARAMETERS

Fuel Pressure	100 atm
Average Fuel Temperature	4000 K
Maximum Element Heat Flux	330 W/cm^2
Nominal Element Length	150 cm
Fuel Volume Fraction	0.15
Coolant Volume Fraction	0.15
Moderator Volume Fraction	0.70
Fuel Element Power	0.7 MWt
Element Heat Transfer Area	2170 cm^2
Reactor Core L/D	1.5
Fuel Channel Diameter	0.142 cm
Fuel Channel Sectional Area	0.0158 cm^2
Total Fuel Channel Area Per Element	0.505 cm^2
Fuel Element Sectional Area	3.464 cm^2
Element Diameter (across flats)	2.00 cm
Coolant Channel Diameter	0.142 cm
Coolant Channel Sectional Area	0.0158 cm^2
Total Coolant Channel Area Per Ele.	0.505 cm^2
Core Volume (elements only)	1.053 m^3
Core Power Density	1330 MW/m^3
Fuel Element Mass, Total	1.35 MT
Forward Reflector Mass	0.60 MT
Aft Reflector Mass	0.51 MT
Radial Reflector Mass	2.47 MT
Radiation Shield Mass	0.90 MT
Total Reactor Mass	5.83 MT
Misc Engine Components Mass	0.9 MT
Total Engine Mass	6.83 MT
Engine F/W	5.0 MT



NVTR Cross Section

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HIGH TEMPERATURE NUCLEAR FUELS AND MATERIALS STUDIES

- Experimental Studies Related to a Parallel Program Confirmed UF_4 Compatibility with:

  - W at temperatures up to 2200 K
  (Experiment and post-test analysis at T up to 3000 K in progress)

  - Mo at temperatures up to 2200 K
  (Experiment and post-test analysis at T up to 2600 K in progress)

  - C at temperatures up to 1800 K

- Detailed Thermodynamics Analysis Demonstrated Outstanding Chemical Compatibility Between UF_4 and WC, W_2C, Mo_2C at Temperatures up to 2600 K

- Thermodynamic Studies Revealed Outstanding Properties of UF_4 - UC_2 Mixture for NTVR Fuel

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Compatibility of UF_4 at elevated temperatures with wall materials is a key to successful development of fuel element for NTVR. Experimental studies of UF_4 compatibility with a wide range of materials has shown promising results for Mo, W, and C. Thermodynamic analysis suggested outstanding chemical compatibility of WC, W_2C and Mo_2C at temperatures up to 2600 K. High temperature thermodynamics analysis has also revealed the outstanding stability of UF_4 - UC_2 system. Due to presence of carbon in UF_4 - UC_2 fuel mixture, better compatibility with the fuel element wall materials and gaseous fuel is expected.