N93-26955

NTP SYSTEM SIMULATION AND DETAILED NUCLEAR ENGINE MODELING

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Presented at
Nuclear Propulsion Technical Interchange Meeting
(NP-TIM-92)
October 20-23, 1992

NASA Lewis Research Center
Plum Brook Station

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University of Florida

NTP SYSTEM SIMULATION &
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10/20/92

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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
  - $10 \le T \le 10{,}000$ K
  - $.1 \le P \le 160$ bar
- Models Developed for NTVR, NERVA and XNR 2000
- CFD and Heat Transfer Models for Main NTR Components

10/20/92

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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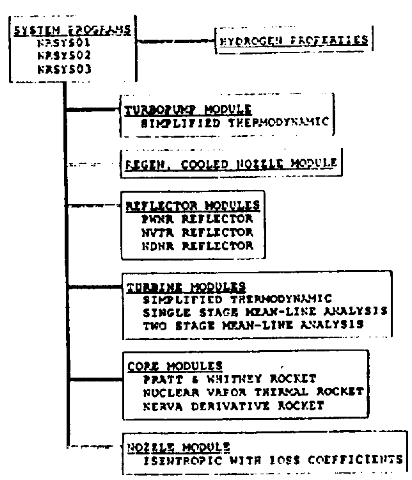
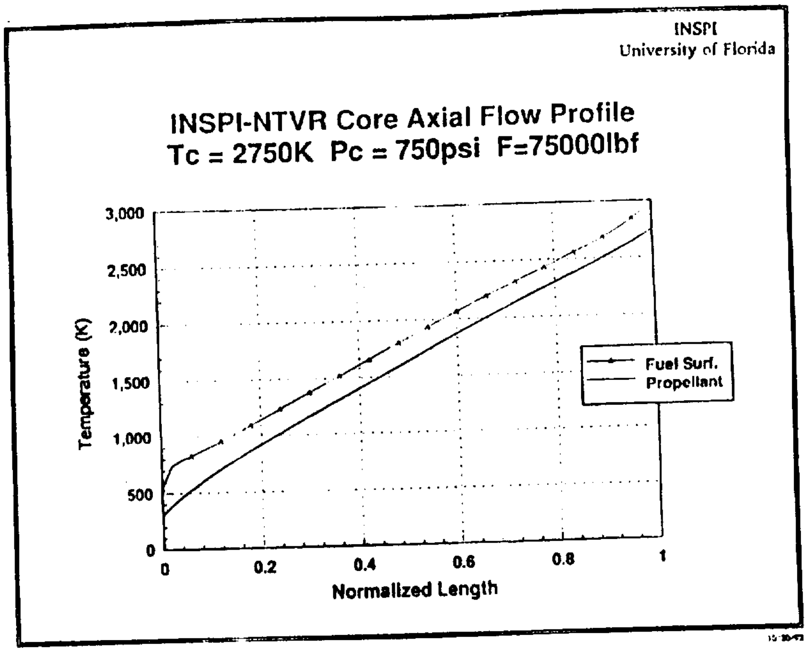
NUCLEAR THERMAL ROCKET SIMULATION SYSTEM

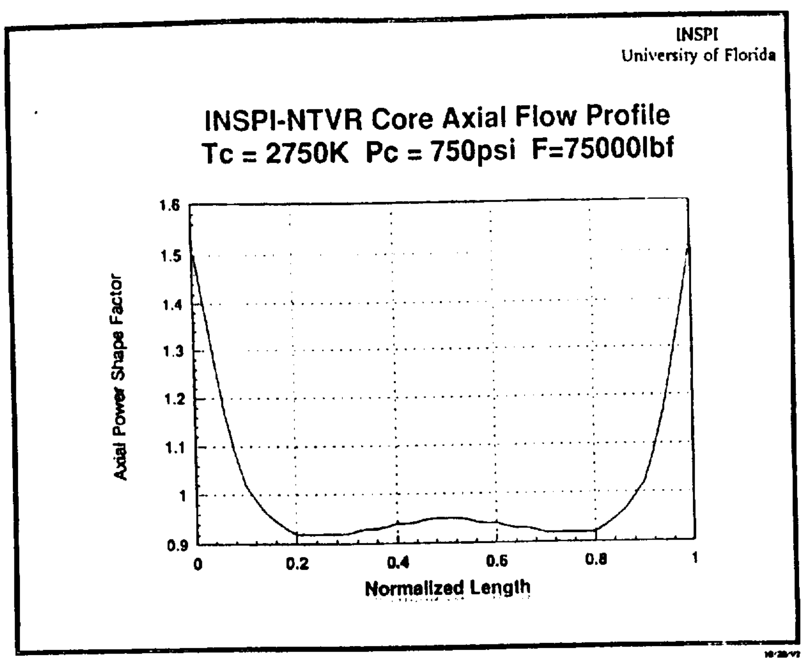


10/20/92

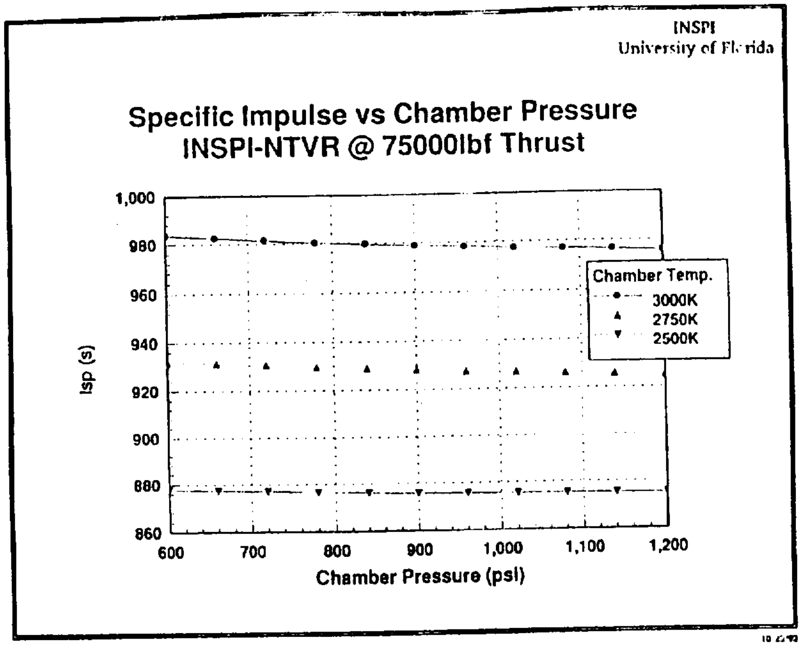
The main program links all the component modules and iterates to arrive at the user specified thrust chamber pressure and temperature and thrust level. Reactor power and propellant flow rate are among outputs of the simulation program. Fuel elements in the core module are prismatic with variable flow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



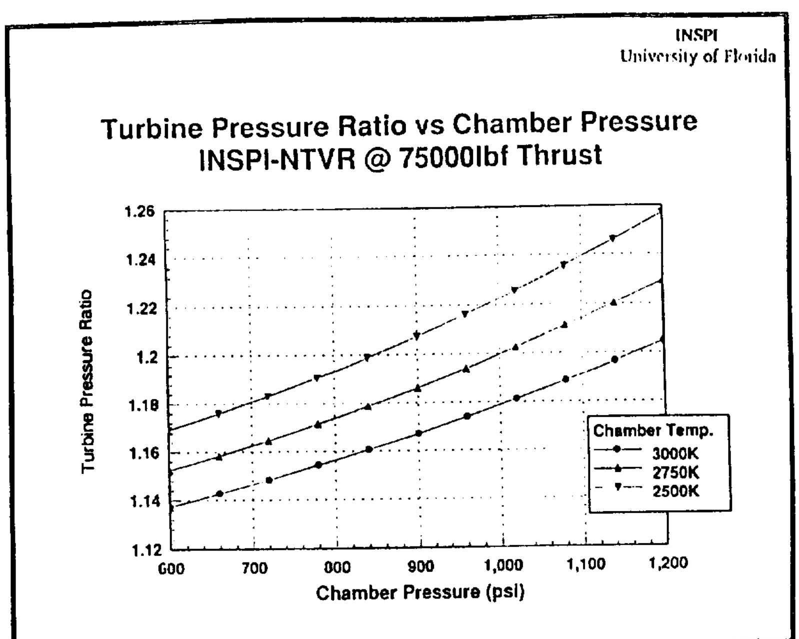
Axial temperature distribution of NVTR fuel surface and propellant in an average power rod. Reactor power is adjusted to achieve the thrust chamber temperature and pressure of 2750 K and 750 psi, respectively.



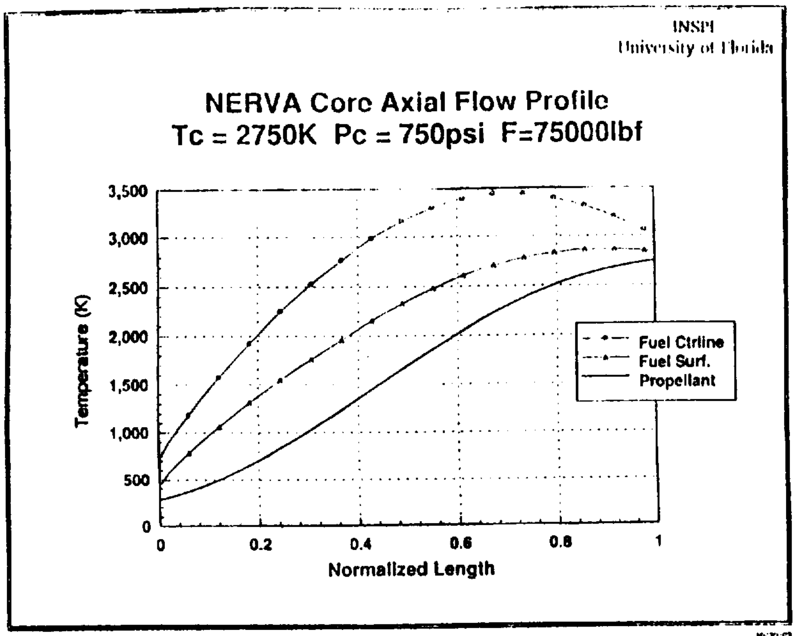
Normalized axial power distribution in C-C composite fuel matrix NTVR, calculated by DOT-2 S_n code. The axial power shape factor is an input for the simulation code.



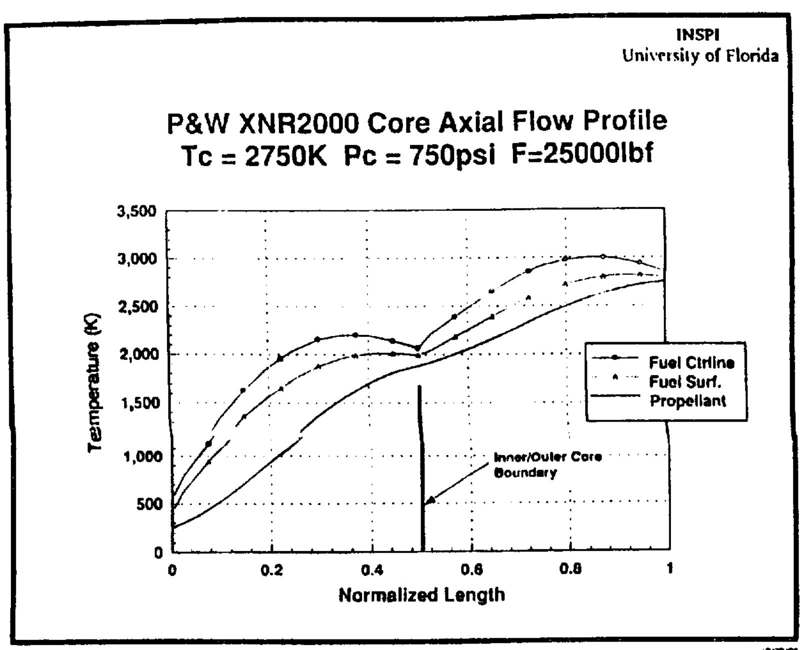
Parametric study of thrust chamber pressure and temperature impact on Isp of NTVR. At higher pressures Isp is less sensitive to thrust chamber temperature.



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.

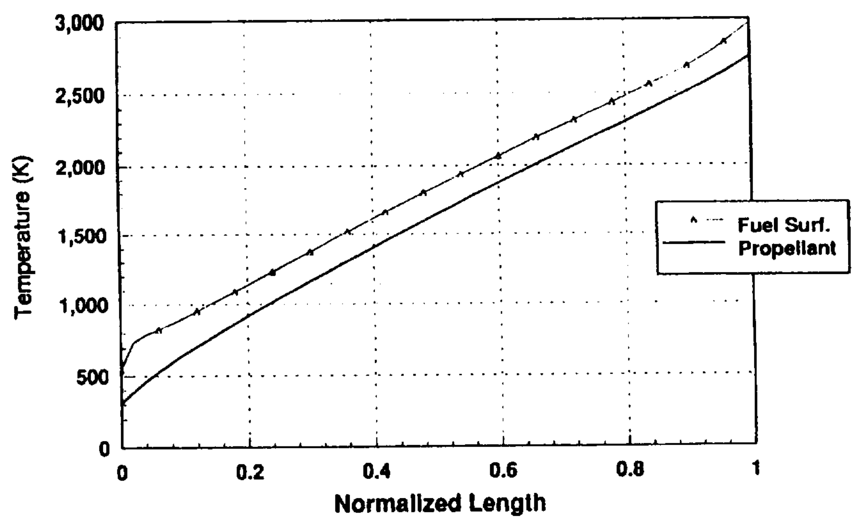


Axial temperature profiles for NERVA-75,000 lbf engine are presented. The maximum fuel temperature is 3490 K at .7 m from the core entrance.

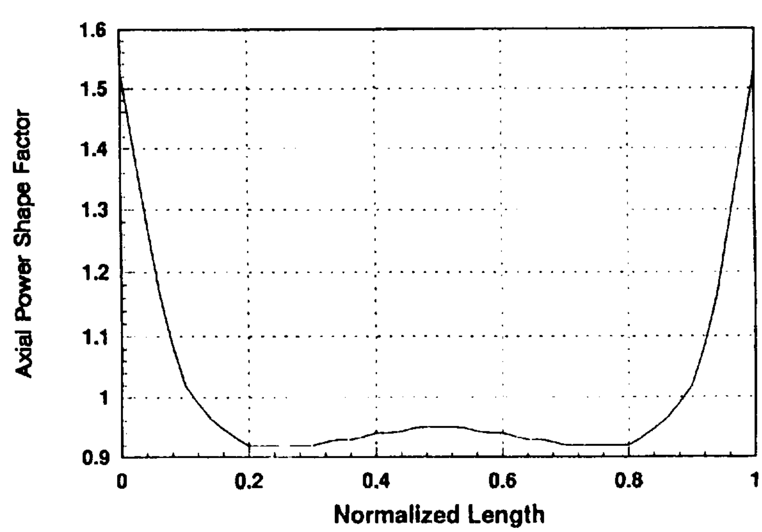


Axial temperature distribution in XNR 2000 core is presented. XNR 2000 features a two path folded flow core fueled with CERMET. The maximum fuel temperature is 3000 K at about 85% from the entrance to the inner core region.

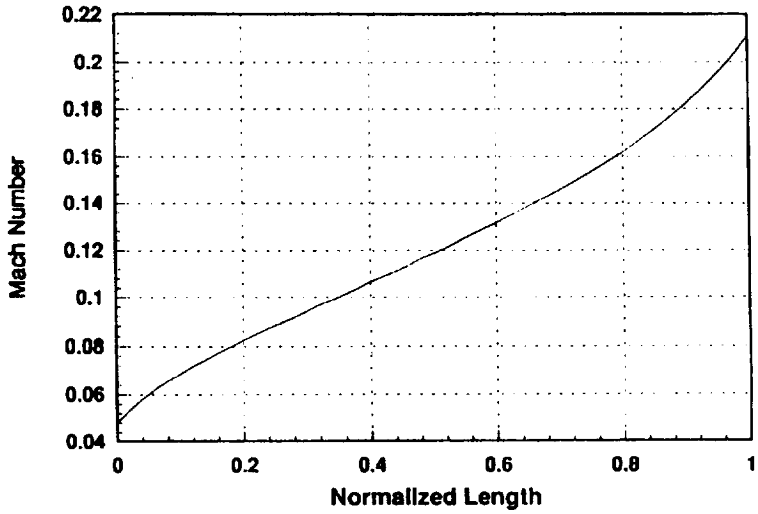
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



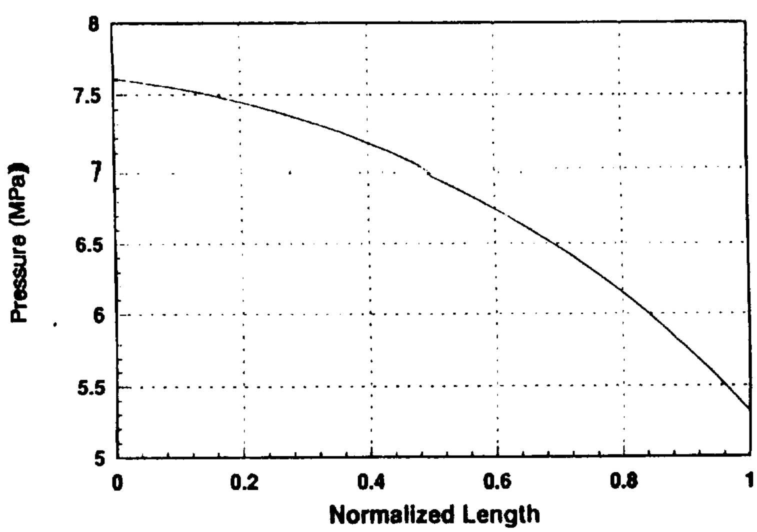
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



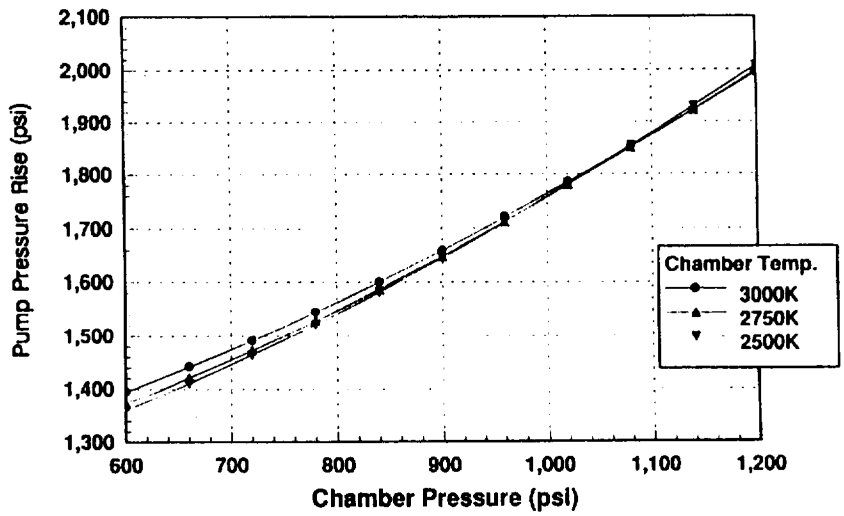
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



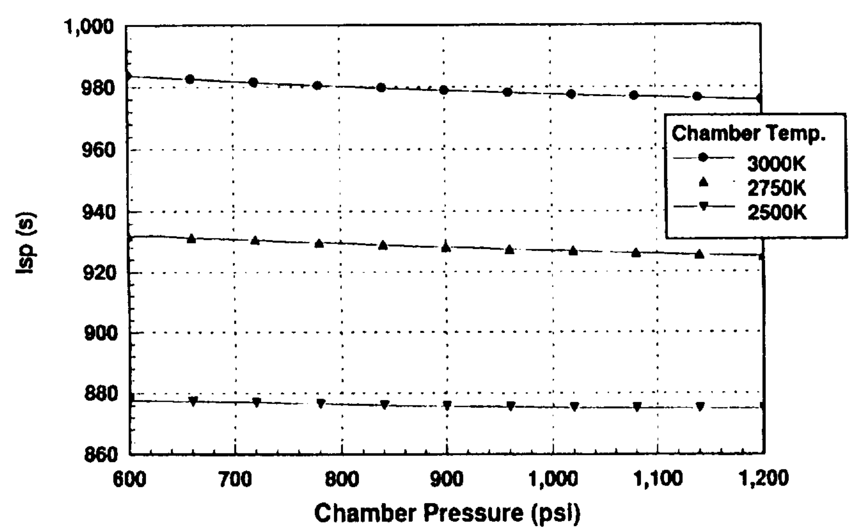
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=75000lbf



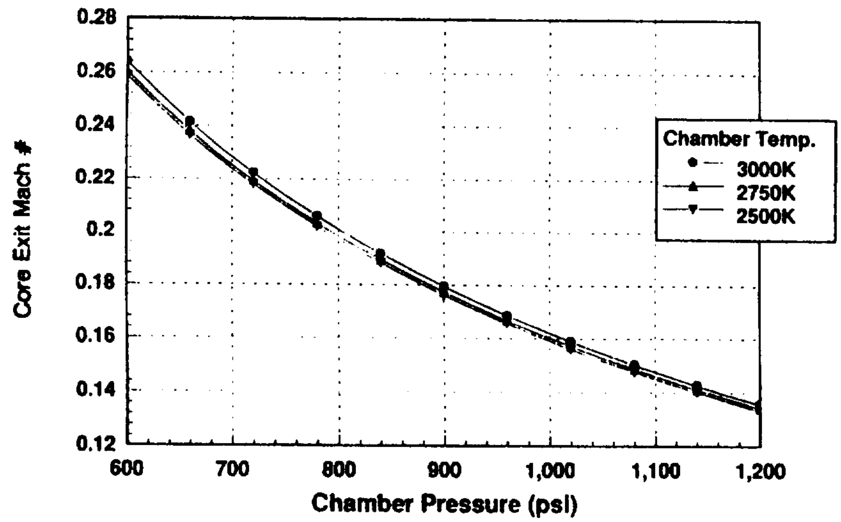
Pump Pressure Rise vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust



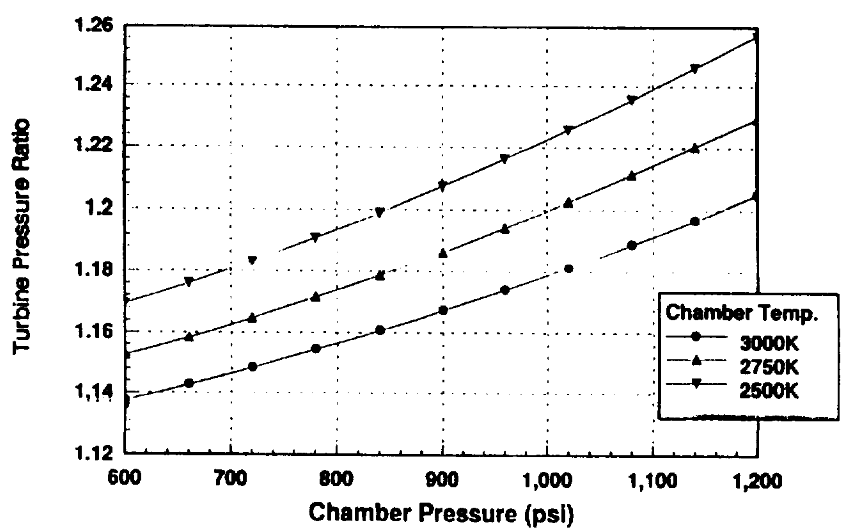
Specific Impulse vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust



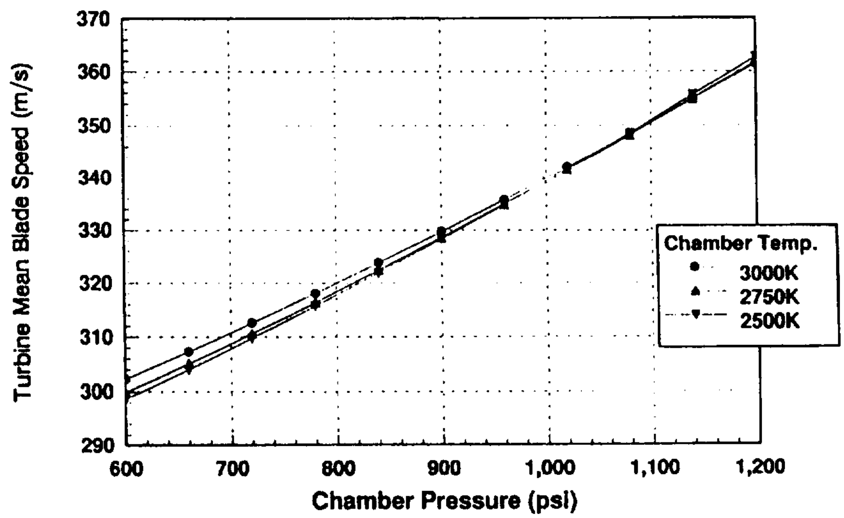
Core Exit Mach # vs Chamber Pressure
INPSI-NTVR @ 75000lbf Thrust



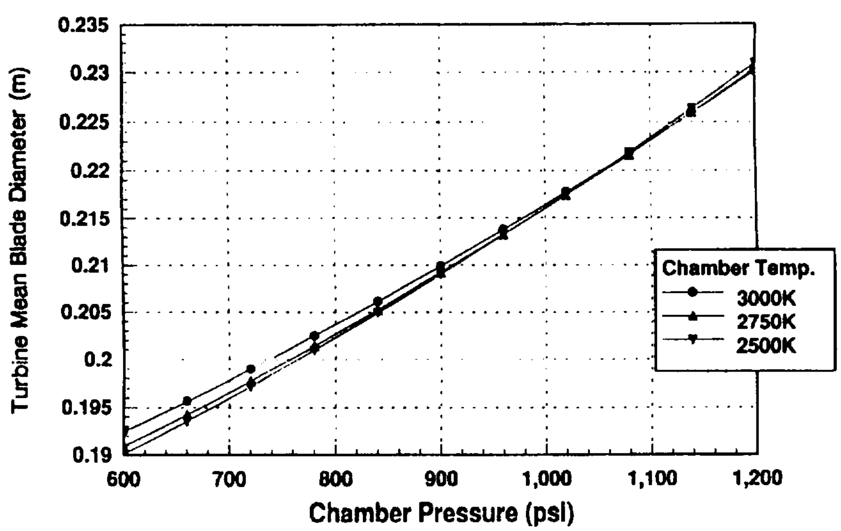
Turbine Pressure Ratio vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

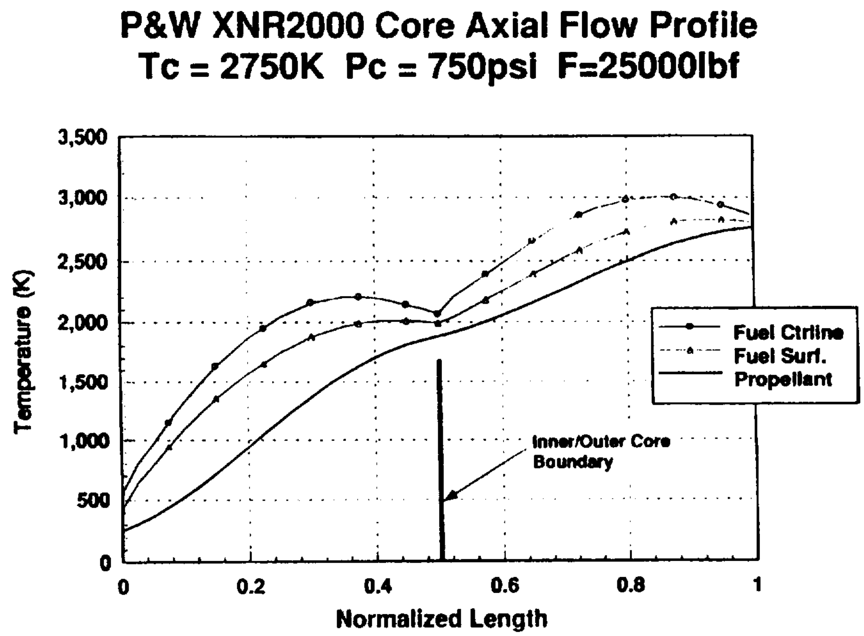


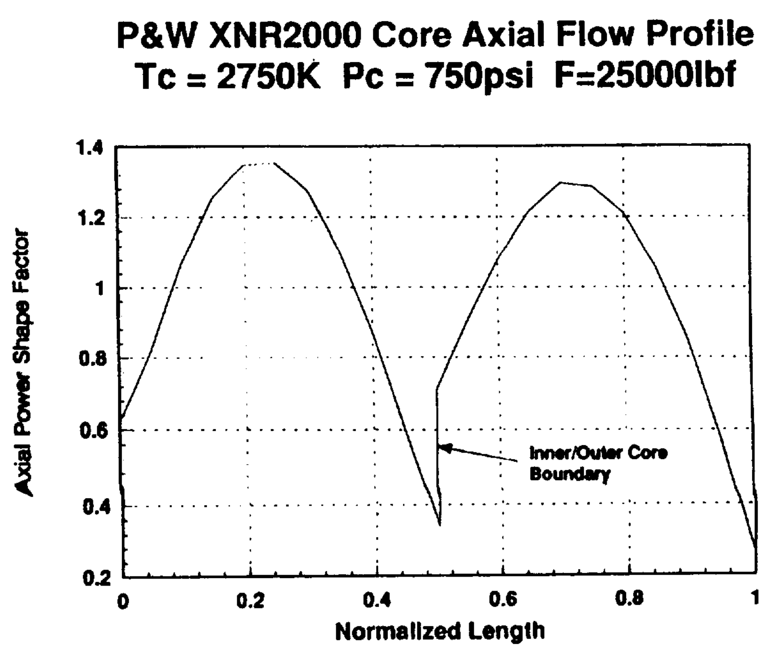
Turbine Blade Speed vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

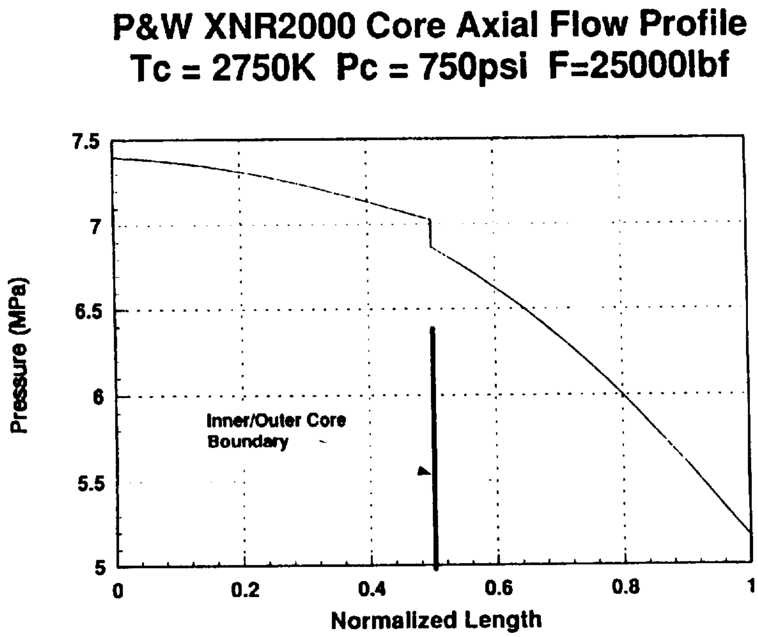


Turbine Blade Diameter vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

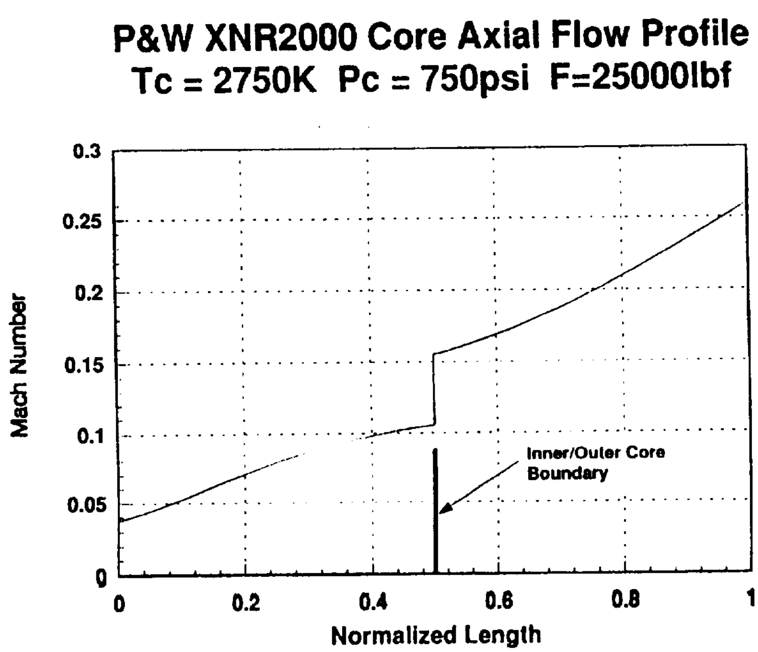



P&W XNR2000 Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=25000lbf
Temperature (K)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
0.2
0.4
0.6
0.8
1
Normalized Length
Fuel Ctrline
Fuel Surf.
Propellant
Inner/Outer Core Boundary


P&W XNR2000 Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=25000lbf
Axial Power Shape Factor
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
Normalized Length
Inner/Outer Core Boundary

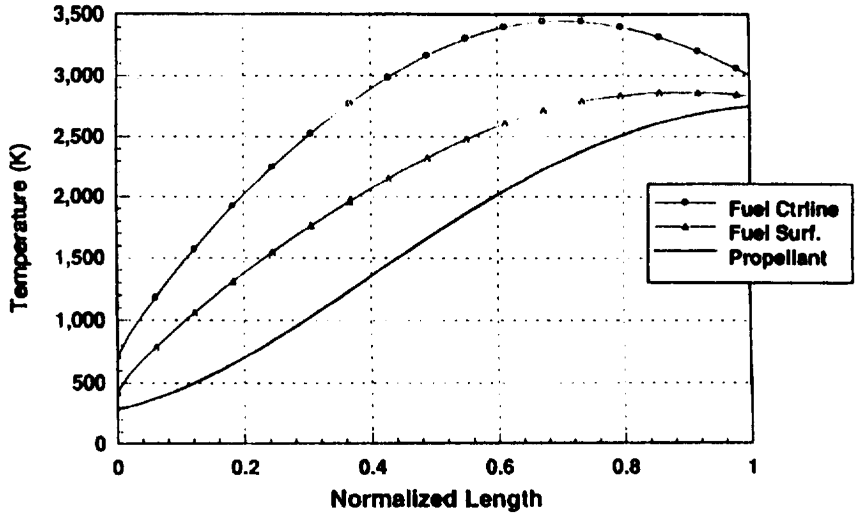


P&W XNR2000 Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=25000lbf
Pressure (MPa)
7.5
7
6.5
6
5.5
5
Inner/Outer Core
Boundary
0
0.2
0.4
0.6
0.8
1
Normalized Length

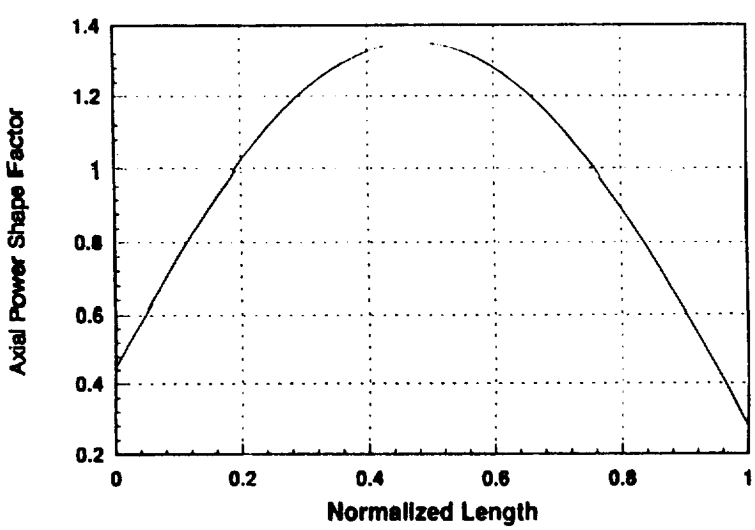


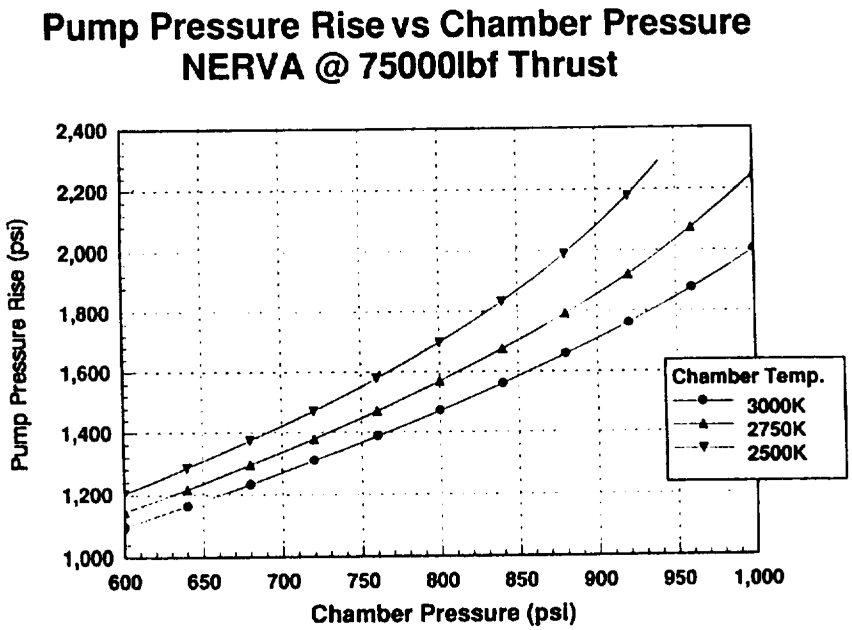
P&W XNR2000 Core Axial Flow Profile
Tc = 2750K Pc = 750psi F=25000lbf
Mach Number
0.3
0.25
0.2
0.15
0.1
0.05
0
Inner/Outer Core
Boundary
0
0.2
0.4
0.6
0.8
1
Normalized Length

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



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





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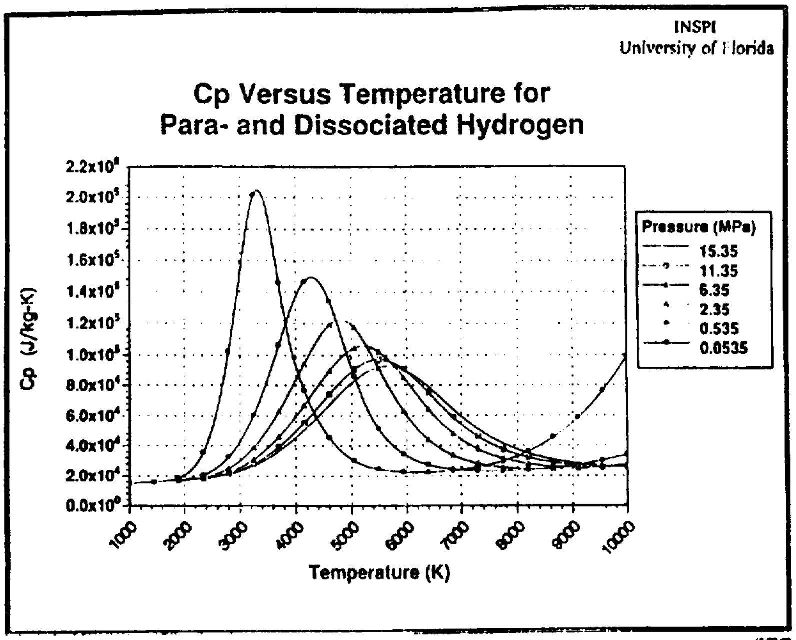
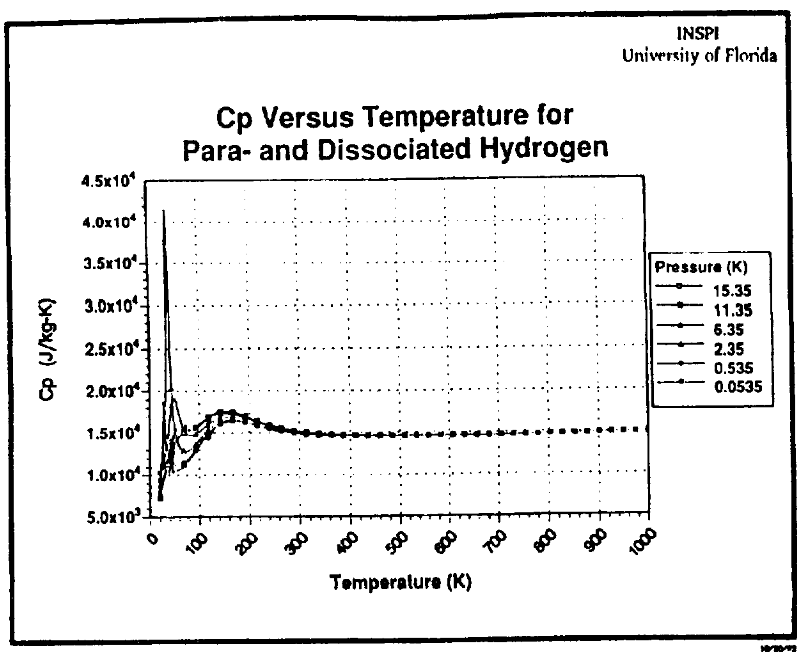
EVALUATION OF PARA- AND DISSOCIATED HYDROGEN PROPERTIES AT T = 10 - 10,000 K

- 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

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.



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.



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.

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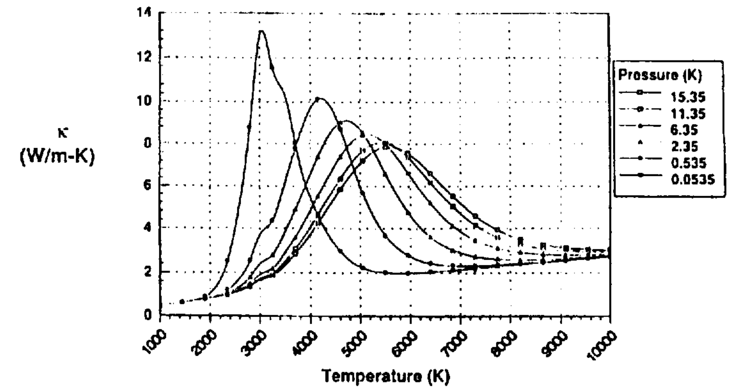
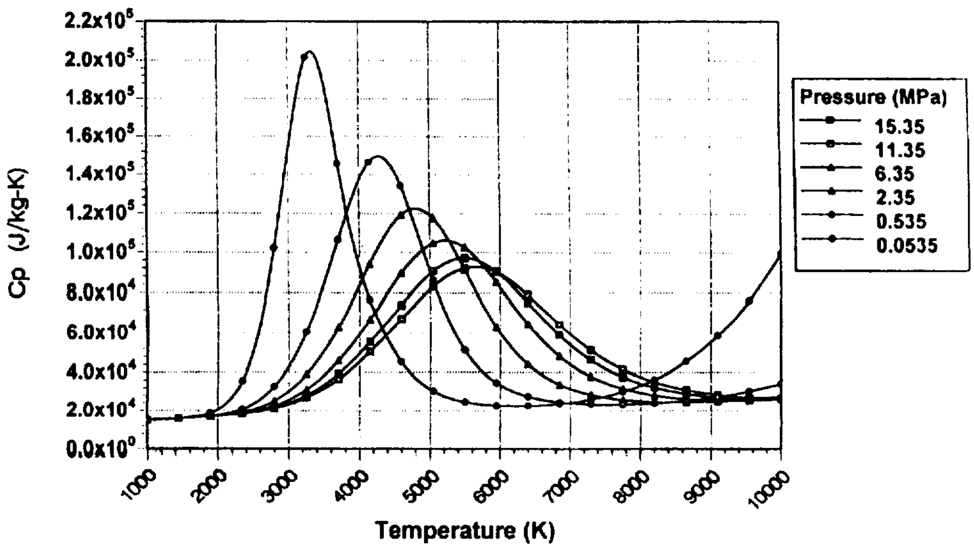
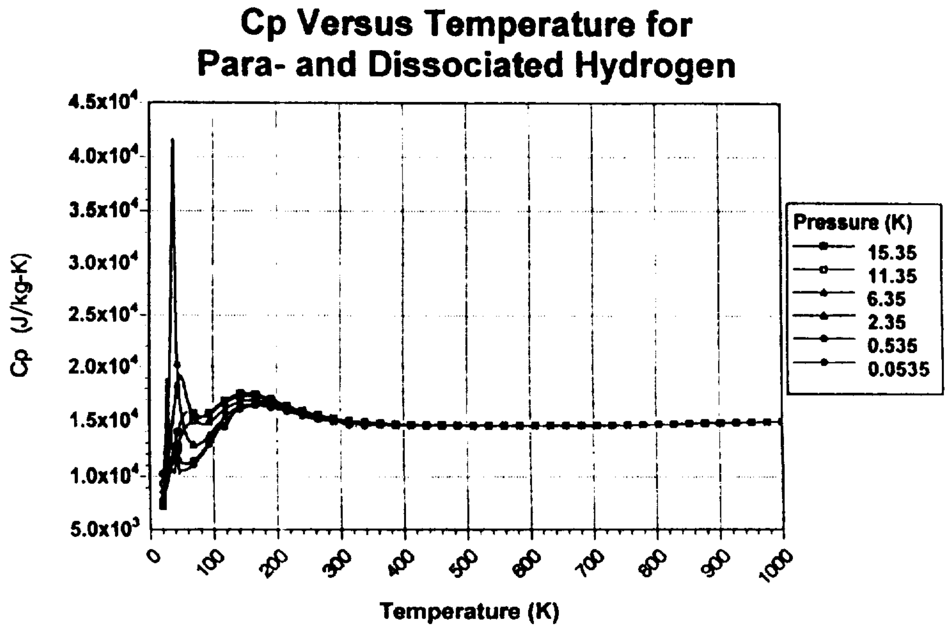
Thermal Conductivity Versus Temperature for Para- and Dissociated Hydrogen

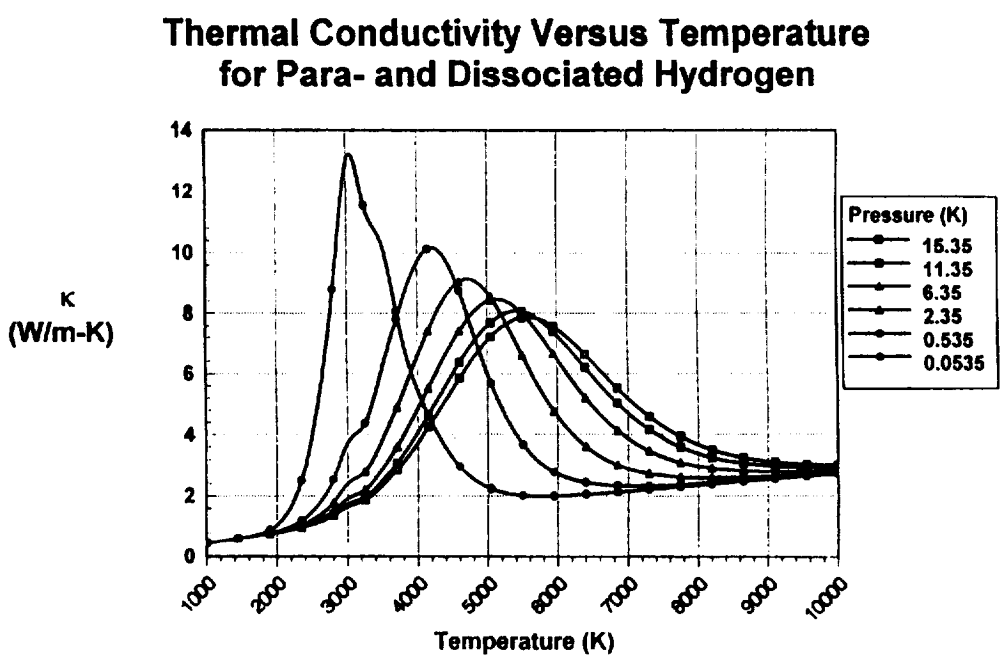


The hydrogen property package is a combination of two subpackages covering the temperature ranges 10 - 3000 K and 3000 - 10,000 K, respectively. The large change of gradients in hydrogen viscosity at 3000 K indicates a non-physical flaw in the model.

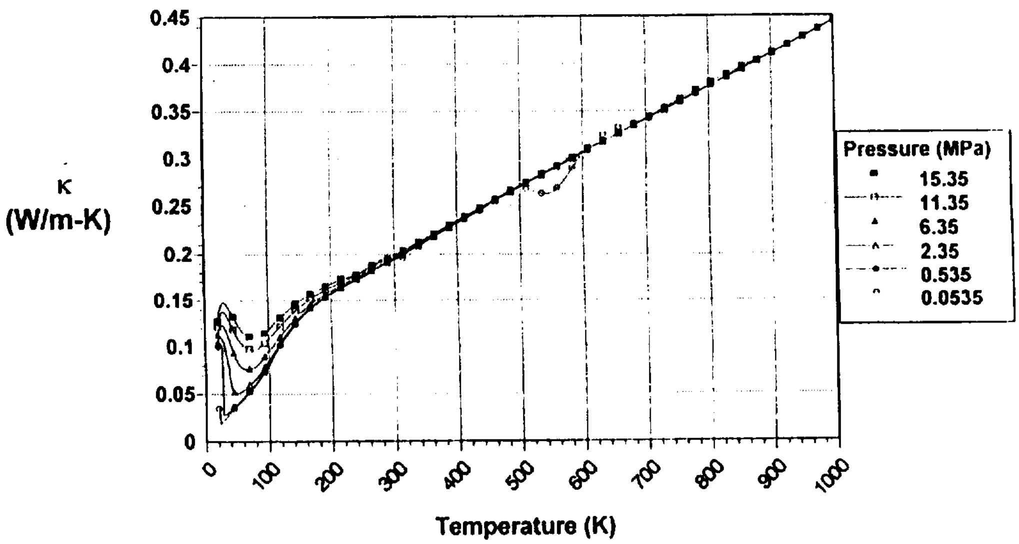
Cp Versus Temperature for Para- and Dissociated Hydrogen




Cp Versus Temperature for
Para- and Dissociated Hydrogen
4.5x10⁴
4.0x10⁴
3.5x10⁴
3.0x10⁴
2.5x10⁴
2.0x10⁴
1.5x10⁴
1.0x10⁴
5.0x10³
Cp (J/kg-K)
0
100
200
300
400
500
600
700
800
900
1000
Temperature (K)
Pressure (K)
15.35
11.35
6.35
2.35
0.535
0.0535


Thermal Conductivity Versus Temperature
for Para- and Dissociated Hydrogen
14
12
10
8
6
4
2
0
K
(W/m-K)
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Temperature (K)
Pressure (K)
15.35
11.35
6.35
2.35
0.535
0.0535

Thermal Conductivity Versus Temperature for Para- and Dissociated Hydrogen



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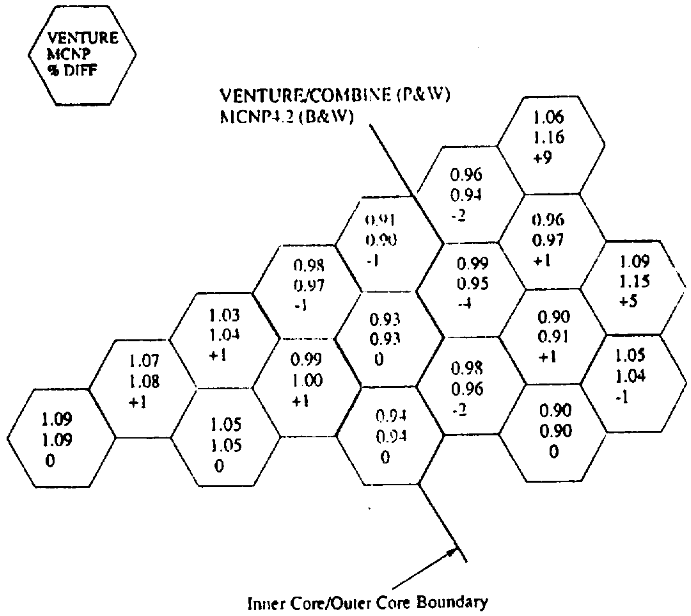
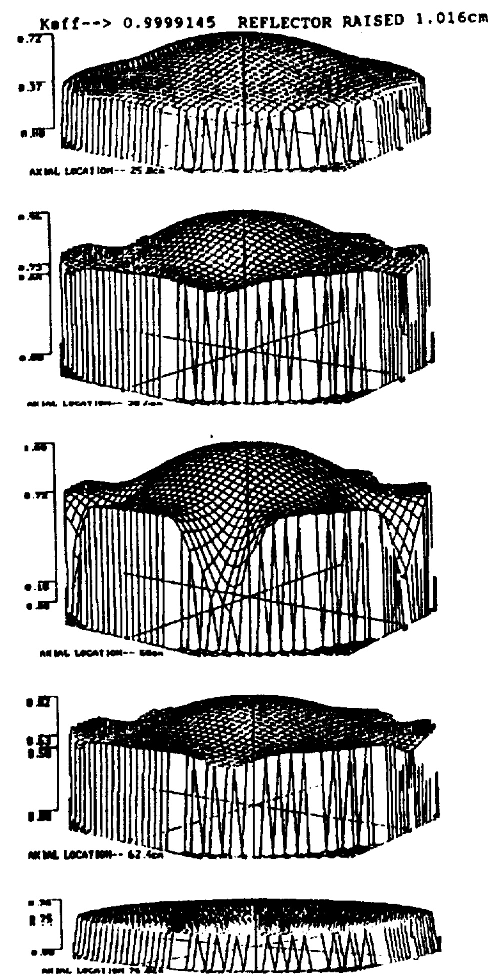
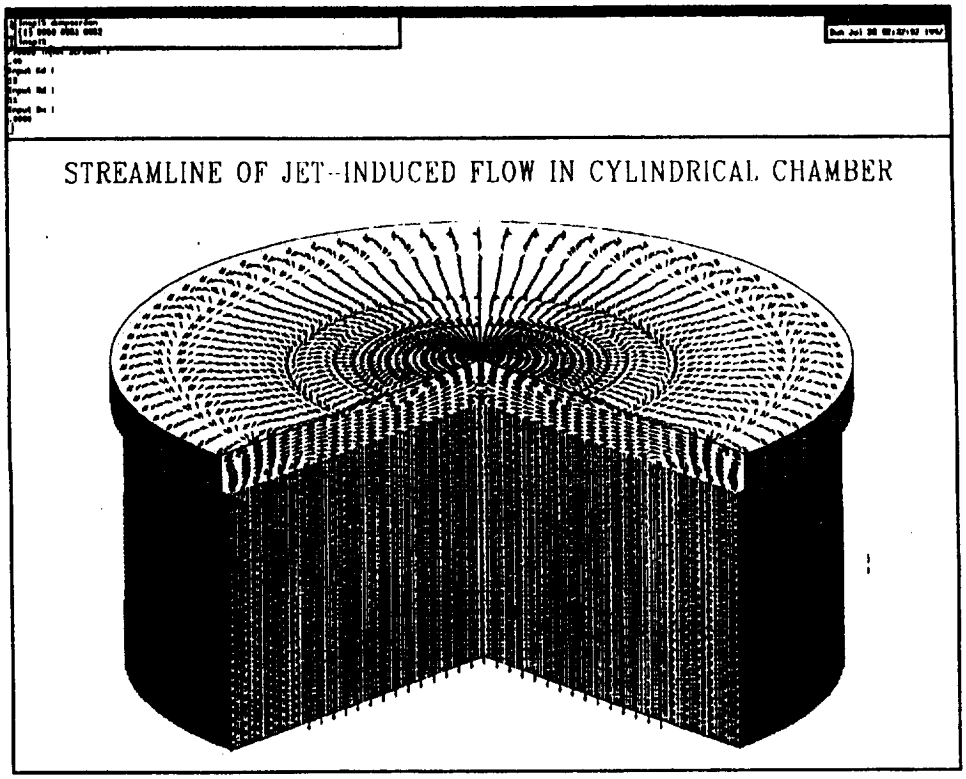
NUCLEAR DESIGN ANALYSIS PACKAGE

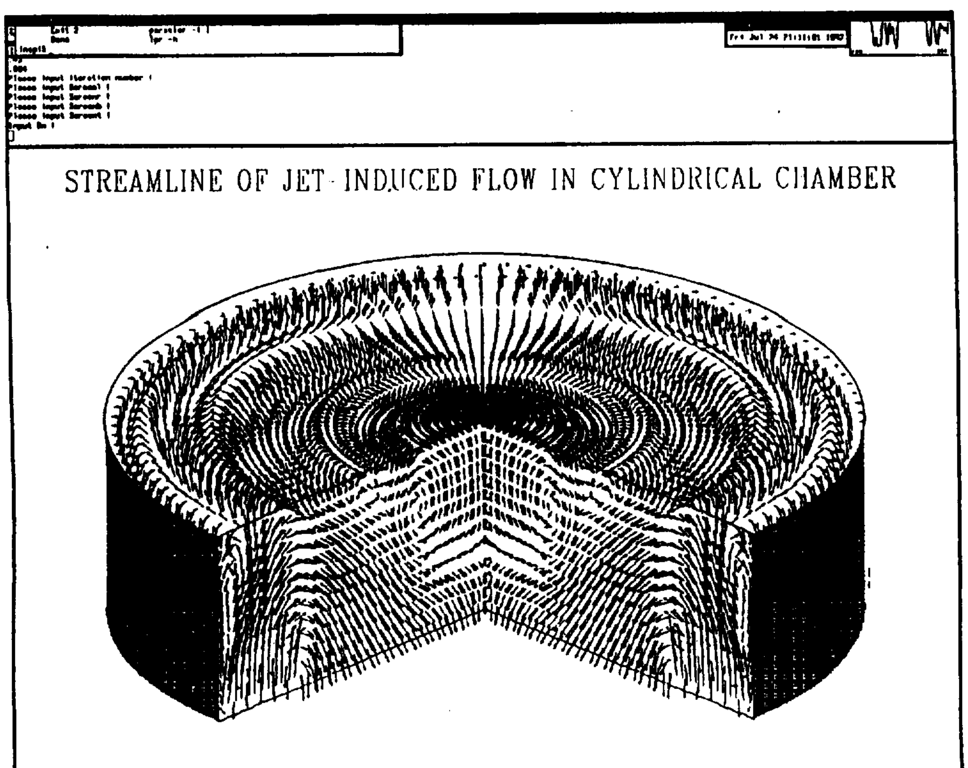
- Multigroup Cross-sections Generated by COMBINE (ENDFB-V)
- MCNP (4.2) for Complex Geometries
- BOLD VENTURE (3-D, Diffusion) for Power Profile and Reactivity Calculations
- ANISN (1-D, S_n) for Analysis of Heterogeneous Boundaries
- DOT IV (1, 2-D, S_n) for Analysis of Reflector
- XSDRNPM (1-D, S_n) TWODANT (2-D, S_n), NJOY, AMPX for Cross-comparison

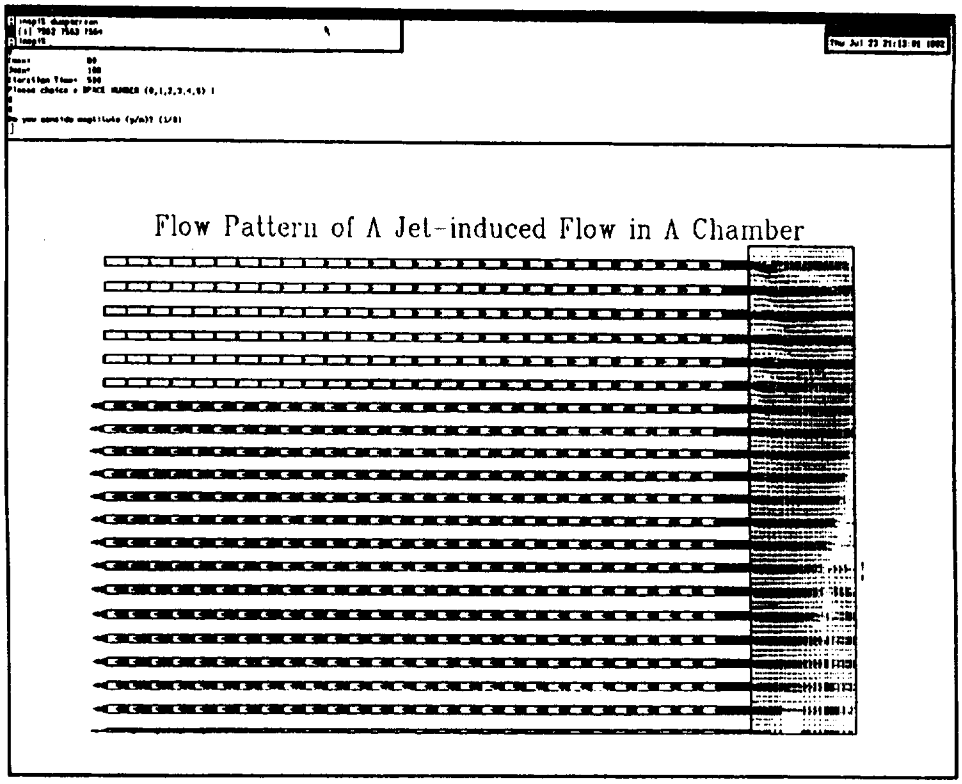
XNR2000 Rodwise Radial Power Distribution (normalized)

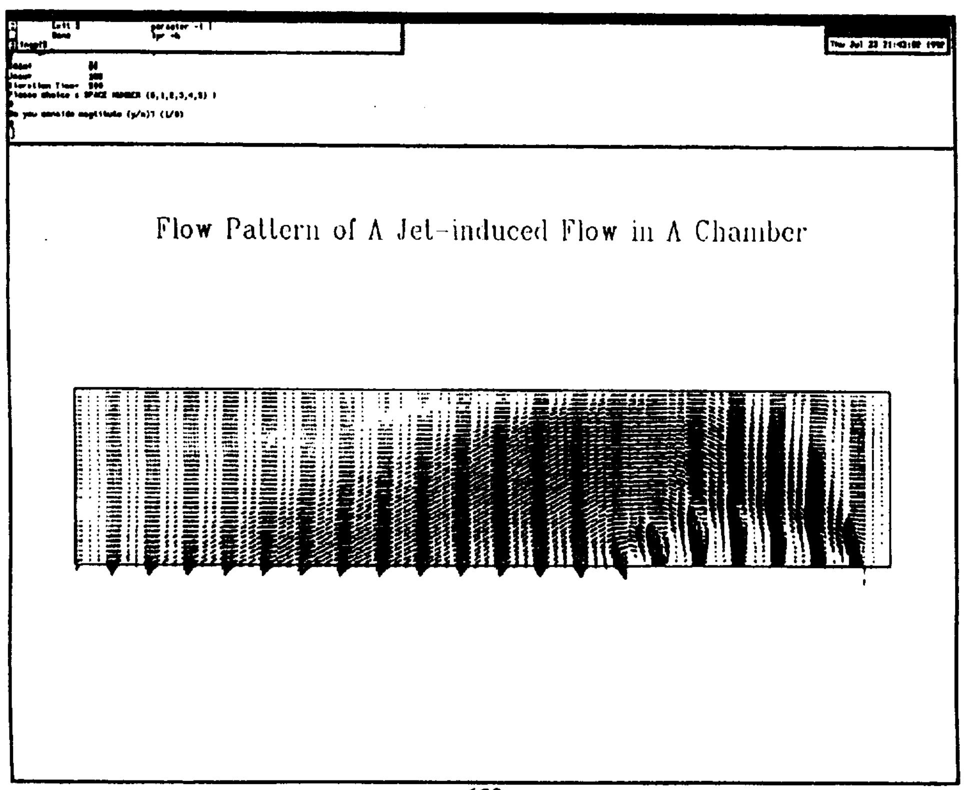


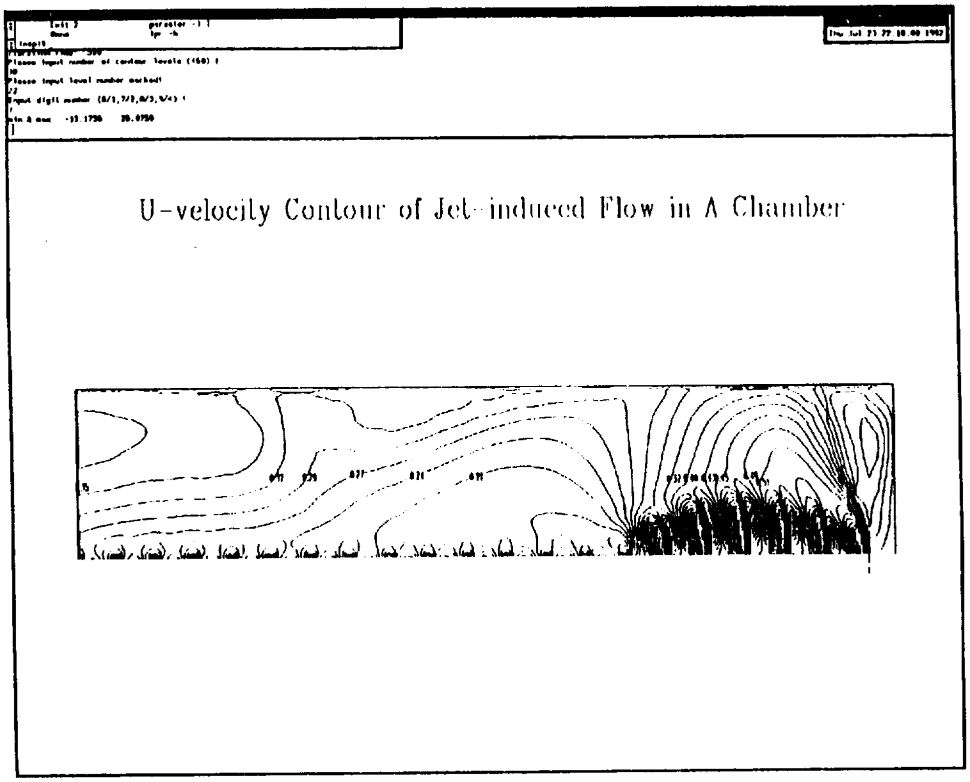


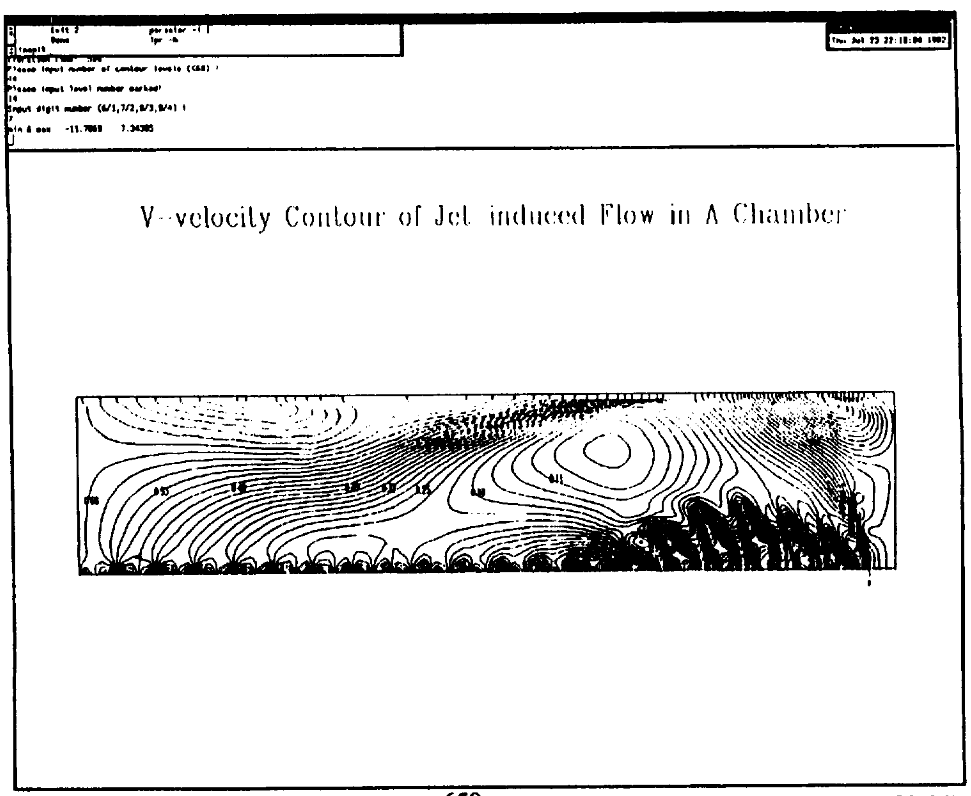

STREAMLINE OF JET-INDUCED FLOW IN CYLINDRICAL CHAMBER

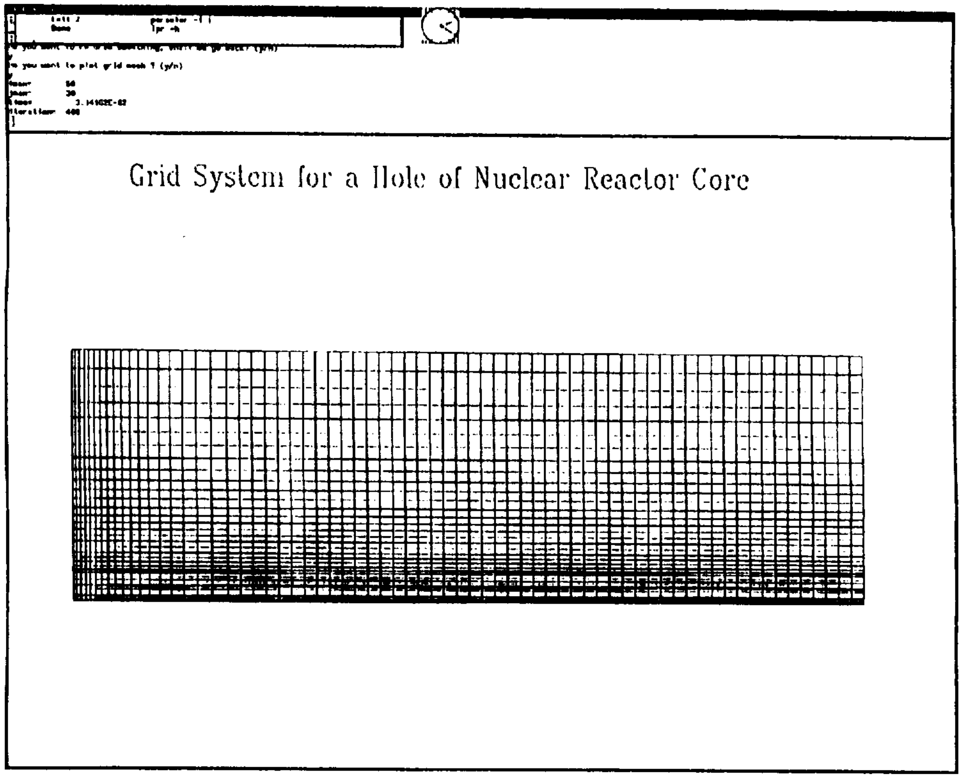

STREAMLINE OF JET-INDUCED FLOW IN CYLINDRICAL CHAMBER

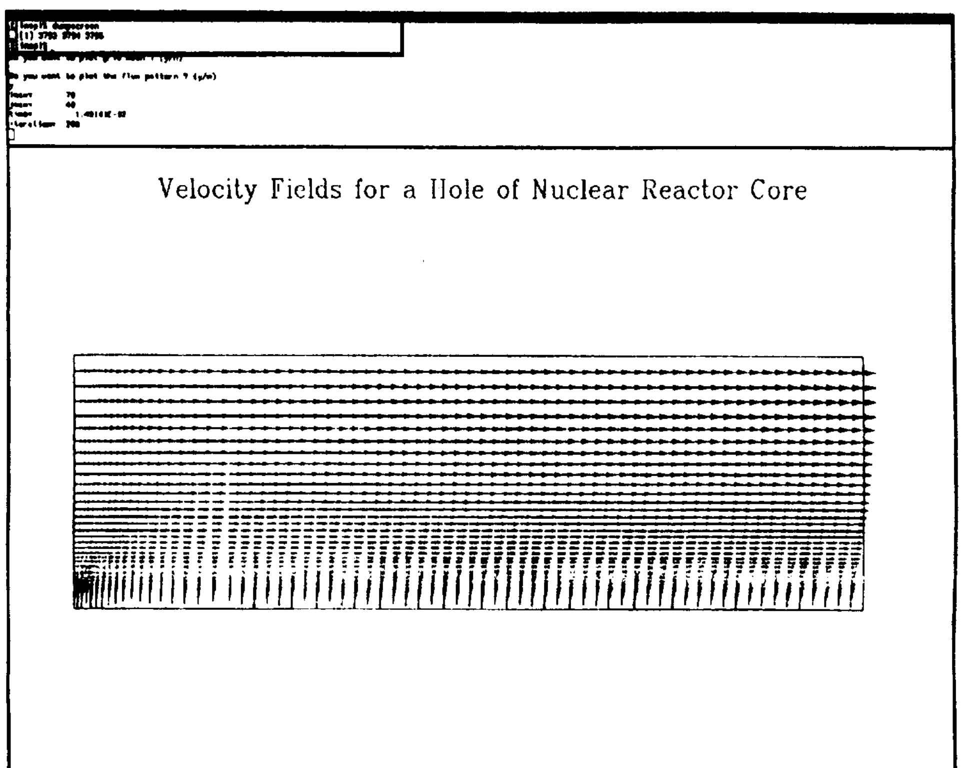

Flow Pattern of A Jet-induced Flow in A Chamber

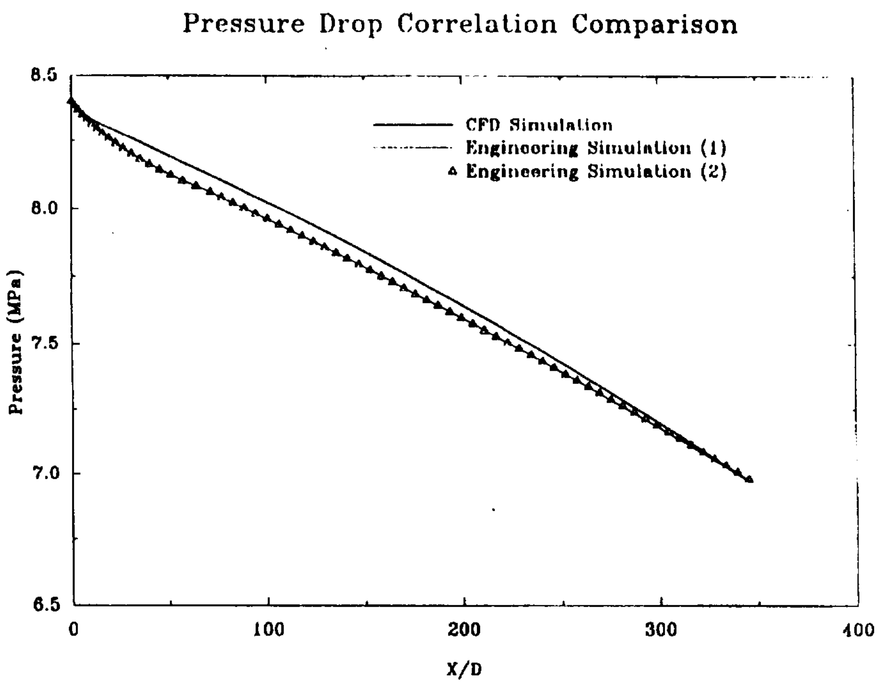

Flow Pattern of A Jet-induced Flow in A Chamber


U-velocity Contour of Jet-induced Flow in A Chamber


V-velocity Contour of Jet induced Flow in A Chamber


Grid System for a Hole of Nuclear Reactor Core


Velocity Fields for a Hole of Nuclear Reactor Core



Nusselt Number (Nu) and Pressure Drop (ΔP) Correlation Comparison with CFD Analysis

(I) CFD Analysis

Energy Equation

$$\frac{\partial}{\partial X}\left((e+\sigma_x)u+\tau_{yx}v-K_c\frac{\partial T}{\partial X}\right)+\frac{\partial}{\partial Y}\left((e+\sigma_y)v+\tau_{xy}u-K_c\frac{\partial T}{\partial Y}\right)=S_e$$

Numerical Algorithm: MacCormack hybrid implicit-explicit, finite volume method

Conductive Heat Flux

$$q_c'' = -K_c\left[\frac{\partial T}{\partial r}\right]_{r=R}$$

Convective Heat Flux

$$q_x'' = h_c(T_w - T_b)$$

$$T_b = \frac{\int_A \rho C_p u T dA}{\int_A \rho C_p u dA}$$

Convective Heat Transfer Coefficient

$$h_c = -\frac{K_c\left[\frac{\partial T}{\partial r}\right]_{r=R}}{T_w - T_b}$$

Nusselt Number

$$Nu = \frac{h_c D}{K_c}$$

□ DIFFUSION APPROXIMATION

$$q_r'' = -\frac{4}{3a_R}\nabla e_b = -\frac{16\sigma_{SB}T^3}{3a_R}\nabla T = -K_r\nabla T$$

$$K_r = \frac{16\sigma_{SB}T_w^3}{3a_R}$$

Using the perfect gas law,

$$k_r = \frac{16\sigma_{SB}\kappa}{3\sigma_{ph}P}T^4$$

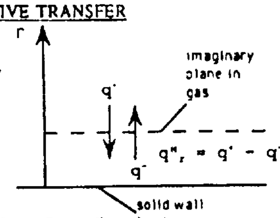
WHERE

a_R : Rosseland Mean Opacity
σ_{SB} : Stefan-Boltzmann Constant
σ_{ph} : Photon Collision Cross Section per Molecule
κ : Boltzmann's Constant
P : Gas Pressure
T : Gas Temperature

□ APPROXIMATION BY USING 1-D EQUATION OF RADIATIVE TRANSFER

$$i(r) = \int_0^r a\, I(r')\exp(-a(r-r'))\,dr'$$

$$q''_r = q^+ - q^- = \pi\,(i^+(r) - i^-(r))$$



WHERE

$i^+(r)$: Radiation Intensity in the Positive Direction(From Gas to Boundary)
$i^-(r)$: Radiation Intensity in the Negative Direction(From Boundary to Gas)
$I(r)$: Source Function ($=\sigma T^4/\pi$)

Nusselt number & Prandtl number

$$Re = \frac{\rho u D}{\mu(T_b, T_1)}$$

$$Pr = \frac{\mu(T_b)C_p(T_b)}{K_c(T_b)}$$

(III) Pressure Drop

Compressible Flow

$$\Delta P = \frac{RG^2T_m}{P_m}\left(ln\frac{\rho_1}{\rho_2} + \frac{2f\Delta Z}{D}\right)$$

$$R = \frac{C_p(\gamma - 1)}{\gamma}$$

$$G = \rho_1\left(\frac{V_1 + V_2}{2}\right)$$

$$T_m = \frac{T_1 + T_2}{2}$$

$$P_m = \frac{P_1 + P_2}{2}$$

Incompressible Flow

$$\Delta P = 2f\frac{\Delta Z}{D}\rho_1 V_1^2\left(\frac{T_1 + T_2}{2T_1}\right) + \rho_1 V_1^2\left(\frac{T_2}{T_1} - 1\right)$$

$$f = 0.0014 + \frac{1}{8}Re^{-0.32}$$

(II) Nusselt Number Correlations

(1) Colburn Equation

$$Nu = 0.023 Re^{0.8} Pr^{\frac{1}{3}}$$

(2) Dittus-Boelter Equation

$$Nu = 0.023 Re^{0.8} Pr^{0.3}$$

(3) Sieder-Tate Equation

$$Nu = 0.027 Re^{0.8} Pr^{\frac{1}{3}} \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

(4) Petukov Equation

$$Nu = \frac{Re Pr}{X}\left(\frac{f}{2}\right)$$

$$X = 1.07 + 12.7\left(Pr^{\frac{2}{3}} - 1\right)\left(\frac{f}{2}\right)^{\frac{1}{2}}$$

$$f = 0.0014 + \frac{1}{8} Re^{-0.32}$$

(5) Karmon-Boelter-Martinelli Equation

$$N_u = \frac{Re Pr \sqrt{\frac{f}{2}}}{0.833\left(5Pr + 5ln(5Pr + 1) + 2.5ln\left(Re \frac{\sqrt{\frac{f}{2}}}{60}\right)\right)}$$

$$f = 0.0014 + \frac{1}{8} Re^{-0.32}$$

Axial Distance Correction

$$Nu(x) = Nu\left(1.957\left(1 + \frac{x}{D}\right)^{-0.15}\right)\sqrt{\frac{T_b}{T_w}}$$

$$Nu(x) = Nu\left(1 + \frac{2ln\frac{Pr}{0.7}}{\frac{x}{D}}\right)$$

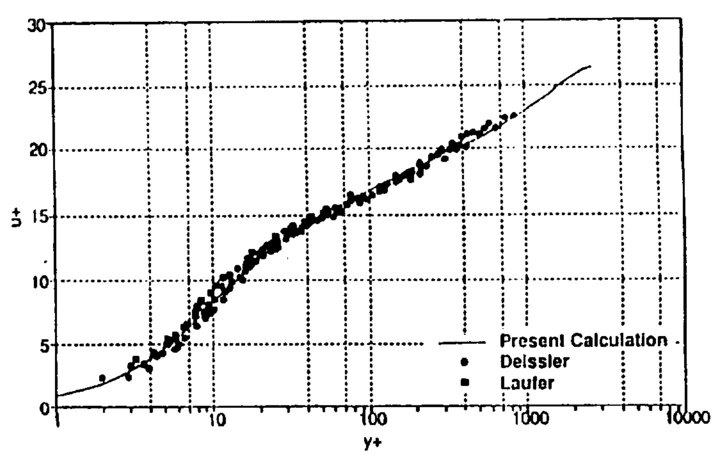


Figure 6.2 Velocity distribution for a fully developed turbulent flow in tube. (Re=1.6 E+4)

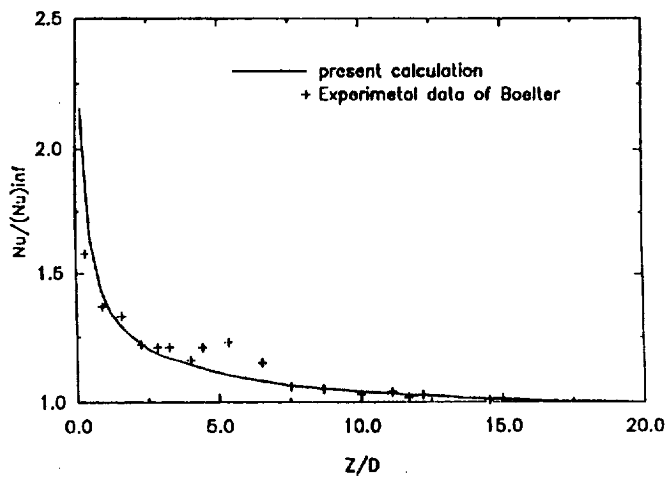


Figure 6.17 Nusselt number vs. axial position for a developing isothermal pipe flow at a Reynolds number of 53000. $(Nu)_{inf}$ is the Nusselt number evaluated at Z/D=20.

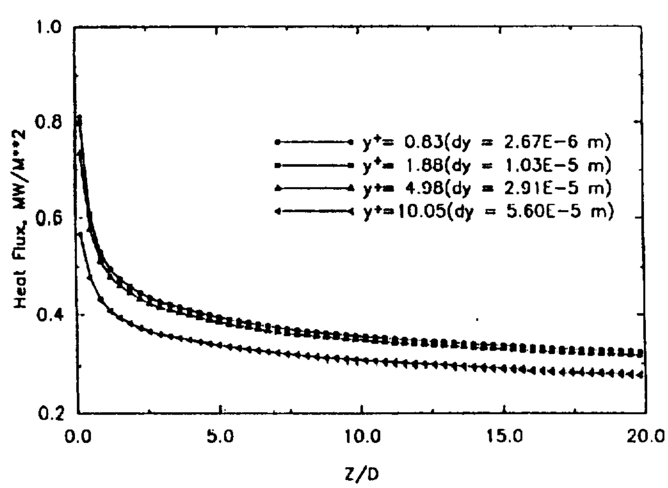


Figure 6.15 Heat transfer rates obtained by Navier-Stokes solver for various boundary cell size. A 60x60 grid is used. (T_{in}=4000 K, T_w=1800 K, P_{in}=1 atm, and P_{out}=0.5 atm)

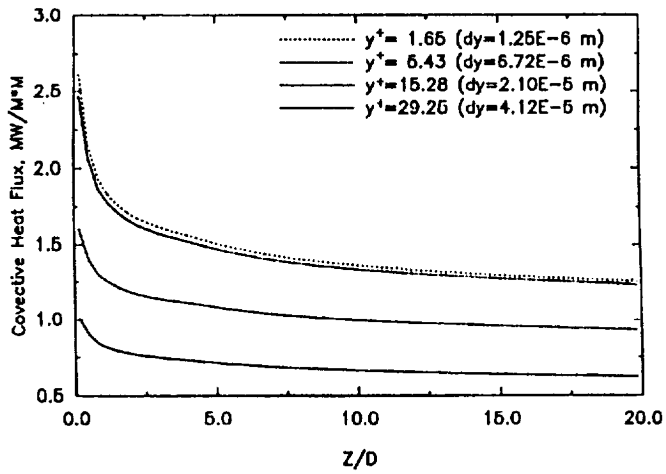


Figure 6.16 Heat transfer rates obtained by Navier-Stokes solver for various boundary cell size. A 60x80 grid is used. (T_{in}=4000 K, T_w=1800 K, P_{in}=10 atm, and P_{out}=9.5 atm)

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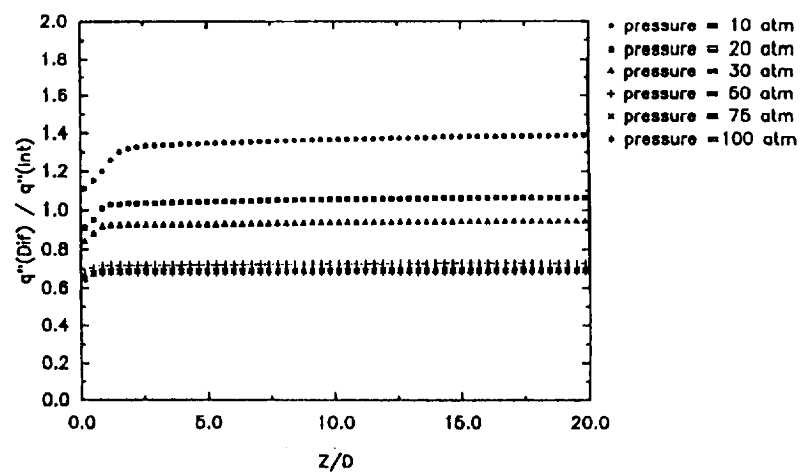

Figure 6.19 Comparative result between diffusion approximation and 1-D integral approximation for varying the gas opacity due to different flow conditions.

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