Nerva-derived reactor coolant channel model for Mars mission applications

Edward W Porta
University of Nevada, Las Vegas

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NERVA-DERIVED REACTOR

COOLANT CHANNEL MODEL FOR

MARS MISSION APPLICATIONS

by

Edward W. Porta

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Mechanical Engineering

Department of Mechanical Engineering
University of Nevada, Las Vegas
May 1995
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ABSTRACT

NERVA-Derived Reactor Coolant Channel Model for Mars Mission

Applications presents the results of a computational fluid dynamics (CFD) study of a 1.3m NERVA-Derived Reactor (NDR) coolant channel.

The CFD code FLOW-3D was used to model the flow of gaseous hydrogen through the core of a NDR. Hydrogen passes through the core by way of coolant channels, acting as the coolant for the reactor as well as the propellant for the rocket. Hydrogen enters the channel in a high density / low temperature state and exits in a low density / high temperature state necessitating the use of a compressible model. Design specifications from a technical paper were used for the model.

It was determined that the pressure drop across the length of the channel was higher than previously estimated (0.9 MPa), indicating the possible need for more powerful coolant pumps and a re-evaluation of the design specifications.
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NOMENCLATURE

English Symbols

\( A \) cross-sectional area of the channel (duct)
\( C_f \) Coefficient of Friction
\( D_h \) hydraulic diameter of the channel (duct)
\( F \) force (as applied to the propulsion of the rocket in this case)
\( g_o \) gravity at sea-level
\( H \) specific energy
\( I_s \) specific impulse
\( I_t \) total impulse
\( k \) thermal conductivity
\( L \) Length
\( m \) mass
\( m \) mass flow rate
\( \bar{M} \) molecular weight of a substance
\( p \) pressure
\( R \) gas constant for a substance
\( \bar{R} \) universal gas constant
\( S \) specific heat
\( T \) temperature
\( TD \) turbulent dissipation
\( TE \) turbulent energy
\( T_o \) stagnation temperature (chamber region)
\( u \) velocity
\( u_1, p_1, T_1 \) conditions at the inlet are denoted by the subscript 1
\( u_2, p_2, T_2 \) conditions at the outlet are denoted by the subscript 2
\( u_e \) exhaust velocity (referring to the exhaust from a diverging nozzle)
\( v_2 \) exhaust velocity (referring to the exhaust from a diverging nozzle)
\( V_{av} \) average velocity
\( W \) mass flow rate (referring to the mass flow rate of an entire core)
\( W_{channel} \) channel mass flow rate
Greek Symbols

\[ \gamma \quad \text{specific heat ratio} \]
\[ \rho \quad \text{density} \]
\[ \mu \quad \text{dynamic viscosity} \]
\[ \nu \quad \text{kinematic viscosity (\( \mu/\rho \))} \]

Dimensionless Values

\[ Re_D \quad \text{Reynolds number for duct flow (\( \rho \dot{V}_{av} D / \mu \))} \]
\[ Pr \quad \text{Prandtl number (\( \mu c_p / k \))} \]
\[ M \quad \text{Mach number} \]
<table>
<thead>
<tr>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>HLLV</td>
<td>Heavy Lift Launch Vehicle</td>
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<tr>
<td>IMLEO</td>
<td>Initial Mass in Low Earth Orbit</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>LMO</td>
<td>Low Mars Orbit</td>
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<td>MEV</td>
<td>Mars Entry Vehicle</td>
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<td>NDR</td>
<td>NERVA-Derived Reactor</td>
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<td>NERVA</td>
<td>Nuclear Engine for Rocket Vehicle Applications</td>
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<td>NTR</td>
<td>Nuclear Thermal Rocket</td>
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<td>RIFT</td>
<td>Reactor In-Flight Test Program</td>
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<tr>
<td>SEI</td>
<td>Space Exploration Initiative</td>
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<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
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CHAPTER 1

INTRODUCTION

During the period of 1989 - 1994, there has been a resurgence in the efforts of the technical community to develop effective propulsion systems for manned Mars missions. The chemical propulsion systems that were the mainstay of previous space endeavors are widely considered to be too inefficient to accomplish the task. Nuclear propulsion is considered to be a key technology in the Mars objective.

The nuclear thermal propulsion systems proposed have included versions of the familiar solid-core nuclear reactors tested in the 1960's, particle bed reactors, pellet bed reactors, and the conceptual gas core reactor. Technology Readiness Level (TRL) factors heavily favor the use of a solid-core nuclear reactor in any near-term launch scenario. A test base was established for the application of solid-core nuclear reactor technology to space missions in past programs. The Rover/NERVA programs (1955 - 1973) tested numerous solid-core reactors with much success. A revitalized space nuclear reactor program will benefit greatly from the simulations that can be performed with the advanced computational fluid dynamics (CFD) codes that are currently available.
The objective of this research was to study the flow of propellant (gaseous hydrogen) through a fuel element of a NERVA-Derived Reactor (NDR) and develop a design correlation useful for design and design trade-off studies. It is anticipated that this research will provide a base from which further study and modeling of other reactor types can begin.

**Thesis Organization**

Chapter 2 provides an introduction to the basics of the manned Mars mission, propulsion, the NERVA program, the NERVA-Derived Reactor (NDR), and the coolant channel flow of a solid-core nuclear rocket.

Chapter 3 briefly describes the problem to be analyzed.

Chapter 4 contains information about the requirements of the model, the choice of CFD code, the computational theory, and the various computational setups.

Chapter 5 contains a discussion of the computational results, one-dimensional analytical results, and the development of a design correlation.

Chapter 6 presents conclusions and recommendations for future work.
CHAPTER 2

RELEVANT ISSUES / MOTIVATION

Mentioned in this section are the relevant issues that guided the current outgrowth of research in this field around the time of the study. Also included is a description of some basic technical issues including the basics of rocket propulsion and the NERVA program.

The Space Exploration Initiative (SEI)

On July 20, 1989, President George Bush set down the Space Exploration Initiative (SEI). President Bush called for the United States to return to the moon and reach Mars before the 50th anniversary of the Apollo 11 landing. First, Space Station Freedom must be established in orbit around the earth. Then, it would be on to the moon to establish a permanent manned presence with a manned Mars mission to follow. Each level of achievement would be a stepping stone to the next. The mission statement given by President Bush set the challenge before us: “We must commit ourselves anew to a sustained program of manned exploration of the solar system and, yes, the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space.” (U.S. President, 1989)
The primary thrust of the SEI was a manned presence in space. President Bush indicated that we should be returning to the moon to "stay". In order to respond to this directive, NASA initiated a 90-day study to establish a starting point for achieving this goal.

**Nuclear Power: The Key to Manned Exploration**

Nuclear power is a key technology for manned missions to Mars. The nuclear thermal rocket (NTR), using an open cycle system, is a strong choice for all major Mars missions. A few of the advantages are:

- twice the *specific impulse* of a chemical propulsion system,
- Significantly reduced transit times (as short as 180 days) reducing an astronauts exposure to the damaging effects of cosmic radiation, weightlessness, etc.,
- Improved launch window opportunities,
- Reusable components,
- Relatively low life-cycle costs. (Borowski 1992)

The National Space Council’s Synthesis Group referred to the nuclear thermal rocket as “the only prudent propulsion system for Mars Transit.” (Borowski 1992)

**Orbital Geometry Considerations**

Any mission to Mars is governed by the orbital geometry of the Earth and Mars. As would be expected there are not many opportunities for launch windows when it comes to a Mars mission. The difficulty lay in the fact that a Earth-Mars-Earth mission
creates a "double rendezvous problem." As noted in Bennett (1992), it takes 26 months for the "identical geometrical Phasing (the synodic period) to occur between the positions of Earth and Mars." In addition, because of eccentricity considerations, the overall orbital geometry repeats on approximately 15-year cycles.

There are two classes of round-trip missions to Mars (Bennett 1992):

1) long stay-time (~500 day) missions which are sometimes referred to as "conjunction-class" missions because they center about a Sun-Earth-Mars conjunction in which the Sun and Mars appear on the same side of the Earth, and,

2) short stay-time (~30 day) missions which are sometimes referred to as "opposition-class" missions because they center about a Sun-Earth-Mars opposition, where the Sun and Mars appear on opposite sides of the Earth.

Therefore, all Mars mission architectures will be centered around one or both of these classes. The mission architectures detailed in this paper center around the "conjunction" type of mission.

**Mars Mission Scenarios**

Numerous Mars mission scenarios have been proposed with an ear tuned to many possible future political obstacles such as the lack of an effective heavy lift launch vehicle (HLLV). Initially, the mission proposals focused on a large single "all-in-one" vehicle which would deliver the rocket, the Mars Transfer Vehicle, and the Mars Entry Vehicle (MEV) in one trip. However, the logistics of such a trip presents difficulties. The main
drive behind going to a nuclear rocket in the first place would be to reduce the initial mass in low earth orbit (IMLEO). The lack of a HLLV capable of lifting such a large spacecraft with cargo into orbit needs to be addressed; options include initiating a new HLLV program (not very cost-effective or practical) and/or assembly in orbit. Significant assembly in orbit would hinder the program because of lack of experience in such large scale operations as well as the possibility of encountering situations that require multiple launches to correct unforeseen difficulties. Aside from the logistics problems, the craft would be launched on a long, possibly two-year mission. This would expose the crew-members to an unnecessarily long period of cosmic radiation and weightlessness.

It was then that the split/sprint mission scenarios started to develop. The split cargo/sprint manned mission offers advantages in modularity, speed, safety, and redundancy. The basic concept involves splitting the crew from the cargo to enhance safety and to reduce the effects of the unknown “human” variable (Shepard 1992). The cargo portion is sent in advance of the manned mission and uses a slower more cost effective trajectory to reach low Mars Orbit (LMO). There is, of course, no great need to deliver the cargo to Mars as quickly as possible as there is with the human side of the mission. A two year gap or more between the launching of the cargo and the manned mission is well within mission requirements. Sending the cargo first results in many positive benefits: 1) it identifies any problems encountered on the earth-Mars trip; 2) the cargo can be confirmed in a good LMO, thus reducing the possibility that the crew will
arrive at Mars and find its cargo has been lost or significantly damaged; and 3) the technology (if similar technology is used for both the cargo and manned missions) can be checked and verified and improved if necessary.

As split/sprint mission architectures were reviewed and improved, it again became apparent that additional changes in the principle concept were necessary to achieve low IMLEO and account for other considerations. The mission was broken down further into three or four spacecraft missions, each delivering an essential part of mission cargo or crewmembers.

According to Borowski (1993), the Mars Exploration Study Team is focusing on a “reference” mission to Mars around 2010 using the “Minimum Piloted Mass” split/sprint mission concept which includes the use of aerobraking and “in situ” refueling. “In-situ” refers to using a substance found on Mars itself as the propellant for the return trip, thus eliminating the need to carry that mass from earth. Both aerobraking and the use of “in-situ” propellant are considered to be significant technological risks. While the specifics of the mission architecture need not be mentioned, a basic overview will be given. The mission parts are placed in orbit by a 200-240 t HLLV. The mission is separated into four parts- three cargo and one piloted vehicle. The three cargo vehicles are launched (proposed September 2007) one to two years ahead of the piloted vehicle delivering the Earth return habitat and all necessary surface equipment. The outbound cargo missions are expected to take ~344 days. Once the cargo vehicles have deployed all cargo, habitats, surface equipment and operational checks have been confirmed, the
piloted vehicle is launched from Earth orbit (proposed November 2009). The fast
conjunction class trajectory is expected to take ~180 days. The stay on Mars is expected
to last 540 days. The manned return trip will also take ~180 days, making a total piloted
mission duration of ~900 days (Borowski 1993).

Nuclear Power Basics

Nuclear reactions provide an enormous amount of power, a great deal more than
chemical reactions. This is primarily because chemical reactions result from a change in
the electron state of atoms, whereas nuclear reactions represent a change in the nuclei of
atoms. In particular, all atoms have a binding energy or mass defect, which is the
difference between the mass of all the protons, neutrons, and electrons (which can
usually be disregarded) that make up the atom individually and the actual mass of the
atom. For example, the mass of constituent particles in a $^{235}_{92}$U atom is 237.033 amu,
while its actual mass is about 235.124 amu, leaving a difference of 1.909 amu. Using a
special form of the theory of relativity ($\Delta E = c^2 \Delta m$), the difference in mass, called the
mass defect, corresponds to a binding energy of 1777 MeV or 7.56 MeV/nucleon (a
nucleon is a proton or neutron, the particles which comprise the nucleus of an atom)
(Hill 1970). The binding energy represents the energy required to break-up the atom or
the energy that is released upon formation of the atom. Different isotopes have different
binding energies per nucleon. There is a rapid increase in the binding energy per nucleon
from 1.0 to about 8.0 MeV/nucleon beginning at a mass number (the total number of
protons and neutrons in the nucleus) of one to a mass number of 20. The binding energy
The radioactive isotope that is of concern in this study is $^{235}\text{U}$ or U235. When it is struck by (or more technically absorbs) a neutron, it undergoes a process called \textit{fission}—the process of an atom breaking apart as a result of the absorption of a neutron. Fission produces two large fission products and two or more neutrons along with gamma radiation, alpha particles, protons, beta particles, and kinetic energy. The fission products radioactively decay releasing more heat and radioactive by-products. Fission produces approximately 200 MeV per event. In general, this is because, the average binding energy per nucleon of the products released in the reaction is $\sim 8.4$ MeV, causing a release of $\sim 200$ MeV (8.4 - 7.5 or 0.9 MeV per nucleon) in each reaction (Hill 1970). Energy is released because the energy required to split the U235 atom is less than the energy released when the resultant particles are formed. Also, many neutrons are released in the decay and go on to strike other U235 particles, and so on. The reaction is enhanced by the use of a \textit{moderator} which is a material that “slows” neutrons to an energy at which they are likely to be absorbed by fissionable material and cause fission. The energy created by the reactions is then transferred through the structural material of the core to the coolant in the form of heat. The energy involved in a nuclear reaction is far greater than that of a chemical reaction, which produces several eV per event.
Another relevant issue is that of the reflector. To maintain criticality (a self-sustaining series of reactions), the neutrons that are captured in a fission process must equal the sum of the neutrons that are captured in non-fission processes and those that escape the reactor. To facilitate smaller reactor size, a desirable end, reflectors can be placed around and on both ends of a reactor. Reflectors are of a material that collide with escaping neutrons and reflect them back into the core. A reflector does not stop all neutrons from escaping the reactor; it reduces the energy of neutrons on the way out, sending some back into the reactor with a better chance of causing a fission process.

The use of reflectors can result in a uniform axial power density, where the transferred thermal power of the reactor is uniform along its length. This is the case with the model discussed in this study. Reactors without reflectors at the ends usually have a cosine shaped axial power density.

This was a brief introduction to nuclear power. For a more thorough discussion of nuclear reactions providing power, refer to Hill (1970) or Lamarsh (1983).

**Propulsion Basics**

The driving force in rocket propulsion is different from most other aerospace propulsion systems, in that a rocket provides its own working fluid whereas the turbojet engine operates on the atmosphere and provides only a trivial amount of its own working fluid in the form of injected fuel. The rocket, carrying its own fuel supply, propels itself by ejecting fuel at high velocity. The force created by ejecting the fuel is countered by
the movement of the rocket in the opposite direction, thus obeying Newton's Third Law of Motion, forces only occur in opposite pairs (Hill 1970).

In the case of the chemical and nuclear rocket, the flow of propellant is similar. The propellant (a fuel/oxidizer mixture for the chemical rocket and pure propellant for the nuclear rocket) enters a chamber where it is heated. In a chemical rocket the heat is produced by the chemical reaction between the fuel and oxidizer. In a solid-core nuclear rocket, the propellant is passed through a solid nuclear core and is, in effect, the coolant for the core. In both cases, the propellant leaves the chamber at an increased energy state (a higher stagnation temperature) headed for the convergent / divergent nozzle (this is due to the much higher pressure inside the rocket vessel than outside). The propellant passes through the nozzle, attaining Mach at the throat and supersonic speeds in the expansion portion. Figure 1 is a schematic drawing of a nuclear rocket.

![Figure 1 Nuclear Rocket Schematic Diagram](image_url)

The following definitions were extracted from Sutton (1986).

The total impulse, \( I_t \), is the thrust force, \( F \), integrated over the burn time, \( t \).
The specific impulse \( I_s \) is the total impulse per unit weight of propellant \( w \).

\[
I_s = \int F dt
\]

The units of \( I_s \) in the metric Standard International (SI) system of units is newtons (thrust) divided by kilogram per second (mass flow) and the sea-level constant \( g_o \) of 9.80 meters per second per second. \( I_s \) therefore has units of \( \text{N-sec}^2/\text{kg-m} \). Since a newton is defined as that force which gives a mass of 1 kilogram an acceleration of 1 m/sec\(^2\) (or 1 kg-m/sec\(^2\)), the units of \( I_s \) can be expressed simply in “seconds.” However, it is really a thrust force per unit weight flow.

The impulse-to-weight ratio of a complete propulsion system is defined as the total impulse \( I \), divided by the initial vehicle weight or loaded vehicle weight \( w_o \) (loaded with propellants). A high value indicates an efficient design (Sutton 1986).

A change in the momentum of the rocket is achieved by ejecting mass (propellant) at high speeds (recalling that momentum is defined as the product of mass and velocity). The change in momentum is thrust force of the rocket. Again, from Sutton (1986).

\[
F = \frac{d}{dt} m v_2 = \dot{m} v_2 = \frac{\dot{w}}{g_o} v_2
\]

where \( v_2 \) is the exhaust velocity.
Therefore, the thrust of the rocket is proportional to the mass flow rate and the exhaust velocity.

**Nuclear vs. Chemical Propulsion**

It has been known for a period of time that chemical propulsion systems are very inefficient in regard to interplanetary travel. The chemical rocket is very limited in energy, and therefore, thrust production. The following passages (the two primary reasons for the limitation of chemical rockets) were derived mainly from Hill (1970), which gives a sound argument for the use of nuclear power in space.

There are two primary reasons for the limitations of chemical rockets:

1) The chemical rocket is limited in the power that it can generate— it depends on the chemical reaction of matter. Chemical reactions occur because of the interaction of electrons between chemical species. The change in energies (binding energy) of the electrons as a result of these interactions is the energy released in the chemical reaction. The energy released by a chemical reaction is on the order of several electron volts. Therefore, the total energy released in a chemical reaction is limited to several electron volts per pair of interacting electrons.

2) In the chemical rocket, the propellant must act as the energy source. No outside element provides significant energy to the propellant. It can easily be deduced that very few chemical species react in a way that will provide the
energy required to power a rocket. The choices for propellant are therefore extremely limited.

The significant advantages of the nuclear rocket are apparent in these same areas. The nuclear reaction produces energy on the order of several million electron volts due to the immense binding energy of the nucleus. From an energy standpoint, relatively little fuel need be carried to produce the required energy. In the solid-core nuclear rocket, the propellant is passed through the core, heated as it goes, and then expanded out of a standard convergent / divergent nozzle. The propellant provides no energy to the system- the energy is provided by the heated core. The choice of propellant is, therefore, much greater than that of the chemical system (Hill 1970).

It is pointed out in chapters 11 and 15 of Hill (1970) that to achieve higher specific impulses the propellant should have low molecular weight and high stagnation temperature. When the cost of placing fuel in Low Earth Orbit (LEO), energy requirements, and efficiency are taken into account, it is desirable to achieve as high a specific impulse as possible. Since specific impulse is proportional to mass flow rate and exit velocity, those are the items which need to be stressed. The mass flow rate is limited in both the chemical and nuclear rocket by flow dynamics and the expansion ratio of the nozzle. However, exit velocity varies between the two systems. Without going into great detail (see Hill (1970) for a more thorough explanation), the exit velocity, noted as $v_2$ in the equations above, has a relationship as follows:
\[ v_2 = u_0 \propto \sqrt{\frac{T_o}{M}} \] (Hill 1970)

where \( T_o \) is the stagnation temperature and \( \bar{M} \) is the molecular weight of the propellant.

Therefore, to increase the exit velocity, and thus thrust and specific impulse, the stagnation temperature should be increased and/or the molecular weight decreased.

The stagnation temperature is the property in which heat addition plays the key role. Although the nuclear reaction produces an enormous amount of energy when compared to the chemical reaction, the type of nuclear reactor limits the amount of energy that can be passed on to the propellant. In the solid-core nuclear rocket, heat is transferred by first heating the structural materials in the core, then passing that heat from the structural core material on to the coolant, in this case the propellant. Therefore, the nuclear core structural components must attain a higher temperature than the propellant in order to have heat transfer (Hill 1970). This is unlike the chemical rocket in which the chemical reaction results in a very high combustion temperature (3200 - 4700K) and the structure itself is kept cooler than the propellant. A common material used in the nuclear core is graphite, but it cannot maintain its integrity at those high temperatures. The highest chamber temperatures reached by today's nuclear rocket engine is \(~2700-3000\)K. The chemical rocket wins the contest of stagnation temperature, using present day materials and technology.

However, the chemical rocket by its nature must carry a fuel and an oxidizer. There are numerous combinations including hydrogen/fluorine, hydrogen/oxygen, and
hydrazine/oxygen. The “propellant” that must be carried is the combination of the fuel and oxidizer. The exact molecular weight of the combustion products in a chemical rocket varies between ~10-23, but the average is ~20 (Hill 1970). Most of the molecular weight is provided by the oxidizer. The solid-core nuclear rocket, on the other hand, using hydrogen as the propellant provides a significantly increased exhaust velocity. The molecular weight of hydrogen (~2) is so much lower (as much as 12 times lower) than chemical propellants that it all but eliminates the advantages of the chemical rocket in regard to stagnation temperature (Hill 1970).

The chemical rocket is limited to a specific impulse of ~400-450 seconds. Based on today’s technology, the solid-core nuclear rocket can deliver ~850-1000 seconds of specific impulse. In the future, if the energy of the nuclear reaction is passed directly to the propellant without the interference of the structural components of the solid-core, the stagnation temperature could be increased dramatically, thus producing specific impulses of ~4 to 5 times that of the solid-core nuclear rocket.

It is also possible that nuclear rockets could use “in-situ” propellants at destinations far from earth. “In-situ” propellants are those materials (perhaps hydrogen) found in abundance on other planets. This would not be nearly as feasible with chemical propulsion systems.

For present day applications, the solid-core nuclear rocket is the most powerful nuclear rocket feasible. The difference in initial mass in low earth orbit (IMLEO) between mission equivalent chemical and nuclear rockets is so great that due to
restrictions on heavy lift launch vehicle (HLLV) capability, production costs, and the limitation on fuels used in the chemical rocket, the use of nuclear rockets and not chemical rockets is mandatory for manned interplanetary travel.

The NERVA Program

In the midst of the space race, a program was initiated to design, build, and test nuclear engines which could be used for space travel. The Rover/NERVA (Nuclear Engine for Rocket Vehicle Application) program spanned the years of 1955 to 1973 with dramatic success. It is from this base of knowledge that the first operational space nuclear thermal reactor will undoubtedly come. Originally intended to develop an engine system for long range ballistic missiles (ROVER), the program turned to space applications when responsibilities were transferred from the Atomic Energy Commission (AEC)/USAF to the National Aeronautics and Space Administration (NASA) in 1958 (Black 1991).

From 1960 to 1963, the NERVA program objective was the Reactor In-Flight Test (RIFT) program, which called for the ambitious goal of full test-firing a version of the KIWI-A (KIWI-B) using liquid hydrogen (LH$_2$) as the propellant prior to 1967. A major set-back occurred in 1962, when the first test-firing of the first LH$_2$ reactors resulted in severe core damage as a result of mechanical vibration caused by leakage flow. The problem was corrected and resulted in a mission qualified support structure for the core. In the fall of 1963, due to political changes, the RIFT program was canceled and the objective of the NERVA program was changed to providing a back-up
to the Saturn-V chemical rocket. The success of the Saturn-V made the use of the
NERVA engine for an upper stage to the Apollo program unnecessary. The entire
program shifted from being a flight-test program to a technology program (Black 1991).

"Manned interplanetary missions became the long-term nonspecific goal for the
growth development program, which consequently extended the original performance
objectives to longer endurance, higher power density, thrust and specific impulse."  
(Black 1991)

The Rover/NERVA test programs lasted from 1959 - 1973 and were extremely
successful.

The NERVA program produced over 20 full-scale reactor tests. The specific
impulse of the NERVA engine was estimated at 850 seconds and the thrust-to-weight
ratio at 5 to 1. The estimated performance using current technology is 925 seconds and
10 to 1 (Black 1991). A NERVA-Derived Reactor (NDR) (a reactor based on the
NERVA accomplishments using advanced materials) could be ready for full scale testing
within six-years and represents the safest, most cost effective technology for
accomplishing the manned Mars mission.

**The NERVA Derived Reactor (NDR)**

The NERVA-Derived Reactor (NDR) is the only type of Nuclear Thermal
Reactor (NTR) that has a considerable test/data base. Technology from the NERVA
program can be directly transferred to the NDR, which is basically the same concept
using advanced materials and other modifications.
The NDR is a graphite moderated homogeneous NTR concept in which the fuel and the neutron moderating materials are intermixed. The NDR design uses a hexagonal-shaped fuel element (0.75" [19.2 mm or 0.754" exactly (Black 1991)] across the flats), which is capable of producing ~0.9 to 1.2 megawatts of thermal power (MWt) with a 52" long [1.3m (Black 1991)] fuel element, and ~0.6 to 0.8 with a 35" long element. Each fuel element has 19 axial coolant channels, which along with the outer surfaces, are coated with zirconium carbide (ZrC) to reduce hydrogen/graphite reactions. A “2-pass” regeneratively-cooled, tie tube assembly supports from 2 to 6 fuel elements forming a fuel bundle...For lower thrust engines (in the 15 to 50 klbf range), criticality can be achieved with reduced core diameters and acceptable thrust-to-weight ratios by augmenting the moderating capability of the graphite core with additional zirconium hydride (ZrH) neutron moderator. The ZrH is contained in the tie-tube support elements which are increased in number for lower thrust engines by decreasing the fuel-to-support element ratio from ~6 to 1 for engine thrust levels of ~50 klbf or greater, down to ~3 to 1 for a 25 klbf-class engine. The 15 klbf NDR design utilizes a 35" long fuel element and has a fuel-to-support element ratio of ~2 to 1. (Borowski 1993 with extracts in brackets from Black 1991)

The rocket is comprised of the storage tank for the LH$_2$ and associated pumping apparatus, the plenum, the core, the chamber, and the convergent/divergent nozzle. The size of the core (and therefore the overall size of the rocket) is determined by the engine power desired. The current push of the manned Mars mission design community is behind using 3 to 4 - 15 klbf rockets on each leg. However, conceptual designs have been accomplished and published primarily for the 50 klbf rocket and above. The technology gained from the study of the 50 klbf rocket can be transferred to the 15 klbf rocket.
The 19-Channel Fuel Element

The fuel element of the NDR was at the center of this research. Specifically, the flow of hydrogen (H₂) through a fuel element coolant channel of the 50 klbf NDR was studied. The fuel element provides on average ~98% of the thermal power of the reactor. The other minimal contribution comes from the tie-tube elements that contain a moderator which reacts with escaped neutrons. The fuel element has a hexagonal shaped cross-section (19.2 mm across the flats) and is 1.3 m long as previously mentioned. It has 19-2.5 mm axial coolant channels that pass the thermal power to the coolant, H₂.

The emphasis of study was an individual coolant channel of the fuel element. A fuel element is shown in Figure 2.
The fuel elements number in the hundreds for the reactors in question and are supported by a tie-tube element structure throughout the core. The fuel element - tie-tube ratio increases for higher power reactors as previously mentioned. Figure 3 shows a portion of core structure with a ratio of ~2 to 1 (indicative of a 15 klbf reactor). The 50 klbf rocket has less tie-tubes and longer fuel elements (1.3 m as opposed to 0.9 m).

Figure 3 Fuel Element - Tie-Tube Structure (Tie-tubes are black)
Literature Search

DOE Proposal

An extensive literature search was conducted on the history of nuclear power as applied to space by myself, Dr. Bahram Nassersharif and Ms. Darby Hailes in late 1993/early 1994. The purpose of the literature search was to develop a proposal for a Department of Energy (DOE) grant, submitted January 31, 1994. The proposal was entitled “Scenario Based Design of Nuclear Propulsion for Manned Mars Mission” and concentrated on a systems approach. The specifics of that search are contained in the proposal itself and are not repeated here (Nassersharif 1994). However, it should be mentioned that the material found in that search has been used in this project. That information was used to gain an understanding of the use of nuclear thermal power in space propulsion systems.

Follow-on Literature Search

A continual technical literature search was conducted after the DOE proposal was submitted concentrating on specific system designs. Notes from a nuclear propulsion course outlined the current and past proposed systems for space nuclear propulsion and many auxiliary systems (Nassersharif 1991). It provided a technical base of information from which one could proceed with confidence into a study of this nature. The information it contained ranged from the NERVA reactor concepts to pellet-bed reactors and gas-core reactors. A paper by Borowski (1994) contained in the
Conference Proceedings of the Eleventh Symposium on Space Nuclear Power and Propulsion, outlined the Mars mission scenario previously mentioned and led to the discovery of other articles on the same topic. Unfortunately, much required material could not be found through literature searches conducted at the UNLV library. A trip was made to Edwards AFB, CA where adequate technical libraries existed and contained the required information. Another paper by Borowski (1993) presented at the AIAA Space Programs and Technologies Conference and Exhibit, contained more detailed information on Mars mission design considerations and options. A paper by David Black and Stanley Gunn (1991) contained a wealth of information on the history of the NERVA program. The technical measurements (temperatures, pressures, mass flows, etc.) used in this study were derived principally from a paper by H. R. Zweig and M. H. Cooper (1991), which outlined the performance characteristics of a 50 kilbf NDR. Many surrounding papers provided additional detail where required. A variety of technical text books were referenced to do “hand calculations” including Hill (1970) and Sutton (1986). Reactor coolant properties were derived from Mark’s Standard Handbook for Mechanical Engineers.
CHAPTER 3

PROBLEM DESCRIPTION

NERVA Derived Reactor (NDR) Specifications

The NERVA-Derived Reactor (NDR) was previously described. The specific inlet and outlet conditions are described in this section. The area of concern was the plenum-core-outlet chamber region. The inlet and outlet conditions, as estimated through previous NERVA work and corresponding material improvement, prescribed the boundary conditions for the problem in question. The estimated inlet/outlet conditions of the 50 klbf NDR rocket are given in Table 1.

Table 1 Estimated Inlet and Outlet Conditions

<table>
<thead>
<tr>
<th>INLET</th>
<th>OUTLET</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p = 5.97772 \text{ MPa (867 psia)} )</td>
<td>( p = 5.40546 \text{ MPa (784 psia)} )</td>
</tr>
<tr>
<td>( T = 136.289 \text{ K (245.3 deg R)} )</td>
<td>( T = 2450.196 \text{ K (4410 deg R)} )</td>
</tr>
<tr>
<td>( W = 26.34 \text{ kg/s (58.08 lbm/s)} )</td>
<td>( W = 26.34 \text{ kg/s (58.08 lbm/s)} )</td>
</tr>
<tr>
<td>( H = 1.546e+6 \text{ J/kg (664.8 BTU/lbm)} )</td>
<td>( H = 2.4758e+7 \text{ J/kg (10644 BTU/lbm)} )</td>
</tr>
</tbody>
</table>

where \( p \) = pressure, \( T \) = temperature, \( W \) = mass flow rate, and \( H \) = specific energy. (Zweig 1993)
The paper by Zweig gives similar estimates at other locations throughout the coolant flow system.

The transferred thermal power of the 1.3 m fuel element is between ~0.9 to 1.2 MWt (Borowski 1993). For the 50 klbf engine designed in the paper by Zweig (1993), the fuel element transferred power is 967.9 MWt and the tie-tube transferred power is 24.5 MWt. The term 50 klbf engine, rocket, etc. will be used throughout the text, as this refers to a certain classification of NDR. However, all specific values are shown in SI units.

Model

One of the objectives of this study was to model flow through a fuel element of a 50 klbf NDR, and provide a descriptive model of the system. The fuel element was represented by a single coolant channel. The characteristics of the coolant channel should be similar for most channels. However, there would be a difference between the most inside channel and one of the most outside channels as far as heat transfer and power density are concerned. Likewise, there would be a difference between an inner fuel element and an outer fuel element where the power density would not be as high. Those issues are not discussed in this study, but are relevant and are certainly logical options for future work. The current study focuses on the average element of a uniform axial power density NDR.

A stair-step approach was used. First, the model of the coolant channel (a generic test channel) was tested in two-dimensions (2D). The purpose of the 2D test
was to check the capability of the code to model the heat transfer. The method used in the two-dimensional test involved two flat plates separated by the coolant channel diameter. The coolant passed through the space between the two plates. The exact parameters were not set in the first 2D tests due to the lack of accuracy in the general shape of the model. The initial 2D test cases were also used to test the possibility of using an incompressible model. A more accurate 2D model was to be constructed later.

The three-dimensional model of the coolant channel (the specific NDR coolant channel) followed. The purpose of the 3D simulation was to test the feasibility of modeling the entire fuel element in the future in three dimensions. Obviously, the desirability of a very accurate model must be played against the heavy use of computational time for such a model. The 3D channel had a 2.5 mm diameter, was 1.3 m long, and was housed in an object (a rectangular block). Open boundaries at each end represented the inlet and outlet. The object provided the thermal transferred power indicative of the reactor.

An additional 2D model was constructed to evaluate the use of the 3D model. The second set of 2D models used cylindrical coordinates. It was actually a 30 degree slice of the channel with symmetry boundaries used to model the rest of the channel. A tighter mesh was used in the radial direction, while only one cell (making it 2D) was used in the theta direction. The same open boundaries created the flow in the 2D case.

Detailed descriptions of the individual models are contained in Chapter 4.
Interpolation to the NDR

The model was used as a basis for the entire NDR system (heated flow portion only). The outlet of each fuel element was considered to have the uniform properties mentioned in this chapter. This did not account for the turbulent outlet region of the chamber (flow in the exit region mixing with gaps formed by the tie-tube elements, support structure, etc.) and represents an ideal situation. The heat loss to the support structure at the exit was neglected as well. Also, any unheated tip region was disregarded. In view of the relatively long length of the channel, the model was considered to be accurate despite the aforementioned issues. The assumptions for the models are contained in Chapter 4.
CHAPTER 4

METHODOLOGY

This chapter details the methods used to analyze the problem and evaluate the solutions for accuracy.

Subject Choice

The choice of the NDR as the reactor for study was based on the probability of that type of nuclear thermal reactor (NTR) being used on a future manned Mars mission. If we do go to Mars, a NDR or similar reactor will most likely be the type of propulsion system used. The NDR is also the one system against which all other systems will be compared. The NERVA program realized success when powerful computers were not available. The new versions, the NDR's, will have the aide of computational research such as this study to optimize performance.

The fuel element is the key to the performance of the NDR. If the fuel element can be accurately modeled, many critical issues can be addressed with correct emphasis. One such area is the carbon loss due to hydrogen-carbon interaction. Hydrogen interacts with carbon causing carbon loss, a difficulty encountered during the NERVA program. Compounds were developed to minimize the carbon loss (including ZrC), but the amount
of carbon loss was never accurately predicted, and it is the objective of this and other studies to provide the temperature profiles required to make accurate calculations for such purposes. A 3D model of a 19-hole fuel element would predict hot spots and problem areas where such losses would occur in a greater proportion. Added emphasis could then be placed on coating those areas with extra protectant or performing whatever procedure necessary to defend against carbon loss.

Another area of emphasis involved the design parameters of the system. This study evaluates the design estimates for pressure, mass flow, etc.

**Computer Codes**

Several computer codes were evaluated for use in this study, some of which are mentioned in this section. The decision on which code was used was based on factors discussed in the code requirements section.

**FIDAP**

FIDAP is a general purpose finite-element computational fluid dynamics (CFD) code.

FIDAP simulates the flow of viscous compressible and incompressible fluids. In an isothermal situation, the governing equations solved by FIDAP are the Navier-Stokes and continuity equations. In a non-isothermal situation, FIDAP solves these equations together with the energy equation for temperature distributions. (FIDAP 1993)
The finite element model represents a powerful CFD tool used in many of today's engineering applications. FIDAP had the ability to model flow through the nuclear core. Development of complex geometries is not as advanced as some other codes, but was acceptable. However, in the Spring to Fall of 1994, the NSCEE experienced a great amount of difficulty with the FIDAP code. There was a major error in the implementation of the code that prevented efficient modeling. Simple inputs would take an unreasonable amount of time to register and the use of the interactive pre-processor was out of the question- one mouse click could take two to three minutes to register. Hence, FIDAP was eliminated from consideration due primarily to inefficiencies or errors in implementation on the NSCEE Cray.

FLOW-3D

FLOW3D is a finite-volume based CFD code which is exceptionally easy to use. It utilizes a pre-processor, a powerful and flexible processor, and a post-processor. The pre-processor uses an input file provided by the user, "prepin.inp". The prepin.inp file can be created by any text editor and is comprised of a series of namelists, a list of which follows (FLOW-3D 1994):

- **XPUT** - PHYSICAL AND COMPUTATIONAL PARAMETERS
- **LIMITS** - COMPUTATIONAL LIMITS
- **PROPS** - FLUID PROPERTIES
- **BCDATA** - BOUNDARY CONDITION PARAMETERS
- **PCAP** - CAPILLARY PRESSURE
- RBDATA - RIGID BODY DYNAMICS
- MESH - MESH GENERATOR
- OBS - OBSTACLE SETUP
- FL - INITIAL FLUID / PRESSURE CONFIGURATION
- BF - BAFFLE SETUP
- TEMP - INITIAL FLUID TEMPERATURE CONFIGURATION
- MOTN - ACCELERATION REFERENCE FRAME
- GRAFIC - GRAPHIC OUTPUT
- PARTS - PARTICLE SETUP

Of course, not all of these namelists are used on any given problem. Most of the essential namelists, such as limits and mesh must always be included, while others may or may not be included in a specific problem by assigning values to certain variables in the primary namelist XPUT. For a more complete description of the FLOW-3D computational process, one should refer to the FLOW3D Quick Reference Guide (1994).

FLOW-3D is produced and maintained by Flow Science Inc., located in Los Alamos, NM.

VSAERO

VSAERO is a computer program used for calculating aerodynamic characteristics in subsonic flow. "VSAERO calculates the linearized potential flow
external to a body or internal to a duct when the normal velocity on the surfaces
bounding the flow is specified; that is, VSAERO solves the Neumann problem of
potential flow.” (VSAERO 1994)

It was available on the NSCEE Cray and was briefly considered for use on this
project. It did not appear to have the desired characteristics.

**Requirements of the Model**

As a whole, the model of the core and the nozzle would require an extremely
flexible code that could model a wide range of speeds, temperatures, etc. Conceivably,
an expanded model could encompass the flow of cryogenic hydrogen from storage tanks
through pumps, through the outer nozzle for cooling purposes (it would be during the
pump/cooling phase that the hydrogen becomes gaseous), into the inlet chamber,
through the core to the chamber, and finally through a converging / diverging nozzle.
The essential area for modeling in this study was the fuel element in the core. The fuel
element, one of hundreds, is hexagonal-shaped (~1.9 cm across the flats) and 1.3 m
long. Each fuel element contains 19 evenly spaced coolant channels, 2.5 mm wide.
From the core, the model could be expanded out into the other regimes.

The flow of hydrogen through the core is subsonic (with an extremely low Mach
number). The hydrogen is exposed to extreme temperatures (~3000K) in the core. The
velocity of the heated hydrogen is increased as it approaches the throat of the nozzle and
achieves M=1 at the throat. In the divergent section of the nozzle, the flow becomes
supersonic. The gas is then expelled into a rarefied gas region.
Therefore, as a minimum, the code was required to model:

- internal flows through the small region of the coolant channels,
- extreme temperature gradients with heat transfer,
- complex geometries,
- compressible or incompressible flow,
- and power generation in the core structures.

To be extended to the nozzle region, the code would also be required to handle transonic and supersonic flows. It should be noted that if the best code for modeling the core did not have the extra capability to model the nozzle, it was not eliminated solely for that reason.

**Final Code Choice**

It was determined that VSAERO did not supply all of the characteristics required for the core model as effectively as the other codes. Meant more for subsonic flows over airfoils and into internal ducts from free-stream situations, this code would have required excessive adaptation and alteration to successfully model the core.

FIDAP was determined to have the ability to successfully model the core itself. The finite-element based code was previously installed on the NSCEE Cray computer and had been used successfully. However, as previously mentioned, the prolonged difficulty experienced with FIDAP eliminated it from consideration. The inability of FIDAP to function correctly was considered by many at NSCEE to be due to errors in
the newest version. Regardless of the reason, the code was not repaired soon enough to be considered.

FLOW-3D was chosen for the NDR core study. Its flexibility, robustness, and ease of use were all major factors in the decision making process.

FLOW-3D

Execution

FLOW-3D has three main processors.

PREP-3D is the preprocessor and requires user created input (the input file prepin.inp). The input file can be created by any text editor and contains a series of namelists which describe the problem in detail. The user is responsible for setting fluid properties, mesh sizes, and most other information. However, the namelist often have common default values which are convenient to the user. The results of PREP-3D can be reviewed with the graphics program, PLTFSI, prior to executing the processor.

HYDR3D is the processor of FLOW-3D and gives valuable execution information to the user in the form of a execution summary and a results summary. FLSCON is the post-processor of FLOW-3D.

A set of execution shell scripts are provided with the program for ease of use. An individual directory is created for each problem and the input file is placed in that directory. The user changes to that directory and uses the commands runpre, runhyd, and runfls to execute the processors individually, or uses the command runall to execute
everything. The program has a restart capability and graphic results can be adjusted by running the preprocessor and post-processor.


Solid Geometry Modeling

FLOW-3D contains a powerful geometry modeler. It creates "primitives" such as cones, spheres, blocks with simple commands. More complex geometries can be created using combinations of the primitives and other shapes which can be created using quadratic equations. The objects that are created can be placed anywhere in the mesh and can be given many different properties to include movement.

Model Defined and Supporting Calculations

The flow of gaseous hydrogen through the core (specifically through the coolant channel) was the basis for this study. Gaseous hydrogen, being a very light gas, was modeled as a perfect gas. The hydrogen was passed through (or past) the object defined in the FLOW-3D input file prepin.inp. All assumptions and model characteristics were also defined in the input file prepin.inp.

Assumptions

- PERFECT GAS AND SUBSEQUENT CALCULATIONS - Hydrogen was considered to be a perfect gas in this model. The perfect gas assumption allows for
the calculation of numerous estimated properties at the inlet and outlet based on the information derived from Zweig (1993).

**Table 2** Estimated Inlet and Outlet Conditions (repeated)

<table>
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</tr>
</tbody>
</table>

where $p =$ pressure, $T =$ temperature, $W =$ mass flow rate, and $H =$ specific energy.

The mass flow rate at the entrance of the channel was approximated from Zweig (1993). The fuel element transferred power was 967.9 MWt for the 50 klbf rocket. Using an average of 1.0 MWt provided by each fuel element, the approximate number of fuel elements was determined to be 968. At 19-coolant channels per fuel element, the final channel count was 18392. Dividing the overall mass flow rate for the 50 klbf reactor, 26.345 kg/s, by the approximate number of channels, 18392, resulted in the approximate channel mass flow rate of:

$$W_{\text{channel}} = 1.432e-3 \text{ kg/s}.$$ 

The gas constant of hydrogen was derived from the following equation:
\[ R = \frac{\overline{R}}{M}, \]

where \( R \) is the gas constant, \( \overline{R} \) is the universal gas constant, and \( M \) is the molecular weight.

For hydrogen (H\(_2\)), \( R = 4124.157 \text{ J/kg } \text{K} \).

Using the perfect gas relationship, the density, the average velocity of flow, and the average Mach numbers were calculated (Hill 1970).

The Perfect Gas Relationship is,
\[ p = \rho RT; \]

and therefore, \( \rho = \frac{p}{RT} \).

From Hill,
\[ \frac{p_2}{p_1} = \frac{u_1 T_2}{u_2 T_1} \quad \text{and} \quad \rho u_2 = \rho u_1. \]

Using the inlet as an example, the calculations proceed as follows:

\[
\rho = (5.97772 \times 10^6 \text{ kg/m}^2 \text{s}^2) \left( \frac{1}{4124.157 \text{ J/m}^2 \text{K}} \right) \left( \frac{1}{136.289 \text{ K}} \right),
\]

\[ \rho_{\text{inlet}} = 10.6 \text{ kg/m}^3. \]

\[ u_1 = \frac{W_{\text{channel}}}{\rho A}, \]

where \( u_1 \) is the inlet velocity, and \( A \) is the cross-sectional area of the channel.

\[ u_1 = (1.432 \times 10^{-3} \text{ kg/s}) \left( \frac{1}{10.635 \text{ kg}} \right) \left( \frac{1}{4.908 \times 10^{-6} \text{ m}^2} \right), \]

\[ u_1 = 27.4 \text{ m/s} \]
\[ M_1 = \frac{\rho u^2}{\gamma p}, \quad \text{assuming } \gamma = 1.4, \]
\[ M_1 = \sqrt{\frac{(10.635 \text{ kg/m}^3)(27.435 \text{ m/s})^2}{(1.4)(5.97772e+6 \text{ kg/m s}^2)}}, \]

\[ M_1 = 0.031 \]

Outlet Velocity Calculation
\[ u_2 = u_1 \frac{P_1 T_2}{P_2 T_1}, \]

\[ u_2 = 545.4 \text{ m/s}. \]

Similar calculations were made at the outlet resulting in the results of Table 3.

**Table 3** Additional Inlet and Outlet Conditions

<table>
<thead>
<tr>
<th>INLET</th>
<th>OUTLET</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p ) = 5.97772 MPa</td>
<td>( p ) = 5.40546 MPa</td>
</tr>
<tr>
<td>( T ) = 136.289 K</td>
<td>( T ) = 2450.196 K</td>
</tr>
<tr>
<td>( W_{ch} ) = 1.432 kg/s</td>
<td>( W_{ch} ) = 1.432 kg/s</td>
</tr>
<tr>
<td>( H ) = 1.546e+6 J/kg</td>
<td>( H ) = 2.4758e+7 J/kg</td>
</tr>
<tr>
<td>( \rho ) = 10.635 kg/m³</td>
<td>( \rho ) = 0.5349 kg/m³</td>
</tr>
<tr>
<td>( u_1 ) = 27.435 m/s</td>
<td>( u_2 ) = 545.441 m/s</td>
</tr>
<tr>
<td>( M_1 ) = 0.031</td>
<td>( M_2 ) = 0.145</td>
</tr>
</tbody>
</table>

- **TURBULENT FLOW** - The flow in the circular duct channel was considered to be turbulent because of the extremely high Reynolds numbers experienced in the flow. This was observed by Hill (1970), "Since the Reynolds numbers will be high, the
flow will be turbulent [referring to flow through coolant channels of a hydrogen cooled solid-core nuclear rocket].” General calculations were used to confirm this situation.

From the definition of Reynolds number for duct flow,

\[ \text{Re}_D = \frac{D V_{av}}{\nu}, \quad \text{(Burmeister 1993)} \]

where \( \text{Re}_D \) = Reynolds # for duct flow,
\( D \) = diameter of the duct,
\( V_{av} \) = average velocity, and
\( \nu \) = kinematic viscosity (\( \mu / \rho \)).

Approximations for the dynamic viscosity at the inlet and outlet were approximated from White (1991), based on temperature in those regions.

<table>
<thead>
<tr>
<th>INLET REGION</th>
<th>OUTLET REGION</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D = 0.0025 \text{m}, )</td>
<td>( D = 0.0025 \text{m}, )</td>
</tr>
<tr>
<td>( V_{av} = 27.435 \text{m/s}, )</td>
<td>( V_{av} = 400 \text{m/s}, )</td>
</tr>
<tr>
<td>( \frac{\nu}{\rho} \leq 9.4e^{-7} \text{m}^2/\text{s}, )</td>
<td>( \frac{\nu}{\rho} \leq 7.5e^{-5} \text{m}^2/\text{s}, )</td>
</tr>
<tr>
<td>( \text{Re}_D \geq 72000. )</td>
<td>( \text{Re}_D \geq 13000. )</td>
</tr>
</tbody>
</table>

Because flow in circular pipes is turbulent when the \( \text{Re} > 2000 \) (White 1991), the flow in this model can be considered turbulent throughout the realm of flow.

- **FULLY DEVELOPED FLOW** - The flow was considered fully developed because of the large length to channel hydraulic diameter ratio (Hill 1970). It should be noted that the Prandtl number for flows of hydrogen coolant flows through nuclear reactors is approximately \( \text{Pr} = 0.660 \) at 555K (Avallone 1987) and will not change appreciably with temperature. “Molecular effects predominate everywhere when Pr
is small [referring to turbulent flow in ducts]; not only is the temperature profile similar to that for laminar flow, but the thermal entry length and the response to changes in wall temperature are also similar to the laminar case.” (Burmeister 1993) This correlation indicates that the thermal entrance region of this particular turbulent flow will correspond to the laminar case. Burmeister (1993) further indicates that when \( Pr \sim 1.0 \) (which is the case for gases), as was the case in this study, ‘the temperature and velocity profiles develop at about the same rate.’ An approximation from Burmeister (1993) revealed that for circular duct flow with \( Re = 100000 \), and \( Pr = 0.7 \), the thermal (and similarly the velocity) entrance effects became insignificant at \( x/D=10 \) (0.025 m in this case) and almost completely disappeared by \( x/D=30 \) (0.075 m). Considering the length of the NDR coolant channel (1.3 m), the flow was, with certainty, characterized as fully developed throughout the flow region. A sophisticated core inlet system assures smooth flow into the channels which causes the flow to be developed as well.

- **VISCOUS STRESS AND HEATING MODEL REQUIRED** - Hill (1970) indicated that the ‘local heat transfer is directly proportional to the local wall shear stress.’ Therefore, the viscous stress and heating models were used.

- **UNIFORM AXIAL POWER DENSITY** - This is a good assumption if a reflector is positioned at both ends of the reactor (Hill 1970). A cosine axial power density does not differ greatly from the uniform axial power density in reference to the overall heat transfer. However, in the case of the NDR, a cosine axial power density would
be more accurate than a uniform axial power density and the inclusion of a cosine axial power density in future work is a consideration.

- **COMPRESSIBLE FLOW** - Large changes in the macroscopic density of the hydrogen flow prevented the use of an incompressible flow model. Normally with very low Mach numbers, compressible flows over short distances can be modeled as incompressible. However, with the significant addition of heat as in this case, that assumption cannot be made.

**Program Execution**

**Lessons Learned**

This section deals with problems encountered during the use of FLOW-3D and the solutions utilized. It is meant for the reader who is interested in continuing work of this nature using CFD codes.

One difficulty that was encountered during the execution was a large use of computational time to solve the one channel 3D problem, a problem that was foreseen as being somewhat inherent in solving a 3D problem. Initially, the problem was set up with 10 cells across the channel. This, of course, gave a well defined flow, but resulted in very large CPU times (~27000 seconds). Initially, a try was made at disconnecting the automatic time step function from the pressure iteration process. This, however, resulted in excessive pressure iteration failures and hence the failure of the code. It was thereafter determined that because of the inherent complications of running 3D-compressible problems, the best way to cut computational time was to decrease the size
of the mesh. The mesh size across the channel was reduced from ten to three to facilitate faster run times and to gain a general idea of the results before executing a more accurate model. The three cell model was not considered to be accurate for the end modeling of such a flow. It was intended to provide many fast runs to approximate results. This eliminated another problem that was encountered during the initial runs. As a result of the excessive run times, the time of the run was limited to ~0.01 seconds, which was not enough time for one pass of hydrogen through the channel. It was also not enough time for the transitory characteristics to dampen out. As a result, only snapshots of a transient behavior could be analyzed. Although the end result could be approximated from those snapshots, it was determined that longer actual run times were required.

Another difficulty that was encountered during the initial runs, was the inadequate transfer of heat from the channel to the hydrogen flow. The heat was "sticking" to the sides of the channel and not mixing into the flow. The result was an exit condition that had fluid temperatures of ~250K in the center of the channel (a wide cool spot) and fluid temperatures near the wall of ~1500K. Not enough heat mixing was taking place and the wall temperature of 1500K was in itself not acceptable in view of the fact that the objective was ~2450K average temperature. It was discovered that the object (channel) temperature had defaulted to 373.15K. The code was calculating the heat transfer based not only on the power that was set in the input file, but also from the temperature difference between the fluid and the wall. Hence, the code was adding heat to the fluid only to subtract most of it as a result of the fluid becoming hotter than the
wall. The solution was to set a flag in Sobs that prevented the temperature difference of the wall and fluid from providing any input into the heat transfer calculation.

**Two-Dimensional (2D) Test Cases**

Two two-dimensional (2D) test cases were examined to test the feasibility of using an incompressible flow model and evaluate the capability of FLOW-3D. The two dimensional models were not exact models of the NDR channel flow, but represented only general properties of coolant channel flow. The 2D cases used were not adequate for solving the problem because of the method used. The model was set-up with two plates opposite one another with a channel diameter separation. The third dimension was set at a unit depth to make the problem 2D. However, since the unit depth was so much greater than the channel diameter, the model was considered inaccurate. Flow Science confirmed that a better 2D model would involve cylindrical coordinates. That model is discussed later.

The initial 2D test cases did confirm the fact that a compressible model was required as predicted in the hand calculations. A schematic of the initial 2D test case model is shown in Figure 4.

![Figure 4 Initial Two-Dimensional Test Case Model](image)
The 2.5 mm channel diameter was specified in all of the model geometries.

Three Cell
Three-Dimensional (3D) Models

Two three-dimensional (3D) models were developed. The size of the model was the same in both cases. An obstacle was created to represent the coolant channel. A cylindrical hole was created to run axially down the center of the object (see Figure 5). The object was 1.3208 m long and was rectangular, having sides of 0.004 m. The hole was 2.5 mm in diameter.

Thirty cells were established down the length of the channel, as was the case with all of the models. In the first two 3D cases, three cells were placed across the channel in both the x and y direction (z was the axial direction). The rough mesh was intended to ease computational time and determine what power level setting resulted in expected temperature profiles. The initial temperature, pressure, density, and velocity profiles were set using linear equations from inlet and outlet hand calculations. The inlet velocity was set at 27.635 m/s in all of the 3D models and used as the boundary condition for that face. The outlet pressure was set at 5.4 MPa and was used as the boundary condition for that face. The mass flow at the inlet was defined by the velocity and density at the inlet. Specifications for the fluid properties of hydrogen are contained in the input file. One model was run at 1.0 MWt and another was run at 1.1 MWt. The transferred thermal power of the obstacle was defined by dividing the power of the fuel element by 19, the number of coolant channels. The results of the 1.0 MWt and 1.1 MWt runs
determined what power would be set for the following tighter mesh model. Copies of
the input files for the 1.0 MWt and 1.1 MWt model are contained in Appendices A and
B, respectively.

Figure 5 Three-Dimensional Coolant Channel Model

Seven Cell
Three-Dimensional (3D) Model

A model was created with the same specifications as the 1.1 MWt three-cell
model, except having seven cells across the channel. The objective of the tighter mesh
was to gain better accuracy in the model. The input file is contained in appendix C.
Four Cell
Two-Dimensional (2D) Model

A model was created with the 1.1 MWt specifications for power except in a cylindrical 2D form. The model was basically a 30-degree "pie-slice" of the coolant channel (see Figure 6). The axial direction was the z-direction as it had been before. However, the x-direction became the radial direction and the y-direction became the theta direction. The power was adjusted by dividing the 3D power by 12. The number of cells in the radial direction was defined as four to test the equivalency of the 3D and 2D 1.1 MWt models. One cell was defined for the theta (y) direction, thus making the problem 2D. Thirty cells were again used for the axial direction. The 2D model was expected to provide lower computational times and if accurate should be used instead of the 3D model.

Figure 6 Two-Dimensional Coolant Channel Model
Eleven Cell
Two-Dimensional (2D) Model

A model using the same specifications as the Four-Cell 2D model was created using eleven cells in the radial direction. Because the 2D model represented only half the channel width, the 3D equivalent would be 22 cells across the channel. To model that number of cells in 3D would require unreasonably large amounts of computational time. The eleven cell 2D model was designed to give a precise picture of the radial and axial distribution of flow characteristics.

One-Dimensional Analytical Solution

A one-dimensional analytical solution was derived for comparison purposes. The inlet conditions were prescribed by the previous design estimates from Zweig (1993). An outlet temperature of 2350 K was specified to ensure an adequate comparison to the computational models.

A Brief 15 klbf NDR Core Design

Methodology for Determining the Size of Core for a 15 klbf Rocket

As a side issue, the sizing of a 15 klbf NDR core was accomplished. This may assist in future work if downscaling to this size rocket is a concern in the design process. The units are in English for the most part and are not meant to be applied to other sections of this work.
A scaling method was used to determine the size of the core itself. The objective was to design a NDR which would power a 15 klbf rocket. Several NERVA designs were looked at to determine the core power output to rocket force ratio, and all yielded similar results. One design, the NRX Series NERVA design, yielded 55 klbf from 1100 MWt (Borowski 1993). That is a 20 MWt / 1 klbf ratio. Therefore, for a 15 klbf rocket a core which produces 300 MWt is required.

For a 15 klbf rocket, core power ~300 MWt.

Using the average production from a 35 in NDR fuel element, 0.7 MWt (range ~0.6 to 0.8 MWt) (Borowski 1993), the number of fuel elements can be calculated.

For a 300 MWt core, ~429 fuel elements required

Because a 15 klbf rocket using 35 in fuel elements has a fuel to support element ratio of ~2 to 1 (Borowski 1993), the total number of elements required is ~643.

With a fuel to support element ratio of ~2 to 1,

~643 total elements required.

These numbers would of course be for the average fuel element power and can only be used as rough estimates for the number of elements in the core. The results of the Fuel_Elment FORTRAN program yield a more definitive answer as to how many fuel and support elements would make up the core.
Fuel Element FORTRAN Program

The problem of calculating the number of total fuel elements in the geometric configuration of the core needed to be solved. To calculate this problem by hand seemed too lengthy and no optimization code existed that was readily available.

The key assumption was to assume a hexagonal core. The fuel elements are hexagonal and thus lend themselves to be fused into an overall hexagonal shape. The hexagonal core is set into a cylindrical housing for support.

Assumptions for a 15 klbf NDR rocket (Borowski 1993):

1. hexagonal fuel element
2. width across flats - 0.75”
3. length of fuel element - 35”
4. fuel-to support element ratio - ~2 to 1
5. thermal power per fuel element - ~0.6 to 0.8 MWt
6. coolant channels pass axially through each fuel element

In the core there is a center hexagon. The first ring added around the center hexagon, therefore, contains six hexagons-one attached to each face (Note: Each ring will be referred to as a level-the first added ring being the second level). If successive hexagons were added straight out from each face, the result would be six spokes of hexagons. However, in the core of the NDR the space between the spokes must be filled in. After the second level of six hexagons (or fuel elements) is added, an additional hexagon must be added for each level for the space in between each spoke. Therefore, the second level contains six, the third level contains 12, the fourth level contains 18, etc.
The FORTRAN code, Fuel_Element, calculates the cumulative number of fuel elements at each level using the formula:

$$ELEM(N) = ELEM(N-1) + [6 \times (N-1)]$$;

$$N \geq 2$$ and $$ELEM(1) = 1$$.

With the fuel-to-support element ratio being ~2 to 1, the number of fuel elements at each level is then calculated by dividing the total number of elements minus one [$$ELEM(N) - 1$$] by three and multiplying by two. The remaining elements are the support elements. The approximate corner-to-corner diameter of the core can be found by first calculating the radius. The radius (corner-to-corner) is the width across the flats of each fuel element multiplied by the level number minus 1/2 a fuel element width (to account for the half fuel element at the center. Geometric calculations yield the approximate core diameter across the flats. The low, average, and high core power levels are found by multiplying the number of fuel elements by 0.6, 0.7, and 0.8 MWt respectively.

**Sizing Results**

The results of the program Fuel_Element and the code are contained in Appendix F.

The key figure in determining the size of the core is the power produced assuming the power range of each fuel element is ~0.6 to 0.8 MWt. The average power should be well above the 300 MWt figure to ensure adequate power in most circumstances. The core with 631 total elements should produce 252.6 MWt, 294.7 MWt, or 336.8 MWt if all fuel elements operated at 0.6 MWt, 0.7 MWt, or 0.8 MWt.
respectively. This did not provide the necessary safety factor to ensure proper power production. Therefore, the core with 721 total elements was chosen.

Table 4 Fuel Element Results

<table>
<thead>
<tr>
<th>#ELEM</th>
<th>#FE</th>
<th>#SE</th>
<th>DIA_CC</th>
<th>DIA_FL</th>
<th>LOW</th>
<th>AVG</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>721</td>
<td>481</td>
<td>240</td>
<td>23.25</td>
<td>20.14</td>
<td>288.6</td>
<td>336.7</td>
<td>384.8</td>
</tr>
</tbody>
</table>

It should be noted that the number of fuel elements contained in this core is well above the estimate provided earlier in this section—another positive safety item.

The relationship of the core diameter to the core length should also be considered. In many cases, NERVA reactors have a 2/3 diameter-to-length ratio (Chi 1989). The core described above has a ratio of ~23.25 in / 35 in, or ~2/3.
CHAPTER 5

RESULTS / DISCUSSION

The model showed a high degree of success in the modeling of the NDR channel flow. The temperature profile supported the estimations mentioned in chapter 3. It was assumed that the fixed pressure in the chamber (the outlet region) could be held at a uniform value. In reality, the pressure drop of the channels would play the largest role in determining the chamber region pressure. The outlet pressure and an inlet velocity were prescribed in the code to set up the flow. A larger pressure drop than expected occurred across the channel.

Three Cell 3D Models

Two runs were accomplished using a 3D model of a 2.5 mm coolant channel, one with 1.0 MWt power and the other with 1.1 MWt power. The rough mesh allowed for only approximate temperature distributions, which were used to determine which power setting would be used with the more accurate mesh. The three cell models were not intended to provide accurate temperature distributions.
1.0 MWt Model

The parameters for the run are shown in Table 5.

**Table 5** Three Cell 3D 1.0 MWt Specifications

<table>
<thead>
<tr>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 3 x-y mesh cells across the channel, 30 axial</td>
</tr>
<tr>
<td>• inlet velocity/temperature and outlet pressure prescribed</td>
</tr>
<tr>
<td>• power = 0.05263 MWt (corresponds to 1.0 MWt fuel element)</td>
</tr>
<tr>
<td>• time = 0.05 seconds</td>
</tr>
</tbody>
</table>

Refer to Appendix A for the graphical results of this run. Table 6 shows data at various cells throughout the flow.

**Table 6** Three Cell 3D 1.0 MWt Results

<table>
<thead>
<tr>
<th>Cell Position</th>
<th>4,4,2</th>
<th>4,4,3</th>
<th>4,4,31</th>
<th>5,4,31</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ (MPa)</td>
<td>~8.47</td>
<td>~8.45</td>
<td>~5.58</td>
<td>~5.58</td>
</tr>
<tr>
<td>$w$ (m/s)</td>
<td>~46.3</td>
<td>~61.6</td>
<td>~774</td>
<td>~493</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>~205</td>
<td>~264</td>
<td>~2178</td>
<td>~2210</td>
</tr>
<tr>
<td>$\rho$ (kg/m3)</td>
<td>~9.99</td>
<td>~7.76</td>
<td>~0.62</td>
<td>~0.61</td>
</tr>
<tr>
<td>$\mu$ (Pa-s)</td>
<td>~4.66e-3</td>
<td>~7.05e-3</td>
<td>~1.42e-2</td>
<td>~2.44e-3</td>
</tr>
<tr>
<td>$TE$</td>
<td>~15.5</td>
<td>~41.3</td>
<td>~9957</td>
<td>~1986</td>
</tr>
<tr>
<td>$TD$</td>
<td>~4.39e+4</td>
<td>~1.6e+5</td>
<td>~3.67e+8</td>
<td>~8.45e+7</td>
</tr>
</tbody>
</table>

where $p$ = pressure, $w$ = z velocity, $T$ = temperature, $\rho$ = density, $\mu$ = dynamic viscosity, $TE$ = turbulent energy, and $TD$ = turbulent dissipation.
All of the cells marked 4,4 are in the center of the flow. The last number represents the axial cell number (z). The axial cells of 2 and 3 are near the inlet, while the axial cells of 31 are near the outlet. The cell 5,4,31 is a cell near the outlet, near the wall. The exit velocity appeared to slightly exceed previously reported values and could have been the effect of a higher mass flow rate at the exit than expected- depending on the method which the code chose to calculate the velocity. Also, the pressure at the inlet could not be set as a boundary condition if the velocity boundary was set which allowed the pressure at the inlet to exceed expected values, corresponding to higher required inlet pressures. Interestingly, the pressure at the inlet yielded a more reasonable value in large mesh runs. The above values were observed at 0.025 actual seconds and consumed ~8000 CPU seconds.

The peak velocity at the outlet was 729 m/s, a greater velocity than expected. The peak temperature at the outlet was ~2200K. The pressure at the inlet increased to a value of 8.5 MPa, a value much greater than expected. The high value of required inlet pressure accompanied most of the rough mesh calculations and did not affect the choice of power level. Density contours revealed relatively large changes in density near the inlet that would predominate in all of the calculations. The values of density and temperature at the inlet in the graphical representations show the “trend” of the value at the inlet. The actual value at the inlet was defined in the input file. For example, in the first 3D run the inlet temperature is shown graphically as 205K, but it is actually defined
as 136K. The pressure contours, however, show the approximate pressure that would be required at the inlet to accomplish the given flow pattern.

1.1 MWt Model

The parameters for the run are shown in Table 7.

| Specifics |  
| --- | --- |
| • 3 x-y mesh cells across the channel, 30 axial |  
| • inlet velocity/temperature and outlet pressure prescribed |  
| • power = 0.057895 MWt (corresponds to 1.1 MWt fuel element) |  
| • time = 0.05 seconds |  

Refer to Appendix B for the graphical results of this run.

The objective of this run was to slightly increase the outlet temperature of the hydrogen, which although acceptable, left room for improvement of the model.
Table 8 Three Cell 3D 1.1 MWt Results

<table>
<thead>
<tr>
<th>Cell Position</th>
<th>4,4,2</th>
<th>4,4,3</th>
<th>4,4,31</th>
<th>5,4,31</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p ) (MPa)</td>
<td>(~8.7)</td>
<td>(~8.6)</td>
<td>(~5.6)</td>
<td>(~5.6)</td>
</tr>
<tr>
<td>( w ) (m/s)</td>
<td>(~47)</td>
<td>(~63)</td>
<td>(~842)</td>
<td>(~535)</td>
</tr>
<tr>
<td>( T ) (K)</td>
<td>(~212)</td>
<td>(~277)</td>
<td>(~2385)</td>
<td>(~2420)</td>
</tr>
<tr>
<td>( \rho ) (kg/m³)</td>
<td>(~9.9)</td>
<td>(~7.6)</td>
<td>(~0.57)</td>
<td>(~0.56)</td>
</tr>
<tr>
<td>( \mu ) (Pa·s)</td>
<td>(~4.6 \times 10^{-3})</td>
<td>(~6.9 \times 10^{-3})</td>
<td>(~1.4 \times 10^{-2})</td>
<td>(~2.4 \times 10^{-3})</td>
</tr>
<tr>
<td>( TE )</td>
<td>(~15.7)</td>
<td>(~43.0)</td>
<td>(~11700)</td>
<td>(~2330)</td>
</tr>
<tr>
<td>( TD )</td>
<td>(~4.45 \times 10^4)</td>
<td>(~1.7 \times 10^5)</td>
<td>(~4.75 \times 10^8)</td>
<td>(~1.1 \times 10^8)</td>
</tr>
</tbody>
</table>

where \( p \) = pressure, \( w \) = z velocity, \( T \) = temperature, \( \rho \) = density, \( \mu \) = dynamic viscosity, \( TE \) = turbulent energy, and \( TD \) = turbulent dissipation.

The cell structure in this run was the same as that for the 1.0 MWt run. The total time of the run was 0.05 seconds, and the transient characteristics dissipated \(~0.023\) seconds. The increased power used to achieve the higher expected temperatures was an acceptable procedure and raising the power even higher would have still been acceptable. It was mentioned in section 1 that the approximate rated power of the 1.3m fuel element was \(~0.9 \) to \(~1.2\) MWt. Initially, the power of the object was set to 1.0 MWt. The power was set at a power setting that was not the maximum in order to allow for later increases if necessary. Additionally, it was anticipated that not all fuel elements would operate at the \( 1.2 \) MWt level, due to fabrication variations and some fuel poisoning throughout the reactor. Once again the calculated pressure at the inlet increased. At the outlet, the
velocity in the center of the flow was higher than expected (~840 m/s) indicating an increased mass flow rate. The pressure, temperature, and density approached expected values. Near the wall at the outlet, the velocity tapered to ~535 m/s. The average temperature of the flow was ~2400K, which was within 2% of the expected value. The accuracy of the outlet conditions for this rough model warranted another run at the same power and specifications with a more defined mesh in the channel.

The CPU times in this type of model were ~2300 CPU seconds for 0.025 seconds of actual model time.

Pressure Model

It should be noted that an effort was made to use strictly pressure boundaries to establish flow. The problem did not converge and yielded unreasonable values.

**Table 9  All Pressure Run Specifications**

<table>
<thead>
<tr>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 3 x-y mesh cells across the channel, 30 axial</td>
</tr>
<tr>
<td>• inlet pressure/temperature and outlet pressure prescribed</td>
</tr>
<tr>
<td>• power = 0.05789 MWt (corresponding to 1.1 MWt fuel element)</td>
</tr>
<tr>
<td>• time = 0.025 seconds</td>
</tr>
</tbody>
</table>

The objective of this run was to determine the effect of operating with two pressure boundaries and no velocity boundary. The result showed failure. No smooth flow ever developed and large oscillations predominated in the output. Temperatures, as
a result, reached ~40000K. The use of two pressure boundaries would not be a suitable set-up for a compressible problem of this nature using FLOW-3D.

**Seven Cell 3D Model**

The seven cell 3D model was designed to improve on the 1.1 MWt three cell model. Previous runs with 10 cells across the channel proved to use too much computational time, so the number of cells was reduced to seven.

**Table 10 Seven Cell 3D 1.1 MWt Specifications**

<table>
<thead>
<tr>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 7 x-y mesh cells across the channel, 30 axial</td>
</tr>
<tr>
<td>• inlet velocity/temperature and outlet pressure prescribed</td>
</tr>
<tr>
<td>• power = 0.05789 MWt (corresponding to 1.1 MWt fuel element)</td>
</tr>
<tr>
<td>• time = 0.020 seconds</td>
</tr>
</tbody>
</table>

The seven cell run experienced temperatures of ~2300K at the outlet and a required inlet pressure of ~ 6.9 MPa. The considerable difference in the pressure profile between the three cell model deserves some attention. The pressure drop across the channel increases or decreases significantly with mesh size. Therefore, the mesh size must be large enough to accurately predict the pressure drop and obviously as many cells as practical is desired. Since the seven cell run used large CPU times ~18000 CPU seconds for 0.02 seconds of actual model time, it would be expected that the addition of cells any further would either cause excessive run times or the actual time of the run would have to be scaled back. Scaling back the run would result in encountering
 unacceptable transient behavior characteristics. Therefore, a simpler model was desired that could accurately predict the flow. The 2D model with opposing plates presented difficulty, but a 2D model in cylindrical coordinates was expected to meet the objective.

**Table 11 Seven Cell 3D 1.1 MWt Results**

<table>
<thead>
<tr>
<th>Cell Position</th>
<th>6,6,2</th>
<th>6,6,3</th>
<th>6,6,31</th>
<th>9,6,31</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ (MPa)</td>
<td>~6.9</td>
<td>~6.9</td>
<td>~5.48</td>
<td>~5.48</td>
</tr>
<tr>
<td>$w$ (m/s)</td>
<td>~52</td>
<td>~70</td>
<td>~787</td>
<td>~283</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>~193</td>
<td>~246</td>
<td>~2207</td>
<td>~2340</td>
</tr>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>~8.7</td>
<td>~6.8</td>
<td>~0.60</td>
<td>~0.57</td>
</tr>
<tr>
<td>$\mu$ (Pa-s)</td>
<td>~2.4e-3</td>
<td>~2.2e-3</td>
<td>~1.6e-3</td>
<td>~7.5e-4</td>
</tr>
<tr>
<td>$TE$</td>
<td>~9.3</td>
<td>~17.0</td>
<td>~1850</td>
<td>~1000</td>
</tr>
<tr>
<td>$TD$</td>
<td>~2.7e+4</td>
<td>~7.8e+4</td>
<td>~1.14e+8</td>
<td>~0.7e+8</td>
</tr>
</tbody>
</table>

**Four Cell 2D Model**

A two-dimensional model was created using the methods described in chapter 4. It was created for comparison against the seven cell 3D model. The four cells represented half the cells of the seven cell model (the fourth cell was half of the center cell in the 3D model).
Table 12 Four Cell 2D 1.1 MWt Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 4 radial cells, 1 theta cell, 30 axial cells</td>
</tr>
<tr>
<td>• inlet velocity/temperature and outlet pressure prescribed</td>
</tr>
<tr>
<td>• power = 0.05789 MWt (corresponding to 1.1 MWt fuel element)</td>
</tr>
<tr>
<td>• time = 0.025 seconds</td>
</tr>
</tbody>
</table>

If the property profiles in the two models were in close agreement, the 2D model could be used in place of the 3D model, thus saving a large amount of computational time and improved results. The peak temperature at the outlet of the four cell 2D model was ~2340K, less than 10 degrees difference from the 3D model (~2330K). The velocity differed by ~ 20 m/s which may have been due to the codes cell placement. The density profiles were almost identical and the required inlet pressure varied by 0.2 MPa.

Therefore, because the four cell 2D model and the seven cell 3D model yielded answers that were very close, it was determined that subsequent models should be run in two dimensions as opposed to three. The significant reduction in CPU run time should be noted. The four cell 2D model used ~480 CPU seconds to accomplish 0.025 seconds of modeling time, whereas the same 3D model used ~18000 CPU seconds for 0.02 seconds of modeling time (over 36 times greater CPU time). It was most apparent that the 2D model should be utilized.
Eleven Cell 2D Model

The reduced CPU times involved with the 2D model made more refined models possible. The radial direction was divided into 11 cells, with a tighter mesh near the wall.

Table 13 Eleven Cell 2D 1.1 MWt Specifications

<table>
<thead>
<tr>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 11 radial cells, 1 theta cell, 30 axial cells</td>
</tr>
<tr>
<td>• inlet velocity/temperature and outlet pressure prescribed</td>
</tr>
<tr>
<td>• power = 0.05789 MWt (corresponding to 1.1 MWt fuel element)</td>
</tr>
<tr>
<td>• time = 0.025 seconds</td>
</tr>
</tbody>
</table>

The results of the eleven cell model demonstrated the usefulness of a tighter mesh. The eleven cells that spanned the model corresponded to 22 cells in a similar 3D model. The result was a more defined temperature profile which showed a tendency for slightly less temperature mixing toward the center (expected because the heat transfer had to take place through more cells). The temperatures at the outlet averaged ~2200 - 2300K with peak temperatures of ~2400K at the channel wall. The velocity profile showed the bulk flow bluntness expected of a turbulent flow. The peak velocity was ~660 m/s at the center of the outlet and represented velocities close to the average of ~545 m/s expected.

The pressure drop across the channel represented the most significant results of the study. The required inlet pressure for the most defined model, the eleven cell model
was around 0.9 MPa, 0.3 MPa greater than reported in previous studies. The difference resulted from the inclusion of pressure loss due to wall friction and other models used in the code.

A compilation of the results of this model are contained in Appendix E.

One Dimensional Flow
Analytical Solution

There are no consistently accurate analytical solutions for compressible flow with heat addition in pipes, and a numerical solution is required for most situations. However, if the fluid is assumed to be a calorically perfect gas, a series of analytical solutions can be used to solve the problem in one dimension (Anderson 1990). The solution for this type of one dimensional flow problem can be found in most gas dynamics text books including Anderson (1990). In general, the properties at the inlet and outlet of a circular duct are derived from the amount of heat added and the Mach number at the inlet and outlet. The specific application of the equations from Anderson (1990), section 3.8, to the coolant channel problem in question is detailed in Hill (1970). The equations of interest are the inlet and outlet ratios of stagnation temperature and pressure from Hill (1970).

\[
\frac{T_{o2}}{T_n} = \frac{M_2^\gamma \{1 + [(\gamma - 1) / 2] M_2^2 \{1 + \gamma M_2^2 [1 - (C_f L / D_n)] \}^2\}}{M_1^\gamma \{1 + [(\gamma - 1) / 2] M_1^2 \{1 + \gamma M_1^2 [1 + (C_f L / D_n)] \}^2\}}, \text{ and,}
\]

\[
\frac{p_2}{p_1} = \frac{1 + \gamma M_1^2 [1 - (C_f L / D_n)]}{1 + \gamma M_2^2 [1 + (C_f L / D_n)]},
\]
where $T_o$ is the stagnation temperature, 
$M$ is the Mach number, 
$\gamma$ is considered to be 1.4, 
$C_f$ is the coefficient of friction, 
$L$ is the length of the channel, 
$D_H$ is the hydraulic diameter of the channel ($D$ in this case), 
$p$ is the pressure, and 
the subscripts 1 and 2 denote the inlet and outlet respectively.

The equations are identical to those found in Anderson (1990) with the exception of the addition of the friction term. The friction term includes the coefficient of friction, the length of the channel, and the diameter of the channel. The length and diameter of the channel, 1.32 m and 2.5 mm respectively, were known values. The coefficient of friction was derived from Mark's (1987). At very high Reynolds numbers, the coefficient of friction can be assumed to be a constant, $C_f = 0.005$. Using a temperature at the channel outlet of $\sim 2350$ K and an estimated value for the outlet Mach number of $M = 0.14$, the flow tables in Anderson (1990) were referenced to obtain the stagnation temperature-temperature ratio ($T_o / T$). The ratio of 1.004 corresponded to an outlet stagnation temperature of $\sim 2360$ K (the equivalent of 3.37 J/kg of heat added). The much lower Mach number at the inlet allowed the assumption of equality between the stagnation temperature and the temperature ($\sim 136$ K). The stagnation temperature ratio ($T_{o2} / T_{o1}$) of 17.35 and the inlet Mach number, $M = 0.031$, were used to determine the outlet Mach number. A trial and error procedure was used to solve the equation for the outlet Mach number. The resulting outlet Mach number, $M = 0.143$, was used to solve
for the outlet pressure, assuming an inlet pressure of $p_i = 5.978$ MPa. The analytical results for the one dimensional channel flow with heat addition problem are given in Table 14.

**Table 14 Analytical Inlet and Outlet Conditions**

<table>
<thead>
<tr>
<th>INLET</th>
<th>OUTLET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 136$ K</td>
<td>$T = 2350$ K</td>
</tr>
<tr>
<td>$M = 0.031$</td>
<td>$M = 0.143$</td>
</tr>
<tr>
<td>$p = 5.978$ MPa</td>
<td>$p = 5.402$ MPa</td>
</tr>
<tr>
<td>$\rho = 10.64$ kg/m$^3$</td>
<td>$\rho = 0.557$ kg/m$^3$</td>
</tr>
<tr>
<td>$u = 27.4$ m/s</td>
<td>$u = 524.6$ m/s</td>
</tr>
<tr>
<td>pressure drop = 0.576 MPa</td>
<td></td>
</tr>
</tbody>
</table>

**Discussion of Results**

The most significant result of the study was the larger pressure drop in the computational models. In a system such as a space vehicle, the constraints on area use, weight, etc. are vital. The pressure and flow rates provided by pumps are dependent on the requirements of the system. An increase in expected pressure drop as found in this study, reveals the need for a more powerful pumping system or an increased load on the present system if possible. If the system cannot meet the required parameters, either the system must be improved or the design must be changed. However, the computational results (referring to the eleven cell 2D model) did not agree with the one dimensional
flow calculations with respect to pressure drop. In fact, the results of the calculations performed in the previous section closely corresponded to the design estimates in Zweig (1993), perhaps because those estimates may have been derived from similar calculations.

Also of some concern is the appearance of a somewhat laminar velocity profile near the end of the channel in the three dimensional computational models. The Reynolds number did decrease along the length of the channel. However, the profile should have remained relatively flat (turbulent) along the length of the channel. The cause of this somewhat laminar looking profile may have been the relatively low number of mesh cells across the channel in the three dimensional cases. Though not severe, the appearance of such a trend must be noted. The eleven cell two dimensional model experienced no such problem and the flow exhibited a definite flat velocity profile.

It is considered acceptable to model compressible flows through short ducts as incompressible as long as the Mach number is less than \( M = 0.25 \) (Mark's 1987). The coolant channel problem does fall within that Mach number range. However, because of the significant heat addition and long length of the channel, it should be modeled as a compressible flow in computational schemes. The use of the compressible model of FLOW-3D was the correct choice for this study. It should be noted that the problem was simplified in FLOW-3D in that only a power was transferred from the object (the core) to the fluid (hydrogen). Values for heat transfer coefficient, coefficient of friction, and wall temperature were not prescribed. The power was transferred directly to the
fluid with accurate results with respect to temperature. The values of coolant
temperature at the outlet were very near to those expected from a 1.3 m fuel element
(within 5%).

The pressure drop variation between the computational model (0.9 MPa) and the
one dimensional analytical method (0.576 MPa) is a cause for concern. The use of a
computational model for compressible turbulent flow in this type of problem has not
been benchmarked and analytical solutions are limited to calorically perfect gas models in
one dimension. Because of this fact, it is difficult to determine the accuracy of this type
of computational model without empirical data. The comparison of such empirical data
with the computational model may be one of the few methods available to determine the
accuracy and usefulness of the computational results.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS
FOR FUTURE WORK

Significant Contributions

The purpose of this study was to analyze the coolant channel of a 50 klbf NERVA-Derived Reactor (NDR) using computational techniques.

Two-Dimensional Sufficiency

The two-dimensional models represented the best use of computational time and yielded accurate results much like the three-dimensional models. Because of the close correlation between the 2D and 3D results, there is no need to model coolant channel flow in three dimensions. A 2D model using cylindrical coordinates in FLOW-3D provides an adequate model. The 2D computational model allowed for the use of more cells across the channel, resulting in a better defined flow.

Use of FLOW-3D

The use of FLOW-3D to solve such a flow problem had not been previously accomplished. The code adapted well to the compressible environment, was extremely flexible, and very robust. By specifying the power, the problem was simplified. The
ability of FLOW-3D to model solid geometries easily was very beneficial. The pressure drop variation between the computational model and the one dimensional analytical solution may indicate a potential problem with the methods employed by the code. However, that problem may also have been the result of not defining the problem to a great enough extent. Additionally, the code may be circumventing some necessary steps in solving the complex compressible turbulent problem, either due to the setup or to the extreme difficulty of the problem.

The use of FLOW-3D involved more sophisticated methods than had been previously used to design the NDR system. This study should provide important data to those who will perform the iterative process of system design.

Pressure Drops

The increase in expected pressure drop across the channel is the most significant finding of the study. The pressure drop was anticipated in previous design studies to be \(-0.57\) MPa, but this study predicted a pressure drop of \(-0.9\) MPa- a 60\% increase. The strict requirements of the pump that provides the pressure in such a space system may need to be reviewed. The pump is powered by the reactors itself and acts to provide pressure and mass flow to the entire hydrogen flow system. An increase in the pump discharge pressure or a design change may be required. It may also be possible to facilitate less pressure drop before the hydrogen reaches the plenum by changing the nozzle cooling requirements of the hydrogen.
However, it should be noted that the computational results of this study did not agree with the one dimensional compressible flow analytical results which closely corresponded to the previous design estimates (~0.576 MPa pressure drop). The fact that a computational problem of this nature has not been previously benchmarked, perhaps because of the inherent difficulty with compressible turbulent flow, require that the results of this computational analysis be verified by another method, perhaps empirical data since no true analytical solution exists.

**Improvements/Possible Adjustments to this Model**

The values of specific heat and thermal conductivity were held constant in this study. If it were possible to create a table for variable values, the results would improve. The amount of improvement must be weighed against the necessary time spent creating the table and altering the code as required.

The choice of boundary conditions could be adjusted to determine what is best. In this study, a combination a velocity and pressure boundary conditions were used with specified inlet and outlet temperatures (the inlet and outlet temperatures setting the densities at each end as well). Only a pressure or velocity boundary condition could be set in FLOW-3D on each end. It was determined that the inlet should have a velocity condition and the outlet a pressure boundary condition. Adjustment of these could result in an improvement. The outlet boundary condition could be set as a continuative boundary- indicating that the flow would go on for a great distance. The compressible
flow model should be tested with a continuative boundary at the outlet, with all inlet conditions specified.

Starting Point

The essential effort to begin work on modeling nuclear core flow at the NSCEE has been enhanced by this study. Future work on the NDR concept can branch out from this study. That future work could include, but is certainly not limited to the following items:

- **Modeling of the entire fuel element** - The 19-hole fuel element presents a difficult problem as far as computational time is concerned. If the entire fuel element was modeled with an extensive mesh (> 5 cells across), the computational time could be unreasonable considering the exhaustive computational time spent in this study to model one channel. For a culminating, one-time, analysis, that option could be valuable. However, other options should and must be used to model the fuel element that are more efficient and applicable to class-room studies.

- **Fuel Element Bundle** - The fuel element bundle, the fuel elements, and their support element could be modeled to determined the heat loss to the support element structure. In both of the first two cases, it may be necessary to model heat transfer due to temperature difference rather than simply thermal power transfer to gain the most benefit.
• Utilization of the Two-Dimensional Case - The 2D model should be expanded to include more cells to examine its effects. The effects should not be great, but it would be of value to determine at what point an increased number of cells does not improve the model. That limit may have been reached in this study.

• Corner-to-Corner 2D model of the fuel element - A 2D model should be constructed in some way so that five channels could be studied at one time. A 2D corner-to-corner cut of the model would provide benefits in analyzing the radial heat distribution in the fuel element.

• Cosine Axial Power Density - As previously noted, a uniform axial power density was used with this study. In the future, consideration should be given to using the more accurate cosine axial power density model. Such a model would have required an alteration of the FLOW-3D code to accomplish, but may be possible in the future without a great deal of complications. Perhaps the use of another code should be explored for such an option.

• Extension to the Convergent/Divergent Nozzle Region - Calculations dealing with the nozzle flow could be accomplished as two-dimensional problems and could encompass the cooling of the nozzle by hydrogen as it passes through channels around the nozzle. FLOW-3D is fully capable of solving such nozzle problems.
• Extension to the Cryogenic Hydrogen Storage Tank - The requirements for maintaining cryogenic conditions for hydrogen in space are very rigid and provide an additional area of possible study.

• 15 klbf Rocket - This study concentrated on the attributes of the 50 klbf NDR rocket. It was pointed out in the introduction that the 15 klbf rocket is the most likely prospect on a manned Mars mission. The interpolation of this data to the 15 klbf rocket would be most valuable. The outlet conditions (pressure, temperature, etc.) are expected to be the same as for the larger versions. As previously mentioned, the 15 klbf rocket uses a shorter fuel element that provides less thermal power.

• Plume Study - The exhaust plume at the end of the nozzle could be studied to determine shielding requirements. Some reactivity will be passed on to the hydrogen and proper shielding must ensure that cargo and personnel aboard are exposed to no more than permissible amounts of radiation. The plume region would require a code capable of coping with a rarefied gas region.

Questions

Questions about this study should be directed to Edward W. Porta or Dr. Bahram Nassersharif, at the University of Nevada, Las Vegas.
REFERENCES


APPENDIX A

THREE CELL 3D MATERIAL

1.0 MWT FUEL ELEMENT
One-hole 3D Compressible Channel Flow w/ Heat

This problem represents flow through a coolant channel in a NDR reactor. Units are in MKS. This is a rough test case to approximate a final answer.

\[
\begin{align*}
\text{$xput$} \\
trest &= 2.50012e-02, \quad \text{remark=' restart '}, \\
twfin &= 0.05, \quad \text{remark=' 0.02 second finish time '}, \\
dtmax &= 0.01, \quad \text{remark=' maximum step time '}, \\
delt &= 0.000001, \quad \text{remark=' initial time step '}, \\
prtdt &= 0.025, \quad \text{remark=' print at interval '}, \\
plttdt &= 0.025, \quad \text{remark=' plot at interval '}, \\
iconprs &= 1, \quad \text{remark=' compressible flow '}, \\
ifenrg &= 2, \quad \text{remark=' solve transport equation '}, \\
\text{for internal energy '}, \\
nmat &= 2, \quad \text{remark=' 2 materials for compressible '}, \\
ifrho &= 2, \quad \text{remark=' solve transport eq. for density '}, \\
ivhtc &= 1, \quad \text{remark=' heat transfer option on '}, \\
ivish &= 1, \quad \text{remark=' include viscous heating effects '}, \\
ivvis &= 4, \quad \text{remark=' Renormalized Group Theory model (RNG) '}, \\
iwsh &= 1, \quad \text{remark=' include wall shear stress '}, \\
icolor &= 1, \quad \text{remark=' color on spatial plots '}, \\
idadix &= 1, \\
idadiy &= 1, \\
epsi &= 1000, \quad \text{remark=' course press conv criterion '}, \\
\end{align*}
\]

Send

$limits

Send

$props

\[
\begin{align*}
cv2 &= 1.517786e+4, \quad \text{remark=' specific heat of H2 '}, \\
r£2 &= 4.124257e+3, \quad \text{remark=' gas constant of H2 '}, \\
mu2 &= 1.7361e-5, \quad \text{remark=' dynamic viscosity of H2 '}, \\
\text{thc2} &= 3.876e-1, \quad \text{remark=' thermal conductivity of H2 '}, \\
\end{align*}
\]

Send

$bcdata

\[
\begin{align*}
pbctyp &= 1.0, \quad \text{remark=' stagnation pressure boundaries '}, \\
\text{REMARK=' INLET CONDITIONS '}, \\
w&b &= 5, \quad \text{remark=' THIS IS NOT READ AS BOUNDARY'}, \\
pbct(1,5) &= 5.97772e+6, \quad \text{remark=' specified pressure boundary '}, \\
\end{align*}
\]
remark=' (Pa) 

wb=6, 
wbct(1,5)=27.435, remark=' specified velocity boundary ' ,
remark=' on the minimum z side (m/s) ',
tbct(1,5)=136.289, remark=' specified temp boundary (K) ',

REMARK=' OUTLET CONDITIONS ',
wt=5, remark=' specified press. boundary ',
pbct(1,6)=5.40546e+6,
tbct(1,6)=2450.196, remark=' temperature of chamber region ',

wf=1, wbk=1, remark=' front and back - symmetry ',
wl=1, wr=1, remark=' left and right - symmetry ',

Send
$mesh
pz(1)=0.0, pz(2)=1.3208,
nzcelt=30,

py(1)=-0.002, py(2)=-0.00125,
py(3)=0.00125, py(4)=0.002,
nycelt=5,
nyceil(2)=3,

px(1)=-0.002, px(2)=-0.00125,
px(3)=0.00125, px(4)=0.002,
 nxcelt=5,
 nxcell(2)=3,

Send
$obs
nobs=1,
iofo(1,1)=1,
ral(1)=0.00125,
pobs(1,1)=0.05263e+6, remark=' obs 1 provides 0.05263 MWt ',
twobs(1,1)=0.0, remark=' no contribution to the heat ',
remark=' comes from hA(Tw - Tf) ',

Send
$fl
REMARK=' Set initial velocity, pressure, and density ',
REMARK= 'distributions as linear functions of known ',
REMARK= 'inlet and outlet conditions.

nfls=3, remark= 'Three(3) fluid functions ',

ifdis(1)=6, remark= 'Set W equal to function ',
fcc(1)=27.435,
fcz(1)=391.86,

ifdis(2)=2, remark= 'Set P equal to function ',
fcc(2)=5.97772e+6,
fcz(2)=-4.3327e+5,

ifdis(3)=7, remark= 'Set RHO equal to function ',
fcc(3)=10.635,
fcz(3)=-7.647,

Send $b f $Send

REMARK= 'Set initial temp distribution close to ',
REMARK= 'solution (inlet - 136K, outlet - 2450K) ',

ntmp=1, remark= 'One(1) temp function ',
itdis(1)=1, remark= 'Set T = function ',
tcc(1)=136, remark= 'Inlet temp ',
tcz(1)=1751.97, remark= 'coeff. of z ',

Send $grafic

REMARK= 'contour plots ',
ncplts=4,
contyp(1)='p', remark= 'pressure contour ',
inperc(1)=3,
contyp(2)='rho', remark= '2D x-z slice ',
inperc(2)=3,
contyp(3)='tn', remark= 'fluid temp contour ',
inperc(3)=3,
contyp(4)='tw', remark= 'wall temp ',
inperc(4)=3,

REMARK= 'velocity plots ',
vplts=1,
iperv(1)=3, remark= '2D x-z slice ',
contpv(1)='tn',

REMARK='history plots',
  zloc(1)=0.00, xloc(1)=0.0, yloc(1)=0.0,
  zloc(2)=0.05, xloc(2)=0.0, yloc(2)=0.0,
  zloc(3)=1.3, xloc(3)=0.0, yloc(3)=0.0,
  zloc(4)=1.3, xloc(4)=0.00124, yloc(4)=0.0,
  zloc(5)=1.3208, xloc(5)=0.0, yloc(5)=0.0,
$end
$parts
$end
y-z grid plot

FLOW-3D®  t=0.0  x=6  y=2 to 6  z=2 to 31
02:48:28  12/08/94  lnac   hydr3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
pressure contours

FLOW-3D®  t=.0500  x=2 to 6  y=4  z=2 to 31
02:48:28  12/08/94  lnacl  hyd3d:  version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
density contours

FLOW-3D®  t=0.0500  x=2 to 6  y=4  z=2 to 31
02:48:28  12/08/94  lnac  hyd3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature contours

FLOW-3D® t=.0500 x=2 to 6 y=4 z=2 to 31
02:48:28 12/08/94 lnac hydr3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature and vectors

FLOW-3D®

The model uses the FLOW-3D® software for the simulation of fluid flow and heat transfer in complex geometries. The model represents a three-dimensional fluid flow problem involving heat transfer.

The vectors indicate the direction and magnitude of the fluid flow and temperature vectors. The color gradient represents the temperature distribution across the model.

The model is designed to analyze the interaction between fluid flow and heat transfer in a specified domain.
APPENDIX B

THREE CELL 3D MATERIAL

1.1 MWT FUEL ELEMENT
One-hole 3D Compressible Channel Flow w/ Heat

This problem represents flow through a coolant channel in a NDR reactor. Units are in MKS. This is a rough test case to approximate a final answer.

$\texttt{Xput}$

\begin{verbatim}
twfin=0.05, remark=' 0.02 second finish time',
dtmax=0.01, remark=' maximum step time',
delt=0.000001, remark=' initial time step',
prtmax=0.025, remark=' print at interval ',
pltdt=0.025, remark=' plot at interval ',
icmprs=1, remark=' compressible flow ',
ifenrg=2, remark=' solve transport equation ',
                remark=' for internal energy ',
nmat=2, remark=' 2 materials for compressible ',
ifrhom=2, remark=' solve transport eq. for density ',
htc=1, remark=' heat transfer option on ',
ivish=1, remark=' include viscous heating effects ',
ifvis=4,remark=' Renormalized Group Theory model (RNG) ',
                remark=' for viscosity evaluation ',
            iwsh=1, remark=' include wall shear stress ',
icolor=1, remark=' color on spatial plots ',
idadix=1,
idadiy=1,
epsi=1000, remark=' course press conv criterion ',
\end{verbatim}

$\texttt{End}$

$\texttt{Limits}$

$\texttt{End}$

$\texttt{Props}$

\begin{verbatim}
cv2=1.517786e+4, remark=' specific heat of H2 ',
rf2=4.124257e+3, remark=' gas constant of H2 ',
mu2=1.7361e-5, remark=' dynamic viscosity of H2 ',
thc2=3.876e-1, remark=' thermal conductivity of H2 ',
\end{verbatim}

$\texttt{End}$

$\texttt{Bcdata}$

\begin{verbatim}
pbctyp=1.0, remark=' stagnation pressure boundaries ',
REMARK= ' INLET CONDITIONS ',
wb=5, remark=' THIS IS NOT READ AS A BOUNDARY ',
pbct(1,5)=5.97772e+6, remark=' specified pressure boundary ',
\end{verbatim}
wb=6, remark=' (Pa) ',
wbct(1,5)=27.435, remark=' specified velocity boundary ',
remark=' on the minimum z side (m/s) ',
tbct(1,5)=136.289, remark=' specified temp boundary (K) ',

REMARK=' OUTLET CONDITIONS ',
wt=5, remark=' specified press. boundary ',
pbct(1,6)=5.40546e+6,
tbct(1,6)=2450.196, remark=' temperature of chamber region ',

wf=1, wbk=1, remark=' front and back - symmetry ',
wl=1, wr=1, remark=' left and right - symmetry ',

$end
$mesh
pz(1)=0.0, pz(2)=1.3208,
nzcelt=30,

py(1)=-0.002, py(2)=-0.00125,
py(3)=0.00125, py(4)=0.002,
nycelt=5,
nycell(2)=3,

px(1)=-0.002, px(2)=-0.00125,
px(3)=0.00125, px(4)=0.002,
nxcelt=5,
nxcell(2)=3,

$end
$sobs
nobs=1,
iofo(1,1)=1,
ral(1)=0.00125,
pobs(1,1)=0.057895e+6, remark=' 1.1 MWt fuel element ',
twobs(1,1)=0.0, remark=' no contribution to the heat ',
remark=' comes from hA(Tw - Tf) ',

Send
$sfl
REMARK=' Set initial velocity, pressure, and density',
REMARK=' distributions as linear functions of known',
REMARK=' inlet and outlet conditions.',

nfls=3,      remark=' Three(3) fluid functions',

ifdis(1)=6,   remark=' Set W equal to function',
fcc(1)=27.435,
ficz(1)=391.86,

ifdis(2)=2,   remark=' Set P equal to function',
fcc(2)=5.97772e+6,
ficz(2)=-4.3327e+5,

ifdis(3)=7,   remark=' Set RHO equal to function',
fcc(3)=10.635,
ficz(3)=-7.647,

REMARK=' Set initial temp distribution close to',
REMARK=' solution (inlet - 136K, outlet - 2450K)',

ntmp=1,       remark=' One(1) temp function',
itdis(1)=1,    remark=' Set T = function',
tcc(1)=136,    remark=' Inlet temp',
tcz(1)=1751.97,remark=' coeff. of z',

REMARK=' contour plots',
ncplts=4,
contyp(1)='p', remark=' pressure contour',
iper(1)=3,     remark=' 2D x-z slice',
contyp(2)='rho',remark=' density contour',
iper(2)=3,
contyp(3)='tn',remark=' fluid temp contour',
iper(3)=3,
contyp(4)='tw',remark=' wall temp',
iper(4)=3,

REMARK=' velocity plots',
nvplts=1,
iperv(1)=3, remark=' 2D x-z slice ',
contpv(1)=''tn'',

REMARK=' history plots ',
zloc(1)=0.00, xloc(1)=0.0, yloc(1)=0.0,
zloc(2)=0.05, xloc(2)=0.0, yloc(2)=0.0,
zloc(3)=1.3, xloc(3)=0.0, yloc(3)=0.0,
zloc(4)=1.3, xloc(4)=0.00124,yloc(4)=0.0,
zloc(5)=1.3208, xloc(5)=0.0, yloc(5)=0.0,
y-z grid plot

FLOW-3D®  t=0.0  x=6  y=2 to 6  z=2 to 31
09:47:24  12/07/94  cjno  hydr3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
x-y grid plot

FLOW 3D® t=0.0  x=2 to 6  y=2 to 6  z=2
09:47:24 12/07/94 cjnc  hyd3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
One-hole 3D Compressible Channel Flow w/ Heat
density contours

FLOW-3D®

t = 0.0500 x = 2 to 6 y = 4 z = 2 to 31
09:47:24 12/07/94 cjno hydr3d: version 6, mod 0, cray 195
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature contours

FLOW-3D®  t = 0.0500  x=2 to 6  y=4  z=2 to 31
03:47:24  12/07/94  cjno hydr3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature and vectors

FLOW-3D®  12/11/94  12.37 1994  Compresible Channel Flow w/Heat
APPENDIX C

SEVEN CELL 3D MATERIAL
One-hole 3D Compressible Channel Flow w/ Heat

This problem represents flow through a coolant channel in a NDR reactor. Units are in MKS. This run contains a more definitive mesh, with seven cells across the channel in the x and y directions and 30 cells in the axial z direction.

$xput$

twfin=0.03, remark=' 0.03 second finish time',
dtmax=0.01, remark=' maximum step time',
delt=0.000001, remark=' initial time step',
prtdt=0.01, remark=' print at interval',
pltdt=0.01, remark=' plot at interval',
imeprs=1, remark=' compressible flow',
ifenerg=2, remark=' solve transport equation',
               remark=' for internal energy',
nmat=2, remark=' 2 materials for compressible',
ifrho=2, remark=' solve transport eq. for density',
ihct=1, remark=' heat transfer option on',
ivish=1, remark=' include viscous heating effects',
ifvis=4, remark=' Renormalized Group Theory model (RNG)',
               remark=' for viscosity evaluation',
iwsh=1, remark=' include wall shear stress',
icolor=1, remark=' color on spatial plots',
iadix=1,
iadiy=1,
epsi=1000, remark=' course press conv criterion',

$end$

$limits$

Send

$props$

cv2=1.517786e+4, remark=' approx. specific heat of H2',
rf2=4.124257e+3, remark=' gas constant of H2',
mu2=1.7361e-5, remark=' dynamic viscosity of H2',
thc2=3.876e-1, remark=' thermal conductivity of H2',

$end$

$bcdata$

pbctyp=1.0, remark=' stagnation pressure boundaries',
REMARK=' INLET CONDITIONS',

wb=5, remark=' THIS IS NOT READ AS A BOUNDARY',
pbct(1,5)\textasciitilde{}5.97772\times10^6, \text{remark='specified pressure boundary', remark='(Pa)'},
\text{wb}=6,
wbct(1,5)=27.435, \text{remark='specified velocity boundary', remark='on the minimum z side (m/s)'},
tbtc(1,5)=136.289, \text{remark='specified temp boundary (K)'},

\textbf{REMARK='OUTLET CONDITIONS'},
wt=5, \text{remark='specified press. boundary'},
\text{pbct(1,6)=5.40546\times10^6},
tbtc(1,6)=2450.196, \text{remark='temperature of chamber region'},
\text{wf}=1, \text{wbk}=1, \text{remark='front and back - symmetry'},
wl=1, \text{wr}=1, \text{remark='left and right - symmetry'},

\$\text{Send}\$
\$\text{Smesh}\$
pz(1)=0.0, \text{pz(2)=1.3208},
\text{nzcelt}=30,
py(1)=-0.002, \text{py(2)=0.00125},
py(3)=0.00125, \text{py(4)=0.002},
nycelt=9,
nycell(2)=7,
px(1)=-0.002, \text{px(2)=0.00125},
px(3)=0.00125, \text{px(4)=0.002},
nxcelt=9,
nxcell(2)=7,

\$\text{Send}\$
\$\text{Sobs}\$
nobs=1,
iofo(1,1)=1,
ral(1)=0.00125,
pobs(1,1)=0.057895\times10^6, \text{remark='1.1 MWt fuel element'},
twobs(1,1)=0.0, \text{remark='no contribution to the heat'},
\text{remark='comes from hA(Tw - Tf)'},

\$\text{Send}\$
\$\text{Sfl}\$
REMARK=' Set initial velocity, pressure, and density ',
REMARK=' distributions as linear functions of known ',
REMARK=' inlet and outlet conditions. ',

nfls=3,  remark=' Three(3) fluid functions ',
ifdis(1)=6,  remark=' Set W equal to function ',
fcc(1)=27.435,
fcz(1)=391.86,

ifdis(2)=2,  remark=' Set P equal to function ',
fcc(2)=5.97772e+6,
fcz(2)=-4.3327e+5,

ifdis(3)=7,  remark=' Set RHO equal to function ',
fcc(3)=10.635,
fcz(3)=-7.647,

Send
$bf
Send
$end
$temp

REMARK=' Set initial temp distribution close to ',
REMARK=' solution (inlet - 136K, outlet - 2450K) ',

ntmp=1,  remark=' One(1) temp function ',
itdis(1)=1,  remark=' Set T = function ',
tcc(1)=136,  remark=' Inlet temp ',
tcz(1)=1751.97,  remark=' coeff. of z ',

Send
$graphic

REMARK=' contour plots ',
ncplts=4,
contyp(1)='p',  remark=' pressure contour ',
iper(1)=3,  remark=' 2D x-z slice ',
contyp(2)='rho',  remark=' density contour ',
iper(2)=3,
contyp(3)='tn',  remark=' fluid temp contour ',
iper(3)=3,
contyp(4)='tw',  remark=' wall temp ',
iper(4)=3,

REMARK=' velocity plots ',
nvplts=1,
iperv(1)=3,  remark=' 2D x-z slice ',

$
contpv(1)= 'tn',

REMARK=' history plots',
zloc(1)=0.00, xloc(1)=0.0, yloc(1)=0.0,
zloc(2)=0.05, xloc(2)=0.0, yloc(2)=0.0,
zloc(3)=1.3, xloc(3)=0.0, yloc(3)=0.0,
zloc(4)=1.3, xloc(4)=0.00124, yloc(4)=0.0,
zloc(5)=1.3208, xloc(5)=0.0, yloc(5)=0.0,
y-z grid plot

FLOW-3D®  t=0.0  x=10  y=2 to 10  z=2 to 31
09:34:25  12/08/94  kkql  hydr3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
x-y grid plot

Flow-3D® t=0.0  x=2 to 10  y=2 to 10  z=2
09:34:25 12/08/94 kkql  hydr3d: version 6, mod 0, cray 1994
One-Hole 3D Compressible Channel Flow w/ Heat
pressure contours

FLOW-3D®  t=.0200  x=2 to 10  y=6  z=2 to 31
09:34:25  12/08/94  kkql  hydr3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
density contours

FLOW3D®  t=0.0200  x=2 to 10  y=6  z=2 to 31
09:34:25  12/08/94  kkql  hydr3d: version 6, mod 0,  cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature contours

FLOW-3D®  t=.0200  x=2 to 10  y=6  z=2 to 31
09:34:25  12/08/94  kkql  hydr3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature and vectors

FLOW-3D® t=0.200 x=2 to 10 y=6 z=2 to 31
09:34:25 12/08/94 kbql hyd3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
fluid temperature and vectors

FLOW3D®
09:34:25 12/08/94 kkgl
hyd3d: version 6, mod 0, cray 1994
One-hole 3D Compressible Channel Flow w/ Heat
APPENDIX D

FOUR CELL 2D MATERIAL
One-Channel 2D Compressible Flow w/ Heat Mod 11

This problem represents flow through a coolant channel in a NDR reactor. Units are in MKS. This run is a 2D type problem. It is done in cylindrical coordinates to examine the radial distribution of heat. It will have 4 radial cells, one theta cell, and 30 axial cells.

```
Sxput
  twfin=0.025, remark=' 0.025 second finish time',
  dtmax=0.01, remark=' maximum step time',
  delt=0.000001, remark=' initial time step',
  prtdt=0.025, remark=' print at interval',
  pltstd=0.025, remark=' plot at interval',
  icmprs=1, remark=' compressible flow',
  ifemrg=2, remark=' solve transport equation',
          remark=' for internal energy',
  nmat=2, remark=' 2 materials for compressible',
  ifrho=2, remark=' solve transport eq. for density',
  ihtc=1, remark=' heat transfer option on',
  ivish=1, remark=' include viscous heating effects',
  ifvis=4, remark=' Renormalized Group Theory model (RNG)',
          remark=' for viscosity evaluation',
  iwsh=1, remark=' include wall shear stress',
  icolor=1, remark=' color on spatial plots',
  iadix=1,
  iadiy=1,
  cyl=1.0, remark=' cylindrical coordinate flag',
  epsi=1000, remark=' course press conv criterion',
Send
Slimits
Send
Sprops
  cv2=1.517786e+4, remark=' approx. specific heat of H2',
  rf2=4.124257e+3, remark=' gas constant of H2',
  mu2=1.7361e-5,     remark=' dynamic viscosity of H2',
  thc2=3.876e-1,     remark=' thermal conductivity of H2',
Send
Sbcdata
  pbctyp=1.0, remark=' stagnation pressure boundaries',
  REMARK=' INLET CONDITIONS',
```
wb=5, remark=' THIS IS NOT READ AS BOUNDARY',
pbct(1,5)=5.97772e+6, remark=' specified pressure boundary ',
                    remark=' (Pa) ',
wb=6,
wbct(1,5)=27.435, remark=' specified velocity boundary ',
                    remark=' on the minimum z side (m/s) ',
tbct(1,5)=136.289, remark=' specified temp boundary (K) ',

REMARK=' OUTLET CONDITIONS ',
wt=5, remark=' specified press. boundary ',
pbct(1,6)=5.40546e+6,
tbct(1,6)=2450.196, remark=' temperature of chamber region ',

wf=1, wbk=1, remark=' front and back - symmetry ',
                    remark=' min and max y ',
wl=1, wr=1, remark=' center - symmetry ',

Send
$mesh
pz(1)=0.0, pz(2)=1.3208,
nzcelt=30,

py(2)=7.85398e-4,
nycelt=1,

px(2)=0.0001786, px(3)=0.00125, px(4)=0.0015,
nxcelt=5,
xnecell(2)=3, nxcell(3)=1,

Send
$obs
nobs=1,
iofo(1,1)=1,
ral(1)=0.00125,
pobs(1,1)=4.82458e+3, remark=' 1.1 MWt fuel element ',
twobs(1,1)=0.0, remark=' no contribution to the heat ',
                    remark=' comes from hA(Tw - Tf) ',

Send
$fl
REMARK= Set initial velocity, pressure, and density ,
REMARK= distributions as linear functions of known ,
REMARK= inlet and outlet conditions,  

nfls=3 ,remark= Three(3) fluid functions ,

ifdis(1)=6 ,remark= Set W equal to function ,
fcc(1)=27.435 ,
fcz(1)=391.86 ,

ifdis(2)=2 ,remark= Set P equal to function ,
fcc(2)=5.97772E+6 ,
fcz(2)=-4.3327E+5 ,

ifdis(3)=7 ,remark= Set RHO equal to function ,
fcc(3)=10.635 ,
fcz(3)=-7.647 ,

$end
$bf
$end
$temp
REMARK= Set initial temp distribution close to ,
REMARK= solution (inlet - 136K, outlet - 2450K) ,

ntmp=1 ,remark= One(1) temp function ,
itdis(1)=1 ,remark= Set T = function ,
tcc(1)=136 ,remark= Inlet temp ,
tcz(1)=1751.97 ,remark= coeff of z ,

$end
$grafic
REMARK= contour plots ,
ncplts=4 ,
contyp(1)="p" ,remark= pressure contour ,
iper(1)=3 ,remark= 2D x-z slice ,
contyp(2)="rho" ,remark= density contour ,
iper(2)=3 ,remark= 2D x-z slice ,
contyp(3)="tn" ,remark= fluid temp contour ,
iper(3)=3 ,
contyp(4)="tw" ,remark= wall temp ,
iper(4)=3 ,

REMARK= velocity plots ,
nvplts=1 ,
iperv(1)=3, remark=' 2D x-z slice',
contpv(1)='tn',

REMARK=' history plots ',
zloc(1)=0.05, xloc(1)=0.0,
zloc(2)=0.05, xloc(2)=3.125e-4,
zloc(3)=0.05, xloc(3)=6.25e-4,
zloc(4)=0.05, xloc(4)=9.375e-4,
zloc(5)=0.05, xloc(5)=1.2e-3,
zloc(6)=1.3, xloc(6)=0.0,
zloc(7)=1.3, xloc(7)=3.125e-4,
zloc(8)=1.3, xloc(8)=6.25e-4,
zloc(9)=1.3, xloc(9)=9.375e-4,
zloc(10)=1.3, xloc(10)=1.2e-3,

$end
$parts
$end
pressure contours

FLOW-3D®  t=.0250  x=2 to 6  y=2  z=2 to 31
15:40:03 12/10/94 hval  hydr3d: version 6, mod 0, cray 1994
One-Channel 2D Compressible Flow w/ Heat Modell
density contours

FLOW-3D®  t=0.0250  x=2 to 6  y=2  z=2 to 31
15:40:03  12/10/94  hval  hydr3d: version 6, mod 0, cray 1994
One-Channel 2D Compressible Flow w/ Heat ModII
fluid temperature contours

FLOW-3D®

$t = 0250 \ x = 2 \ to \ 6 \ y = 2 \ z = 2 \ to \ 31$

15:40:03 12/10/94 hval hydr3d: version 6, mod 0, cray 1994
One-Channel 2D Compressible Flow w/ Heat Modll
fluid temperature and vectors
APPENDIX E

ELEVEN CELL 2D MATERIAL
One-hole 2D Compressible Channel Flow w/ Heat

This problem represents flow through a coolant channel in a NDR reactor. Units are in MKS. This run is a 2D type problem. It is done in cylindrical coordinates to examine the radial distribution of heat. It will have 11 radial cells, one theta cell, and 30 axial cells.

Sxput
twfin=0.05, remark=' 0.05 second finish time ',
dtmax=0.01, remark=' maximum step time ',
dt=0.000001, remark=' initial time step ',
prtfdt=0.025, remark=' print at interval ',
pltdt=0.025, remark=' plot at interval ',
icmprs=1, remark=' compressible flow ',
ifens=2, remark=' solve transport equation ',

nmat=2, remark=' 2 materials for compressible ',
ifrho=2, remark=' solve transport eq. for density ',
ihtc=1, remark=' heat transfer option on ',
ivish=1, remark=' include viscous heating effects ',
ifvis=4, remark=' Renormalized Group Theory model (RNG) ',
iwsd=1, remark=' for viscosity evaluation ',
icolor=1, remark=' color on spatial plots ',
iadix=1, iadix=1, cyl=1.0, remark=' cylindrical coordinate flag ',
epsi=1000, remark=' course press conv criterion ',

Send $limits
Send $props
$props
cv2=1.517786e+4, remark=’ approx. specific heat of H2 ‘,
rf2=4.124257e+3, remark=’ gas constant of H2 ‘,
mu2=1.7361e-5, remark=’ dynamic viscosity of H2 ‘,
thc2=3.876e-1, remark=’ thermal conductivity of H2 ‘,

Send $bcdata
pbctyp=1.0, remark=’ stagnation pressure boundaries ‘,
REMARK=’ INLET CONDITIONS ‘,
wb=5,  remark=' THIS IS NOT READAS A BOUNDARY',
pbct(1,5)=5.97772e+6,  remark=' specified pressure boundary ',
                    remark=' (Pa) ',
wb=6,  wbct(1,5)=27.435,  remark=' specified velocity boundary ',
                    remark=' on the minimum z side (m/s) ',
tbct(1,5)=136.289,  remark=' specified temp boundary (K) ',
REMARK=' OUTLET CONDITIONS ',
wt=5,  remark=' specified press. boundary ',
pbct(1,6)=5.40546e+6,
tbct(1,6)=2450.196,  remark=' temperature of chamber region ',
wf=1, wbk=1, remark=' front and back - symmetry ',
                    remark=' min and max y ',
w1=1, wr=1,  remark=' center - symmetry ',

$end
$mesh
pz(1)=0.0,  pz(2)=1.3208,
nzcelt=30,
py(2)=7.85398e-4,
nycelt=1,
px(2)=0.00045,  px(3)=0.00125,  px(4)=0.0015,
nxcelt=12,
nxcell(2)=8,  nxcell(3)=1,

$end
$sobs
nobs=1,
iofo(1,1)=1,
ral(1)=0.00125,
pobs(1,1)=4.82458e+3,  remark=' 1.1 MWt fuel element ',
twobs(1,1)=0.0,  remark=' no contribution to the heat ',
                    remark=' comes from hA(Tw - Tf) ',

$end
$fl
REMARK=" Set initial velocity, pressure, and density ",
REMARK=" distributions as linear functions of known ",
REMARK=" inlet and outlet conditions. ",
nfls=3,       remark=" Three(3) fluid functions ",
ifdis(1)=6,  remark=" Set W equal to function ",
         fcc(1)=27.435,
         fcz(1)=391.86,
ifdis(2)=2,  remark=" Set P equal to function ",
         fcc(2)=5.97772e+6,
         fcz(2)=-4.3327e+5,
ifdis(3)=7,  remark=" Set RHO equal to function ",
         fcc(3)=10.635,
         fcz(3)=-7.647,
$end
$bf
$end
$temp
REMARK=" Set initial temp distribution close to ",
REMARK=" solution (inlet - 136K, outlet - 2450K) ",
ntmp=1,      remark=" One(1) temp function ",
itdis(1)=1,  remark=" Set T = function ",
tcc(1)=136,  remark=" Inlet temp ",
tcz(1)=1751.97, remark=" coeff. of z ",
$end
$grafic
REMARK=" contour plots ",
nclpts=4,
contyp(1)='p',   remark=" pressure contour ",
iperc(1)=3,   remark=" 2D x-z slice ",
contyp(2)='rho', remark=" density contour ",
iperc(2)=3,   remark=" 2D x-z slice ",
contyp(3)='tn', remark=" fluid temp contour ",
iperc(3)=3,   remark=" wall temp ",
contyp(4)='tw', remark=" wall temp ",
iperc(4)=3,
REMARK=" velocity plots ",
nvplts=1,
iperv(1)=3, remark=' 2D x-z slice ',
contpv(1)='tn',

REMARK=' history plots ',
zloc(1)=0.05, xloc(1)=0.0, yloc(1)=7.3e-4,
zloc(2)=0.05, xloc(2)=3.125e-4,
zloc(3)=0.05, xloc(3)=6.25e-4,
zloc(4)=0.05, xloc(4)=9.375e-4,
zloc(5)=0.05, xloc(5)=1.2e-3,
zloc(6)=1.3, xloc(6)=0.0,
zloc(7)=1.3, xloc(7)=3.125e-4,
zloc(8)=1.3, xloc(8)=6.25e-4,
zloc(9)=1.3, xloc(9)=9.375e-4,
zloc(10)=1.3, xloc(10)=1.2e-3,
x-z grid plot

FLOW-3D®  t=0.0  x=2 to 13  y=2  z=2 to 31
15:56:32  12/08/94  tfhb  hydr3d: version 6, mod 0,  cray 1994
One-hole 2D Compressible Channel Flow w/ Heat
pressure contours

FLOW-3D®

One-hole 2D Compressible Channel Flow w/ Heat
density contours
fluid temperature contours

FLOW-3D®  t=0.0250  x=2 to 13  y=2  z=2 to 31
15:56:32  12/08/94  tfhb  hyd3d: version 6, mod 0,  cray 1994
One-hole 2D Compressible Channel Flow w/ Heat
fluid temperature and vectors

FLOW-3D®
t=0.0250 x=2 to 13 y=2 to 31 z=2 to 31
15:56:32 12/08/94 tfhb hyd3d: version 6, mod 0, cray 174
One-hole 2D Compressible Channel Flow w/ Heat
APPENDIX F

15 KLBF ROCKET SCALING WORK
PROGRAM Fuel_Element

Overview: This program calculates the number of hexagonal fuel/support elements in a Nerva-Derivative-Reactor (NDR) or any reactor with hexagonal elements and an overall hexagonal configuration. The concept works in this fashion:

There is one (1) center hexagon. From each surface of the center hexagon, another hexagon attaches; thus if no other hexagons were filled in, there would be a center hexagon with six "spokes" coming out. Therefore, if the center hexagon is at the first level, at the very least six hexagons are added on at each level (the spokes). However, there are more hexagons. After the second layer of six hexagons, an additional six hexagons are added at each level. The formula works out to be:

\[ ELEM(N) = ELEM(N-1) + (6 \times (N-1)) \]

where \( ELEM(1) = 1 \).

If not for the center hexagon, the number of elements would always be a factor of three (3). The equation, \( FE = \frac{(ELEM-1)}{3} \times 2 + 1 \), creates a fuel to support element ratio of ~2 to 1 (i.e. two-thirds of the elements + 1 are fuel elements).

The remaining one-third are support elements. The 2 to 1 ratio is from AIAA-93-4170 (Borowski), and is the correct ratio for a 15 klbf NDR with 35" long fuel elements.

From the same paper, the fuel element is found to have a width (across the flats) of 0.75". Once the number of rings of hexagons is known, the overall diameter, across flats and corner-to-corner, can be determined. Overall power is calculated using the 0.6 to 0.8 MWt rating of the 35" fuel element in AIAA-93-4170.
Support Modules: NONE

Variable Definitions

Variable_Name   Type    Description
ELEM Intr*4    Number of fuel elements
I Intr*4       Counting variable
N Intr*4       Number of rings of hexagonal elements
FE Intr*4      Number of fuel elements
SE Intr*4      Number of support elements
DIA_CC Real*8  Diameter of core, corner-to-corner
W Real*8       Width across flats of a hexagon
A Real*8       Length of any hexagon side
H Real*8       Length of half the distance across the flat of a hexagon
DIA_FLATS Real*8 Diameter of core, across flats
LO_POWER Real*8 Power of reactor assuming low element
                  power production (0.6 MWt)
AVG_POWER Real*8 Power of reactor assuming average element
                  power production (0.7 MWt)
HI_POWER Real*8 Power of reactor assuming high element
                  power production (0.8 MWt)

IMPLICIT LOGICAL (A-Z)

INTEGER*4 ELEM(100), I, N, FE(100), SE(100)
REAL*8 DIA_CC(100), A, H, DIA_FLATS(100), LO_POWER(100)
REAL*8 AVG_POWER(100), HI_POWER(100), W
OPEN (UNIT=12,FILE=FUELELEM.DAT',STATUS='UNKNOWN')

W = 0.75
N = 20
ELEM(1) = 1
WRITE (12,*) " LEVEL #ELEM #FE #SE DIA_CC DIA_FLATS LOW &AVG HIGH"
WRITE (12,*) " (IN) (IN) (MWt) (MWt) (MWt)"
WRITE (12,80) 1, ELEM(1)
DO 10 I = 2,N
    ELEM(I) = ELEM(I-1) + (6 * (I-1))
    FE(I) = (((ELEM(I)-1) / 3) * 2) + 1
    SE(I) = ELEM(I) - FE(I)
    DIA_CC(I) = ((I * W) - (0.5 * W)) * 2.0
    A = 0.5 * DIA_CC(I)
    H = ((0.75 * (A**2.0))**0.5)
    DIA_FLATS(I) = 2.0 * H
    LO_POWER(I) = 0.6 * FE(I)
    AVG_POWER(I) = 0.7 * FE(I)
    HI_POWER(I) = 0.8 * FE(I)
    WRITE (12,81) I, ELEM(I), FE(I), SE(I), DIA_CC(I), DIA_FLATS(I),
    & LO_POWER(I), AVG_POWER(I), HI_POWER(I)
10 CONTINUE
CLOSE (UNIT=12)

*******************************************************************************
**
* Format Statements.
*
80 FORMAT (1X,I4,2X,I6)
81 FORMAT (1X,I4,2X,I6,2X,I5,2X,I5,2X,F6.2,2X,F6.2,2X,F5.1,2X,F5.1,2X,F5.1)

STOP 'Have a Nice Day'

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