CHAPTER 2: REVIEW ON NUCLEAR THERMAL ROCKETS

Man Kind’s destiny point is towards quest of the stars, which is very much difficult to achieve with the current space propulsion technology. The question of travel beyond the solar system will only become practice if we address the needs as time and energy through a powerful space travel mechanism. The prospects of space physics and nuclear propulsion are two coherent branches which have to go forward in this direction; the Use of nuclear energy for space propulsion was under study as early as 1946, when R.Serber from Douglas Aircraft Company published some fundamental considerations of the applications of fission energy for the rocket propulsion in a safest possible manner. The greatest reason to concentrate in this approach is because of the vast distances in the solar system which makes travelling is a very difficult prospect for the astronauts involved in such a mission (Dana, 2004). With today’s standards, even a simple mission to far planets such as Jupiter, Saturn or even a nearby planet like Mars would take a long time, from the NASA mission planers the travel time with chemical propulsion is around 436 days. Even in the case of Mars, you would need to commit more than one year for such a mission. In the case of Jupiter or other far away planets in our Solar System, the travelling times can be more than a decade. It is clear that space propulsion requirements for manned missions are more prominent, in the current scenario the probes that actually can attain a mean speed of 340.0000 and 115.000Km/h. At present no technology, but through a nuclear one can provide accelerations of the order of 0.5-0.3 g (Giovanni, 2003).

However, if you consider out of solar system destinations such as Proxima Centauri, you would need to travel for hundreds of years just to reach there. So, as a result, a more advanced means of travel is required for deep space missions.
Luckily, the option of nuclear energy provides a way to obtain such a mission since the specific impulse of a rocket can be raised by several magnitudes. Moreover, besides the space propulsion applications, it is also imperative to understand that continuous power will need to be provided to the astronauts involved in such a mission. For example, if you were to provide continuous power for three astronauts who are involved in a three year mission, you would have to consider their life support requirements, as well as the operational power for the onboard systems such as navigation, communications as well as various other systems which require electric power (Gunn, 2003). This would accumulate tremendously over time and it could not be met by conventional chemical batteries or even by Nuclear Isotopic Thermal Generators. You would need a full scale nuclear reactor in order to function. The effective specific impulse need to reach specific destinations tabulated in 2.1 and the maximum specific impulse is in the range of 1200 sec and which is quite manageable through gas core reactor systems.

Table 2.1: Possible In Situ NTP Propellant Source and their $I_{sp}$ Potential

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Destination</th>
<th>$I_{sp}$ Potential (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>Martain atmosphere, Martain frost, Earth</td>
<td>160-380</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>Asteroids, Phobus and Deimos, Earth, Outer Planets</td>
<td>460-670</td>
</tr>
<tr>
<td>H$_2$</td>
<td>Lunar polar Ice, Lunar Silane, NEO Asteroids, Earth, outer Planest</td>
<td>800-1200</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Earth, Outer planets</td>
<td>350-700</td>
</tr>
<tr>
<td>He</td>
<td>Lunar Ice, Martian Ice, Planetary Moons</td>
<td>160-240</td>
</tr>
</tbody>
</table>
The idea of using nuclear energy for the space applications goes back to R. Goddard at the time 1906-1907, he started using radium as energy source and realized it emits energy. But the level of energy produced from it will be insufficient for the propulsion applications. Esnault- Pelterie concluded that nuclear energy was indispensable for space travel in 1912. There is specific developments by ash in 1965, Bussard and DeLauer in 1958. The dynamic measurements are reported by Bodenschatz et al. 1966. The there is a two-path flow feedback model was used by smith and stenning in 1961, 1962, 1964, and by wiberg and Woyski in 1968. The reactor core is a homogenous mixture of U$^{235}$ and graphite penetrated by propellant passages.

2.1 THE KIWI and Troy Program

At the inception of the KIWI and Troy programmers, the choice of a working fluid was influenced by concerns over the potential for chemical interactions between the fuel elements and the working fluid. The first major program decision made by the SNPO was the creation of the Nuclear Engine for Rocket Vehicle Application (NERVA) program in 1961. NERVA focused on utilizing and integrating the KIWI B reactor designed into a flight-packaged nuclear rocket engine. Aerojet and Westinghouse were the selected engine system and reactor contractors. NERVA testing Facility In this arrangement the earlier MK 9 liquid hydrogen pumping systems were utilized to support the testing of the NRX A-2, A-3 and A-5 reactors between 24 September 1964 and 23 June 1966. The KIWI test program initially concentrated on relatively modest power-density reactors (KIWI A, A0 and A3), which were rated at 100MW. In 1965 Maxwell R. Morton addresses the problems related to the nuclear space propulsion in his paper named facility design problems associated with static firing of large nuclear rocket stages which is published in nuclear structural engineering. It address the use of nuclear reactors for the interplanetary travel, the capacity that this work suggest is
between 10,000 MW to 20,000 MW for different nuclear rocket stages. He also addressed radiation effects from the reactor core as well from the outer space. In 2001 A Nedaivod produced a work on the comparative analysis of the forecast of development of rocket propulsion facilities and he addressed the need for developing nuclear thermal propulsion systems and which is published in Acta Astronautica.

In 1972 J.W PYM conducted analysis on minimum time trust start-up of a nuclear rocket with Integro- Difference Constrain and he could not able to address the rocket startup problem under critical conditions due to time lag in the neutrons propagation. *Nuclear Rocket Propulsion*, edited by Clayton W. Watson, his description continues with reviews of heat transfer and fluid dynamics, reactor physics and kinetics, materials and radiation effects, and turbines, mid concludes by consideration of the methods and concepts used in rocket engine design. Oleksii. M.Krytonov in his work published in Acta Astronautica in 2011 he analyzed Finite-thrust optimization of interplanetary transfers of space vehicle with bimodal nuclear thermal propulsion and he concluded. The formulation of the problem of optimization of the interplanetary transfer with the combination of high- and low-thrust arcs was presented. The high-thrust burns were considered using finite-thrust approach instead of traditional impulsive approach that is especially important for NTR propulsion.

2.2 LITERATURE REVIEW ON NUCLEAR PROPULSION

In 1947, the Orion project proposed by Stanislaw Ulam suggested dropping little thermonuclear or fission explosive at a distance of 60 m rare of the vehicle shield and to use the mechanism of thick steel platter designed to catch the blast and to propel the vehicle forward by absorbing the impulse from the plasma wave using large multi-story high shock absorbers. This is the first step in testing physical
configuration beyond the theories on nuclear propulsion. In early stages USA and Russian space agencies started activates in addressing the problems of nuclear propulsion. The US nuclear rocket program was named as Rover program which is started on 2\textsuperscript{nd} November 1955 through which two national laboratories has been established to work on specific problems namely Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL). These laboratories build some 20 more reactors and successfully tested as a part of ROVER/NERVA (Nuclear Engine for Rocket Vehicle Applications) program showing the long duration operation during ground testing conditions. The overall performance of the solid graphite reactors was established and they demonstrated the possibilities and success of early nuclear rocket engine program.

2.3 THE NUCLEAR ROCKET

The basic nuclear rocket engine concept is very simple and is consists of nuclear reactor which is used to heat low molecular weight propellant like hydrogen gas to a high temperature as possible, a nozzle through which the gas is expanded and a turbo pump to force it through the system. The reactor must operate at very high temperature and high power densities to minimize the effect of overall system weight. This combination of high temperature and high power densities are going to be a real challenge to reactor designers and material researchers. Under the current conditions that reactors which have been tested for research purposes which are made to be used in nuclear rocket are around at a range of 2500\textdegree C, this testing is done at LASL (Los Alamos Scientific Laboratory) (Gunn, 2003). There are few materials under use to develop reactor interior systems like refractory metals and graphite. The metals should be strong neutron reflectors, whereas graphite is good temperature handling capability but not neutron absorbing strength. But it acts as a neutron moderator in a way it will minimize the amount of enriched uranium required in the reactor core. The only
disadvantage with the graphite in the reactor core is its reactive ability with hot hydrogen to form gaseous hydrocarbons, this problem can be handled by providing a protecting coatings. But one of the biggest challenge in this approach lies with the high temperature resistance of the protective coating under critical stages of nuclear fission reaction.

2.3.1 DESIGN OF NUCLEAR REACTOR FOR ROCKETS

The basic considerations in the reactor design stand on many factors, but the fundamental factors that govern the nuclear fission reaction will be taken into the account to make sure elemental problems are addressed in the microgravity fission analysis, such as neutronics, heat transfer requirements from the core, high mechanical loading, and the complex problem of start-up, control and shutdown. David Bunden, 1992 addressed the safety aspects in using nuclear reactors for rocket applications and important parameters that affect the design in safety aspects. Unplanned nuclear criticality preventive measure and control mechanisms, stable thrust conditions for the safety of the on board systems, core integrity in case of re-entry as well as planetary or interstellar space travel, radiological safety in case of random impact location (Vulpetti, 1985). This work is concentrated and specified NERVA reactor system safety considerations and future improvements in selection of nuclear reactor core designs.

Frank E Rom and Robert G Ragsdale described the heat transfer importance in designing the nuclear rocket reactor systems and compared the difference in using gaseous core instead of solid core reactors. In solid core reactors the limitation of fuel rods are set to be at 4400K, whereas the specific impulse that can be obtained from higher temperature operation of core is very high. In his work the specific impulse that can be reached at 20000 K is above 3456 sec. This is an interesting parameter for mission planners, when a rocket operates at the specific values the
time of travel will reduce by greater fractions. Frank has raised concern towards the development of gaseous core reactor technology by experimenting the reactor model, but a serious problem that need to be addressed before design the reactor is associated with the thermal-hydraulics of the reactor core and the neutron behavior inside the reactor sue to the use of gaseous fuel and propellant. The effective areas to address these problems is to conduct extensive study on hydrodynamics of the reactor core and the heat transfer analysis to investigate radiative and convective heat transfer problems along with the neutron behavior in specific conditions.

Milton Klein conducted a study on nuclear thermal systems developments in 2004, the experimental data was presented for the NERVA program and the different reactors tested at various power ranges. The maximum specific impulse recorded in these testes is at 760 sec which is twice as high as chemical rockets, and the reactor was operated for a period of 10 minutes and able to record 245 KN thrust from the system. The problems addressed in this particular design are related maximum power density and these reactors have an ability to operate over wide range of power conditions, without having any external source the reaction becomes self-sustained in the reactor core (Bussard, 1958). The KIWI series started at 70 MW power range and can able to reach 1096 with the KIWI B 4 E Reactor and all the operations are conducted for 28 times in different time intervals. The next level of work continued and ultimately XE Prime EST 1 could able to attain higher power range compared with all the designs tested, it could able to operate at 1140 MW (Brengel, 1992). Milton described that the level of improvements that can be made from solid core reactors are quite limited so there is a need to establishing a program to develop gas core reactors.
2.3.2 PHYSICS OF FISSION FOR SPACE REACTORS

In fission reactors the energy is released slowly through a radioactive reaction in a highly controlled manner. If a very heavy nucleus has a neutron added to it then it will become so unstable, it will be split into two or more species a process called nuclear fission. In the fission process it releases more neutrons; it will be useful in self-sustaining chain reaction. The kinetics of the reactor core also studied to identify the rate of fission and the interactions with the neutrons with the propellant and the reflector core.

2.3.3 PARTICLE BED REACTORS

H.Ludewig from 1996 considered the design for the particle bed reactor for nuclear thermal propulsion applications. The methods of analysis and their validations are outlined for physics of the reactor analysis using Monte Carlo methods for neurotics of the reactor; several algorithms were developed in order to handle fluid dynamics and heat transfer and transient analysis for the reactor core. In case of simulating structural and thermal aspects of the core as well as shielding is done through commercial codes (Anghaie, 1986). An experiment was also conducted using prototype of PBR to analyses the physics and neutronics of the reactor experiments were also conducted to examine blow down power extraction capabilities, material and Mechanical design aspects validation, and design concepts for fuel elements.

2.4 GAS CORE REACTORS EVALUATION

The first idea of using gas core fission reactors have evolved from Arthur C. Clark as a way of separating the nuclear reactor and the human habitation module. This is an even more advanced concept, initially proposed at the Scientific-Research Institute of Thermal Processes (now Keldysh Research Center), in
Russia [Koroteevet al., 2002]. Studies started in 1954, and somewhat later also NASA-Lewis (now NASA-Glenn Research Center) began to investigate it as well. The original suggestion for gas-phase fission (as opposed to fission in solid materials) actually goes back to 1949 [Bussard and DeLauer, 1958, pp. 322–327],

Jerry Gray in 1959 in his paper described about the possibilities of experimentation for gaseous core reactors for nuclear thermal propulsion in place of solid core reactors. The aspects considered are more on the theoretical level demonstration on exhaust velocity improvements through reaching higher core temperatures so that plasma state of operation can result greatest fraction of specific impulse. In fact this work also suggests the direct interaction of fission region to the propellant so that maximum heat transfer can takes place through convection and radiation. But this work did not demonstrate the methods through which the interactions need to be obtained. This paper also explains the development of cooling system that can keep wall temperature limited, since core is exposed to higher temperatures and the wall do get affected by the thermal radiation. The second aspect is quite interesting part over this thesis, controlling the fission reaction at criticality condition by maintaining the effective temperature (Black, 1991). The third concern raised in his work is to control the propellant flow rate without effecting exhaust velocity, since the radioactive material should not be expelled out when flow becomes turbulent. The basic design need that can make interstellar space propulsion possible is to design at least 1g acceleration attainable vehicle and second aspect is to create small thrust to weight ratio. The proposals from the work on theoretical base have given a cavity reactor model which can work with mixture of propellant and fissionable gas in a dense neutron reflector core.

Samim Anghaie, 2005 worked on optimum utilization of fuel in gas core reactors which are externally reflected and moderated by creating a force to keep fuel with
in the reactor chamber by means of magneto hydrodynamics. The advantage in GCRs is with operating reactor at higher temperatures and actinide formation can be avoided due to the propellant/coolant circulation. Samin proposed GCR-MHD concept for closed cycle gas core reactors through a bypass flow channel in the reactor system. The MHD Generator cycle will directly convert the fission liberated heat to power and the operational temperature suggested in his design are around 1800-2500K. This work did not mention any specific working fluid in terms of operation but it suggests He, KF, LiF, or BeF$_2$ are going to be effective solution (Spencer, 1963). The development in the field of gas core reactors good amount of work supports hydrogen and MHD cycle is a budding concept to secure uranium vapor inside the core. Convectional solid core reactors have limited applicability of MHD generator system, this direction limited amount of work was available. The suggestion made in this work is to make use of MHD to create high neutron flux to achieve non-equilibrium ionization.

S D Howe, 1997 conducted feasibility study on gas core rocket design based on the concept of using fluid dynamics inside the core by creating a vortex. The objective of creating vortex is to contain the nuclear fuel to create high power levels. The power levels vary with the effectiveness of kinetic energy change with in the working fluid with a radiative couplin (Dunn, 1991). This parameter studied for understanding the potential of using gas core reactors for long range missions.

P Sforza, professor at Brooklyn Polytechnic Institute created a clod flow experimental setup to create initial geometry of the core to establish vortex inside the core. He followed annular injection to create a vortex through a base plate, in the initial stages this experiment was conducted with the help of air. This experimental data helped in creating vortex models for gaseous fuel formation requirements to generate the similar phenomena and separate shedding. In case of
fuel injection the base line fuel injection was controlled to establish oscillation to create bleed flow, so that fuel will be contained in the fission region.

Figure 2.1: Experimental Setup Used by Prof. Sforza to Create Cold-Fluid Vortex Region

This work is an important determination in the later stages to design active control mechanisms that can be employed in a reactor core. The chamber that contains high pressure plasma with high temperature hydrogen, the behavior of vortex generation studies is quite difficult in understanding (Edelman, 2001). This experiment created a relationship between the injection velocity of the fuel and the axial position of the inlets, at high injection velocities the axial position of the inlet can be dragged as near as the core region. With the same chamber if nozzle is also attached to study the stability of the vortex a time-independent injection
velocity with an in viscid flow demonstrated the vortex settle down to a fixed axial position. To maintain the uranium criticality inside the code the vortex size need to be defined from the geometry, if the vortex is large then hydrogen and uranium starts mixing inside the chamber. In case of smaller vortex with a bigger core geometry uranium criticality starts degrading so that fission reaction is no more self-sustained. The geometrical modifications based on results obtained by simulating vortex formation in a cylindrical chamber with a base plate described the mechanism of altering the vortex location by controlling the flow through axial injection (Frank, 2012). The annular injection is major parameter in defining the strength of the vortex formed; no shading and vortex breakup in order to maintain uniform fission rate.

2.4.1 METHODS FOR RETAINING FUEL

Various mechanisms have been proposed in creating a mechanism to stop fissionable material from the reactor flow. The first mechanism is based on creating a magnetic bottle kind of approach, since the temperatures high in the core gas can be ionized easily there by using a low molecular weight propellant so that the flow is always on the corner of the core. The second approach suggest is to use difference in atomic mass numbers, like all the nuclear fuels are having higher atomic mass number compared to the propellants like hydrogen or helium as a same time its heat carrying capacity should be impressive (Marx, 1963). On the similar grounds creating a uni-directional flow to create a vortex by which fuel can be contained within the chamber. The third approach is to choose magnetic hydrodynamics approach is to create Vortex Street to protect the gaseous fuel inside the core by providing the centrifugal acceleration for fuel separator. The major consideration in selecting above approaches should also focus on heat-transfer and the thermal emissivity should not be low inside the core.
Vortex containment is commonly used approach in gas core reactors to protect nuclear fuel from expelling out through the propellant. Physical containment introduction is an obstructor to the heat transfer. Jack L Kerrebrock, 1961 has done work on vortex containment mechanism to use them in nuclear rockets. Vortex generation is done through creating a pressure field by diffusing low molecular weight propellant radially into the reactor chamber. In this work a 2-D laminar vortex flow is studied and the fuel is introduced tangentially so that vortex generation can happen due to pressure difference and the circulation happens with low molecular weight propellant (Glasston, 1955). The parameters need to be developed to generate such kind of containment chamber are purely controlled by pressure difference, the mass flow capacity of the vortex per unit of vortex length (Jack, 1961). The entire phenomenon worked out in this concept is independent of vortex diameter since the mass flow rate becomes negligible when it reaches the fission region. So that small diameter vortices filling the given volume, if the tangential Mach number of the radial flow reaches unity in the mixture gaseous fuel and the propellant mass flow capacity will reach 0.01 pounds per second-foot. If the pressure gradient decrease due to the molecular weight difference still the fuel can be maintained inside the core, the difficulty that can occur is due to control over the pump mechanism used for fuel. However at very high temperature ratios and the pressure gradients it cannot be decreased unless the fission dies (Goel, 1991). The problems described through is work are associated with containment mechanism, like the radial heat transfer, difficulty in maintain nuclear fuel in gaseous form, generation of vertices with low radial mass flow rates at high tangential velocities.

Robert V, 1961 formulated a diffusion problem for the vortex containment chamber analysis to address the problems mentioned by Jack he studied the variation of density ration with dimensionless radius by considering the diffusion
velocity of the heavy gas in the ration of 0.7 and two peak comparative variations are obtained at 0.17 and 0.34 under critical conditions. Similarly the energy equation was solved to get the variation of dimensionless temperature to the radius of the core under the assumption that heat rate is proposal to the concentration of the fissionable material. This solution is obtained by solving three first-order differential equations with three variables under constant dimensional radius. This results in terms of observing variation of density ratio along the core radius, through which critical and maximum heating rates can be found, the maximum heating rate value is observed inside the vortex (Howell, 1965). In this work variation of dimensionless fuel concentration across the geometry also investigated and the core is having greater fuel concentration in the vortex region. Significant results are obtained from the analysis described the performance characteristics of the reactor core through vortex generation. Over all temperature ration examined the relative mass flow capacity which indicates overall enthalpy rise of the gas mixture due to the fraction carried by radiation.

2.5 THERMODYNAMIC PERFORMANCE OF GAS CORE REACTORS

W. Boersma-Klein, 1985 preformed analysis on gas core fission reactors to investigate the thermodynamic behavior of the fission products, the rocket engine is visualized as a constant pressure stagnation chamber containing the energy source. The analysis conducted on 1200 MW Power Reactor, with a pressure range of 0.1 MPa and 2.5 Mpa at a temperature range of 1300 K to 10000K for a U-F-C core. The significance of the work comes from usage of plutonium compound in the form of PuF₄ which is recycled with UF₄. The results from the work demonstrated the partial pressure variations after 200 hours of reactor operation at 1200 MW thermal power at a 2.5 MPa with a temperature range of 2500K to 2800 K (Piacentino, 2008). This indicates these are no condensation of fission products inside the reactor core. The thermodynamic behavior of
plutonium with rare earth compounds is limited due to variation in the partial pressure. The plutonium compound can essentially be reprocessed with UF₄ and the whole mixture is easily dissociated and Uranium atoms can be ionized about 65%, so that the exact velocity of the propellant gains the kinetic energy.

Thermodynamic Performance study of possible fluid for nuclear thermal reactors was conducted by Kenneth E. Kissell, the main focus of the study is to analysis the ionization and dissociation effects of the various working fluids. The idea comparison is made with the hydrogen as a working fluid which can have a potential of producing exhaust velocities exceeding 32,000 ft/sec. Liquid hydrogen energy equivalence in terms of heat of formation. The ionizing hydrogen’s equilibrium composition over a temperature range is computed up to 15000 K using thermochemical data. The data plotted from equilibrium composition to obtain entropy and enthalpy relationship at two distinct regions. To generate the data for practical range of rocket chamber pressure from 1 to 500 atm at a pressure ratio of 10 to 1000 from expansion processes. The total enthalpy of hydrogen mixture at 3000 K is nearly intensive to chamber pressure (Kenneth, 1989). In this besides hydrogen water vapor and air is considered as a working fluid, comparing all the physio-thermal properties hydrogen behavior at higher pressure and its variation of exhaust velocities are giving effective relation between entropy and enthalpy.

2.6 GASEOUS FUEL FOR ROCKETS

W Boersema conducted analysis on gaseous core reactors and the behavior of the gaseous fuels inside the reactor and their chemical reactors at various temperatures are investigated. The temperature range considered in this particular work in 1989 by considering 2000 K-10000k, for a pressure range varying from 1 bar to 100 bar. The U-C-F system was analyzed by changing the floride concentration in the
composite system. In this work a dissociation energy levels are determined by creating a mixture of compounds in the fuel. The identifications done from this work is a trendsetter to conduct future research on UF₄ based systems as well as UF₆ developments.

2.7 FLOW ANALYSIS ON GAS CORE REACTORS

Computational fluid dynamic and heat transfer analysis is conducted on gaseous core and gas cooled space power and propulsion reactor system by S. Ahghaie and G.Chen from university of Florida in 1996. This work concentrated in solving a computational model based on the axisymmetric thin layer Navier- Stokes equations and investigated radiative and conductive heat transfers in nuclear reactors using implicit-explicit finite volume, MacCormack method along with Gasuss-Seidel line iteration process for solving governing equations. The considerations are the flow is both subsonic as well as supersonic for hydrogen gas and uranium hexafluoride under variable boundary conditions. The boundary condition consider in S.Ahghaie system are at constant heat flux the process is adiabatic, isothermal to simulate the propellant flow in nuclear reactor core. To obtain the convergent solution an enthalpy-rebalancing scheme is implemented for the wall heat flux. The outcomes of the above work can be a path way to solve thin layer Navier-Stokes equations, radiative heat transfer model using Roseland diffusion approximation, Baldwin and Lomax two layer turbulence models and can be a reliable computational tool for a space nuclear core models. The model reactor system is shown in the figure below. This model was suggested by Kerrebrock and Megheblia that a multiplicity of vortex chamber can contain the fuel inside the reactor core.
Figure 2.2: Gas Core Nuclear Reactor Core Flow Model with Vortex Generation

The thermal hydraulic analysis conducted by Kammash in 1994 considered Navier-Stokes energy, and species diffusion equations for the propellant flow inside the reactor core. The assumptions made in his analysis on constant mass flow rate of the fuel as well as the propellant, thereby it occupies the shape of a cylindrical annulus and converts the radioactive fuel into plasma with reduced cross section near to the throat (Huth, 1960). The propellant enters through a channel attached to the wall surrounded by the reflector so that it can act as a coolant to the core as well as it can take the initial heat before entering into the chamber. Depending upon the heat flux the propellant flow rate was regulated and he identified that, at maximum heat flux the buffer region is having highest rate of heat transfer. The parameters of interest in the analysis are likely to develop effective pressure and temperature values inside the core, this work demonstrated the effect of pressure on $K_{\text{eff}}$. The value getting affected based on density factor of the fuel, since the analysis was conducted under ideal conditions the maximum value of the temperature is at 50,000k (Hsia, 1991). At the same grounds the $K_{\text{eff}}$
value is reaching 1.2 at 1000 atm pressure, which cannot be searched under current conditions.

The second consideration made in this work is to keep the temperature of the core constant at 10000K and start varying the density of the propellant, poor performance was observed under these conditions since the value of $K_{\text{eff}}$ started decreasing and above a certain point it started increasing. This indicates that hydrogen started behaving like a neutron moderator inside the core; this effect was not visible at higher temperatures since the neutrons starts reflecting in reactor core above 10000K (Palaniswamy, 1991). The reflector thickness has its own effects on $K_{\text{eff}}$ it also effects the propellant behavior inside the core, since the reflector thickness is a question of maintaining the fission under control. This work gives a specific idea over the effect of temperature on reactor criticality between 10000K -20000k, the future analysis also done in the similar lines to investigate helium behavior and the effects over the neutronics. The attractive propellant can be hydrogen in case of using high temperature reactor operations.

David I Poston and Terry Kammash, 1994 have done an analysis on thermal hydraulic model of gas core reactors using open cycle nuclear rocket. The solution was obtained by two dimensional Navier-Stokes Equations, species diffusion; energy equation was solved for high temperatures. The analysis provided effective understanding of the fluid dynamics of the core. In this work David considered uranium hexafluoride as a fuel which is heated through fission and plasma region going to created, heat there by transfers to hydrogen propellant. Gas core reactors major problem associated with the mixing of propellant and the fuel. If mixing can be avoided through some mechanism without having any solid boundary the performance of the reactor system will improve and the reactor power that can be produced is at 3000 MW that can produce 3160 sec specific impulse with a thrust of 125 kN (Palaccio, 1950). This analysis conducted on a
code developed by using Navier-Stokes equations by considering constant heat flux, when the wall heat flux becomes maximum the flow rate of propellant will increase. Turbulence model is introduced of eddy viscosity, as an input the turbulent transport coefficients of mass, momentum and heat are specified. The results are presented for 500 MW open cycle GCR design the contours presented in the work are ranging from 5000K to 50000 k (Michal Plavee, 2011).

2.8 NEUTRONICS OF GAS CORE REACTORS

In the area of gas core reactors design and analysis limited amount of work can be found since the availability of expertise and data from the scientific agencies are not accessibly for everyone. Few special cases can be found from the university level research, University of Florida, Delft University and University of Michigan some work was published into research papers. David I, 1994 conducted a study of neutronics on open cycle gas core reactors. This work investigated keff variations as a function of design parameters. The major dependent factor can be temperature, composition of the fuel and propellant along with reflector thickness. This work also investigated coupled thermal-hydraulics which is obtained by solving 2-D steady state conservation of mass equations, species, energy, radial momentum and axial momentum (Michael, 2009). The specific design considered in the solution results various parameters like neutron flux, variation in power density, neutron energy spectra are the outcomes of the solution. The changes that can occur by changing the fuel composition and by changing different fuels along with variety of propellants have been considered. In model the solution is obtained for the core without considering any physical barrier between uranium plasma and to the propellant. Ideal operational parameters includes 3000 MW reactor which can able to produce a specific impulse of 3160 sec with a thrust of 125 kN, it related to maximum heat flux of 100MW/m². In this work the solver chosen to investigate neutronics was TWODANT code, 50 group cross-sections
are the range of material and temperatures in the library. The input requirements for the code are Up scattering, many energy groups, Highly in Homogenous mesh and output Tailoring. This code solves isotropic and linearly anisotropic differential scattering matrix for all cases at an order of $S_{ON}=4$ (Spence, 1965). The fuel material considered are U-235, U-233, Pu-239 with a Beo reflector and the pressure vessel material was considered as Ti with the various propellants like H, D, He.

Volken seker in 2004analysed neutronics of HTR-10 reactor core using MCNP code, HTR-10 is a high temperature gas cooled reactor. The reactor analysis is performed to cheak intial criticality for a pebble bed core and the equations solved in obtaining the effectiveness factor is neutron transport equation. The reactor model considered in this analysis is from jing et al 2002, VOSS code was used in jings model and the volken compared MCNP results aginest VOSS for validation. Tuechurt, 1994 conuced neutronics analysis on the same code but for a pebble bed reactor with a different configuration, in fact helium also has some considerable characteristics but it is not a good neutron moderator there by criticality can’t be controlled in high temperature operations (Stanley, 2001). Goltsev 2005 studded neutronics of a pressurized water reactors system, the analysis focused on kernel inside the fuel system. The reactor parameters considered for analyzing neutronics in the HTR-10 is having a power capacity of 10 MW with 197 cm of core height, 180 cm of core diameter. In the current system helium was used as coolant with an inlet temperature of 350 $^\circ$C and the reactor exit temperatures is 850 $^\circ$C, the operation pressure of the reactor system is at 3Mpa (Sforza, 1992). In the HTR-10 reactor graphite was used as a neutron reflector, keff values are studied for various conditions like vacuum, helium, air. The highest value is passed in vacuum with improved core height, the analysis conducted on HTR-10 core given a relationship between the loading height of the
reactor and the keff factor. With full height the reactors critical value is continuously growing, whereas with the critical height it starts declining.

Summer Shin in 1998 conducted an analysis on neutronics in space reactors which can be used for power and propulsion applications. The reactor was controlled by B₄ C drums attached with a Beo reflector, Uranium Carbide used as a fuel. The idea of investigating the neutronics in this core configuration is to estimate the heating on control drums due to neutron interactions. The reactor is designed to develop a thermal thrust of 5000 N with a specific impulse of 760 sec. Hydrogen is used as a propellant and the core exit temperature of the propellant is at 1900 K. The neutronics analysis is conducted using ANISN code which can solve one-dimensional, two dimensional transport equations with the fission groups S₁₆-P₃ and S₈-P (Taub, 1975). The reflector thickness considered for the core is around 16 cm with the 14 cm control drum thickness the delta Keff is resulted on the fast reactor is around 13.56%, The operational power levels of the reactor is around 50 KWe with a reactor height of 35 cm and its radius is given around 22 cm. This analysis indicates the maximum amount of heat generated in the fission process is used in propulsion phase and the heat is carried by Hydrogen propellant.

2.9 PROPELLANTS FOR GAS CORE REACTORS

Ron J. Litchford conducted analysis on hot hydrogen exposer to various materials and he studies effects of high temperature and pressurized gas behavior inside the reactor core using a non-nuclear means of heating system with the help of arc heater driven by hyper convective and radiative environment. The facility later modified to study the behavior of hydrogen under high temperature in a pressure vessel. The test data available up to 3500k in a 3Mpa environment to support the solid core reactors operation within the temperature range of fuel material limitations (Spence, 1965). The hydrogen performance was estimated at various
mass flow rates varying from 5-10 \text{ g/s} and various levels of efficiencies have been recorded with variation in pressure inside the chamber the maximum pressure that can improve the performance of the system was recorded at 35 \text{ atm} (Thomas, 1993). The behavior starts deteriorating with increase in temperature the power density starts decreasing from the chamber. This work demonstrated the effective operational range and the maximum flow rate levels of the hydrogen.

LASL report on possible propellants for use in nuclear rockets describes the use of Hydrogen, methane, ethane, helium, propane, mixture of hydrazine and these hydrocarbons, ammonia, methanol, ethanol and propanol. The dissociation products and their compounds with in the temperature range of 1000-3000 \text{ K} (Chen, 1996), among all the suggested propellants Hydrogen has a highest mole fraction when temperature starts increasing, methane shows poor performance in terms of thermodynamic aspects. Due to the low molecular weight and the higher mole fraction this study recommends hydrogen as a most suitable propellant for rocket reactors design.