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DROPLET CORE NUCLEAR ROCKET (DCNR)

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The most basic design feature of the droplet core nuclear reactor (Figure 1 & 2) is to spray liquid uranium into the core in the form of droplets on the order of five to ten microns in size, to bring the reactor to critical conditions. The liquid uranium fuel ejector is driven by hydrogen, and more hydrogen is injected from the side of the reactor to about one and a half meters from the top. High temperature hydrogen is expanded through a nozzle to produce thrust.

The hydrogen pressure in the system can be somewhere between 50 and 500 atmospheres; the higher pressure is more desirable. In this system, uranium droplets are intimately mixed with hydrogen. The fission energy transferred to the gas is 30-40% direct. In the uranium (Figure 2), the mean free path of neutrons is very short; most of the fission occurs close to the surface and from 20-40% of the fission fragments is directly stopped in hydrogen. Heat is also transferred from droplets to the hydrogen directly by conduction and also by radiation. In about one and a half meters from the top, the uranium droplets and hydrogen temperature reach close to 4,000 degrees K. From our own calculations, it is evident that uranium impingement on the wall is a function of droplet size and flow conditions in the core. That's a function of the size of the droplet in the boundary layer. If uranium droplets that are larger than about 30 microns enter the boundary layer, they have a tendency to go toward the wall. However, the hydrogen inflow brings back smaller droplets to the center of the reactor.

In the lower core region (about one and a half meters from the top), hydrogen is tangentially injected to serve two purposes: one, to provide a swirling flow to protect the wall from impingement of hot uranium droplets; two, to generate a vortex flow that can be used for fuel separation.

Tangential injection driven vortex flow is ceased after about one meter, where liquid lithium is injected downward along the wall. After tangential hydrogen is stopped, droplets escape in the direction of their tangential velocities, and land on the lithium-6 film on the wall. Liquid uranium is cooled down on the lithium-6 and flows along the wall to a separator where lithium and hydrogen are separated and the uranium is recirculated to the system.

The hydrogen can reach temperatures of 5,000 to 7,000 degrees, depending on the pressure at which the nuclear engine operates. If pressure is 500 atmospheres, which is what we have used for our base-line analysis, the boiling point of uranium is 9,500

Kelvin. The system can be operated to heat-up the hydrogen to 6,000 degrees or so. That's the basis for our calculations and the conceptual design analysis of DCNR.

As is shown in Figure 2, for the first one and a half meters, uranium and hydrogen are intimately mixed. Because of tangential flow and vortex, the droplets are contained and prevented from impacting the wall. Once the tangential injection in the lower region is removed, heavier fuel droplets move in the direction of their tangential velocities and follow a diverging helical trajectory to the wall. That mechanism provides for fuel separation right at the end of the reactor. The nuclear engine is also designed such that about 70 to 80 percent of the power is generated in the upper part of the reactor. Neutron flux peaks at the upper part of the reactor and is highly depressed at the last half meter of the reactor.

The proposed nuclear reactor is about one meter in diameter and three meters in length, which provides for the type of energy release and power distribution needed to operate at very high temperatures.

Design of this core concept has evolved from the colloid core reactor concept that was proposed in the 1960's (Figure 3 & 4). The colloid core concept utilizes fine particles of uranium-zirconium carbide and vortex flow to confine the fuel particles in the reactor. A very important result of the colloid core study was that Anderson and his colleagues (Figure 3) have demonstrated the vortex flow confinement of the particles. They performed an experiment using tungsten particles and also talcum powder to show that particles indeed can be confined in the core. In the liquid uranium droplet concept, we are not trying to confine droplets in the reactor; they can leave the reactor, and be recirculated. However, in the colloide core concept, complete confinement of the fuel was desired. The effectiveness of the vortex confinement process is rather limited. As a result, the uranium loss might be very significant (six kilograms for six minutes or so), and not acceptable for long missions.

The liquid annulus concept (based on what I have read in the open literature) utilizes solid and liquid uranium compound fuel. Hydrogen is forced to bubble through the liquid fuel to reach 5,000K at the core exit. The reactor core has to be rotated at the rate of 7,000 RPM to contain liquid fuel on the wall. Since hydrogen is bubbled though the liquid uranium at high velocities, the fuel loss due to forced vaporization and entrainment can be very high, and beyond the level acceptable to any mission.

In 1987-88 we developed the droplet core reactor concept, primarily for a multi megawatt space power reactor system (Figure 4). For the past few years, we have studied the properties of droplet fuel transport, heat transfer, thermal hydraulics, neutronics, and material aspects of this concept.

The droplet core concept is different from the rotating liquid core concept mainly due to the fact that uranium is not confined in the core but is actually recirculated. Based on

our studies we have concluded that due to the axial velocity of uranium, it is very difficult to achieve effective core confinement. In the droplet core reactor concept, we try to redirect and bring the droplets close to the wall and then separate and re-circulate them.

Uranium has a very broad and stable liquid phase (Figure 5). At 500 atmospheres, uranium melts at 1,400 K and boils at about 9,000 K.

To spray liquid uranium in very small sizes, hydrogen should be injected at velocities ranging from 500 to 2,000 meters per second. This is in the nozzle spray system; to obtain smaller droplet sizes (<5microns), one has to blow hydrogen at higher velocities (Figure 6). However, once the gas comes into the reactor, the average velocity drops to tens of meters/sec. At the top region of the reactor, the average velocity is about four to five meters per second, and near the core exit it is about 30 to 40 meters per second. At these moderate velocities, the uranium droplets and the hydrogen gas do not have a significant relative velocity, which minimizes the forced evaporation of uranium.

In mid-core region, the established method of vortex flow is used to keep droplets having very high temperature away from the wall. The reverse process is used in lower core region to separate the droplets and bring them toward the wall where it is injected by lithium-6. Since lithium, as you know, has enormously high latent heat of vaporization (21MJ/kg), it provides a lot of heat sink capacity to cool uranium droplets from about 6,000 or 6,500 degrees to about 2,000 degrees, which can then be handled in the fuel storage and recirculation system.

As for the hydrogen transport, this system relaxes two major design restrictions. First, the rocket engine is not thrust limited because the hydrogen flow rates can be very high. The liquid uranium volume in the core is about two liters, so loading in a core of this size is about 20 kilograms. The total volume of the core is about 2,5000 liters, so the void fraction for this system is about 99.9. Therefore, hydrogen is practically free flowing, and the mass flow rate of hydrogen is unlimited by core losses and so is the thrust. The heat transfer area is not limited; about 40 percent of the fission fragments energy is directly deposited into the hydrogen propellant. Furthermore, the heat transfer area for fuel droplets is very large. It is about four orders of magnitude larger than any other non-colloid fuel reactor concept.

Another important feature of this nuclear propulsion concept is that it can augment the Isp beyond the temperature limits by radiation-induced dissociation and subsequent recombination of the hydrogen. Since the reactor is operated at a high temperature, even at 500 atmospheres pressure, thermal dissociation of hydrogen is significant (Figure 7). At this pressure, in addition to 20 percent dissociation at 6,000 degrees, there is nuclear enhanced ionization of the hydrogen.

Primary and secondary electronics that are generated by fission fragments increase the

dissociation of hydrogen. The dissociation energy of these hydrogen molecules is fully recovered after expansion through the nozzle because of their non-equilibrium conditions. This is on the top of the thermal dissociation that can further enhance the Isp for the system. For the baseline design, a total of 20% dissociation and recombination is assumed. This leads to 2,000 seconds of Isp.

Materials play a very significant role when you are talking about such extreme temperatures (Figure 8). Tungsten and tantalum are the only two refractory metals that are fully compatible with uranium. Uranium neither dissolves nor forms any kind of metallic or chemical bond with these metals. However, uranium at high temperature attacks both tungsten and tantalum by diffusion through the grain boundary.

But if we use single crystal tungsten or tantalum, the granular attack by uranium can be mitigated. There is existing technology for growing single crystal tungsten, but for tantalum it is still under investigation.

Many other high temperature materials that have become available in recent years can help with the development of high Isp rocket technology. For example, tungsten-rhenium-hafnium carbide alloys (Figure 9) have outstanding mechanical properties at temperatures above 3,000 K, even up to 3,400 K. These alloys have been demonstrated to have acceptable mechanical properties that can be used as structural materials for large reactor vessels.

Let's summarize the basic design features of (Figure 10) uranium fuel droplets and hydrogen propellant when they are intimately mixed. The energy transfer, in addition to direct deposition of fission fragments, is through the high surface area of droplets. In this system, the fuel surface area density (m^2/cubic meters of fuel) is about four orders of magnitude larger than solid core reactor concepts.

Very high propellant temperature can be reached in this rocket engine (3,000 to 7,000K). For the baseline analysis we have used 6,000 degrees. The hydrogen flow rate in this systems is not restricted by fuel heat transfer area.

If pumping power is available, hydrogen can be pumped though the system even at 1,000 kilograms per second. There is no limiting factor for hydrogen flow, although a very high rate of hydrogen flow for this mission is not needed. For the desired thrust for this concept, 17 kilograms per second of hydrogen should be actually pumped though the reactor.

For the baseline design, at 6,000 K propellant temperatures and 20 percent dissociation and recombination, an Isp of 2,000 sec. is calculated.

There is also a very important safety feature for this system. The reactor can be loaded in orbit. Uranium powder can be used for initial start-up. Therefore, the reactor does

not need to be launched with the fuel in the core.

Another feature that could be a liability, (or also could be a benefit of this concept), is that most of the fission fragments escape from the core. It reduces the radioactive loading of the reactor. This is the good aspect of the design if radioactive material release is acceptable.

From my standpoint, the fission fragment release is a benefit of this design. This is a good safety feature of this system, because the reactor is drained of radioactive materials and removes the shielding requirement for non-prompt radiation. This allows for reactor repair after initial start-up.

Low uranium loading is needed for this concept. About 20 kilograms of 95% enriched uranium is needed to reach critical conditions. If the system is optimized, it is expected to reduce the core loading to about ten kilograms. This core loading is defined based on minimum uranium-235 concentrated in the core. In my calculation, it is 20 kilograms of fully enriched uranium. The total inventory of about 100 kilograms of uranium is circulated in the system.

The reactor is designed to maximize the energy generation in the upper region of the core. This is where we have a thick reflector (Figure 11). The core is three meters in length. Figure 14 shows the thermal flux and the fast flux in the core and the reflector. As you can see, the power decreases in the lower core region where lithium-6 is injected. In this region the flux goes down by four to five orders of magnitude. At the end of the reactor, the power generation is minimized.

Again, to summarize (Figure 12), the system can result in an Isp of 2,000 seconds, and a thrust-to-weight ratio of 1.6 for the shielded reactor. The nuclear engine system can reduce the Mars mission duration to less than 200 days. It can reduce the hydrogen consumption by a factor of 2 to 3, which reduces the hydrogen load by about 130 to 50 metric tons.

The engine dimensions are as follows: the inner diameter is basically one meter and the core is three meters in length. The total length of the engine and the reactor is about 13 meters and the thrust to weight ratio with the shield is about 1.6.

The hydrogen flow rate and the reactor power can be scaled up without changing the core dimensions. The same reactor can be made critical and can be operated at different power levels and thrusts. For the baseline, the hydrogen flow rate is 17 kilograms per second and it can go to 25 or maybe even to 150 kilograms per second without changing the dimensions of the reactor.

The only change that can be made by increasing the hydrogen flow rate is the uranium injection rate into the core. This is also regulated by hydrogen flow that drives the liquid

uranium spray system. The maximum level is ultimately limited by the nozzle flow capability. This is obviously a major problem. To expand molecular and atomic hydrogen at 6,000 K through the nozzle, the heat flux would be extremely high and beyond the current technological capabilities. It may force a reduction in the maximum core outlet temperature. However, this is a generic problem for all advanced concepts.

Critical technical issues that need to be addressed are listed in Figure 11. I do not have time to go though all of them. One is modeling of the uranium droplet transport in the hydrogen. This needs to be tested, and the energy transfer process must be analyzed. Droplet fuel separation and uranium loss must be accurately analyzed, especially uranium loss. If uranium loss due to evaporization is high, we have to seed hydrogen with depleted uranium hydride. Uranium hydride at 500 atmospheres dissociates at 1,200 K; it becomes uranium vapor and hydrogen. This can suppress the enriched uranium evaporation and loss. The loss of depleted uranium from the nozzle results in a penalty of 5-10% loss in Isp.

The hydrogen driven uranium spray nozzle design needs to be investigated. For mercury and helium, the weight ratio is not as high as uranium hydrogen.

After separation from lithium and hydrogen, liquid uranium fuel is pumped and recirculated. Pumping of liquid uranium at temperatures and flow rates of interest to this concept has not been done yet. Although the technology of pumping uranium compounds in molten salt reactors is well developed, the forced recirculation and pumping of liquid uranium have to be investigated.

The materials compatibility and fabrication technology for refractory alloys are issues that must be investigated. Last but not least, the rocket nozzle design for operation in a molecular and atomic hydrogen environment at about 6,000 degrees is another key technical issue that must be investigated. And here basically I would like to stop.

A VOICE: You have the gas being rotated in the lower part of the vessel in order to send the uranium to the wall and be collected, whereas in the upper part you want the uranium to be in a colloid. Yet if the rotational motion of the gas in the lower part will also cause the gas in the upper part to rotate to some degree, that will send your colloid to the wall as a liquid layer.

How can you maintain a colloid under those conditions?

MR. ANGHAIE: You mean droplet liquid?

A VOICE: It seems to me that the gas rotation in the lower part of the vessel will translate into some gas rotation in the upper part. It will take this mixture of droplets and cause them to precipitate against the walls of the machine and, thus, instead of getting this very large heat transfer area with all these droplets and suspension, you will

just get a simple liquid layer along the perimeter of the vessel.

MR ANGHAIE: For separation of uranium you do not need very high rotational velocity. Then the forces acting on droplets are (1) the drag force (2) the thermoforetic force that is due to the temperature difference and that pushes the uranium droplets toward the wall; and (3) the dynamic force due to the pressure difference between the walls and the core centerline, which is moving at maximum velocity. This force tends to bring droplets toward the center.

In the upper regions of the core, the pressure difference due to lower velocity at the wall and higher velocity at the center keeps droplets away from the wall. With the type of rotational velocity and because of uranium density that is 300,000 times larger than the density of hydrogen, we don't believe that very high rotational velocities are needed. Therefore, the rotational momentum added in the mid-core regions cannot diffuse to the upper core region. Furthermore, even if droplets would go to the wall, the temperature of uranium droplets is not more than 3,000 to 4,000 degrees in that region, and, again, hydrogen is being injected in the upper core region so it doesn't seem to be a problem in this regard. However, optimization has to be done regarding the balance of the vortex flow containment and separation of liquid uranium.

A VOICE: Well, the rotational lower part has to be substantial or else the uranium will be convected out the bottom of the machine. It won't have time to fall against your collection device unless it is a high G force.

MR. ANGHAIE: It really doesn't need high G force. Once you remove the force, uranium droplets just escape in the direction of their tangential velocities. The axial velocity in this system is about 20 to 30 meters in the upper part. What you need is a velocity of a few meters per second -- because the drag force by axially flowing hydrogen is not that large. Calculation has shown that vortex flow separation is a serious problem; however, this problem has to be further investigated.

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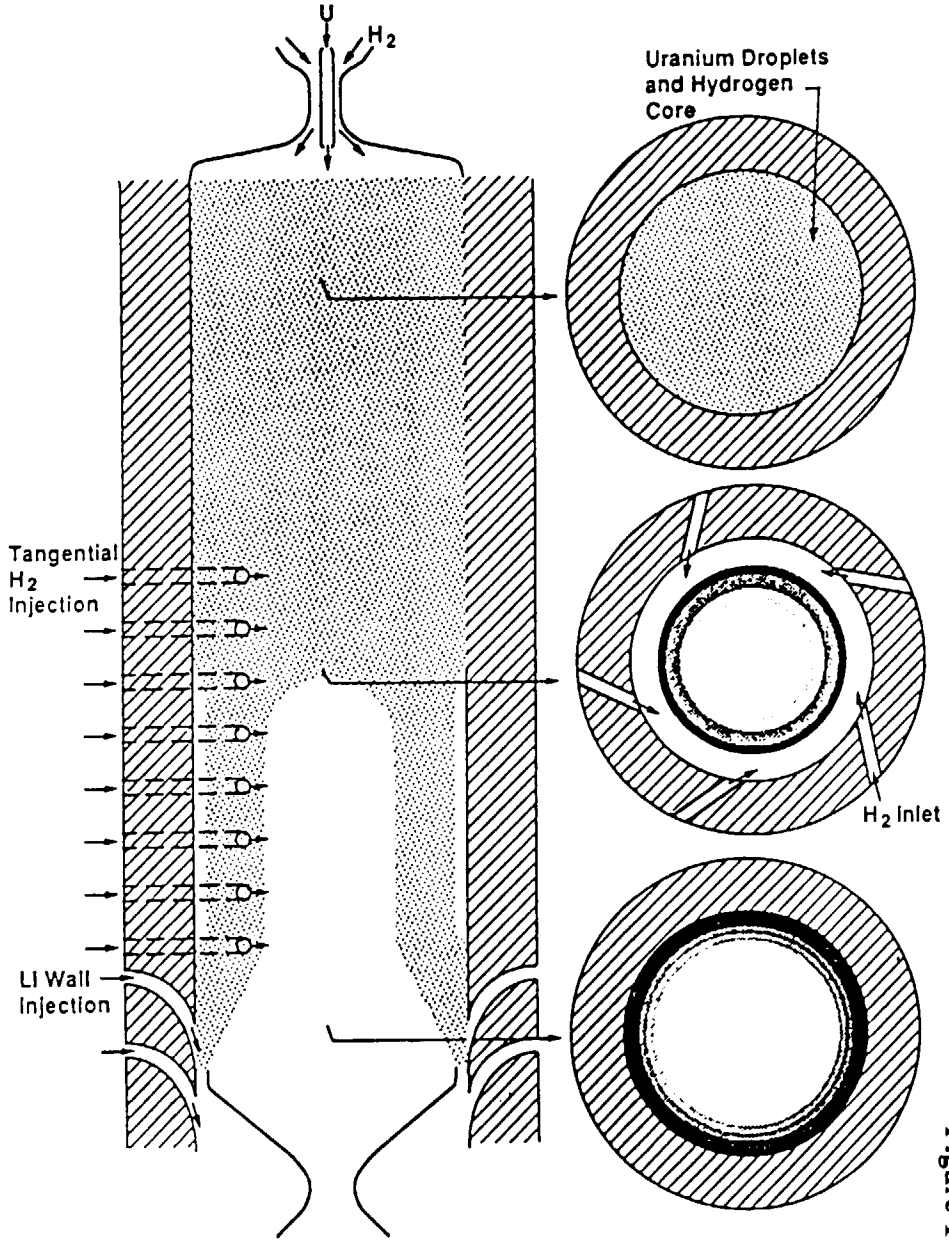


Figure 2

Illustration of Liquid Uranium Droplet Fuel Distribution In DCNR (out of scale).

DROPLET CORE NUCLEAR ROCKET (DCNR)

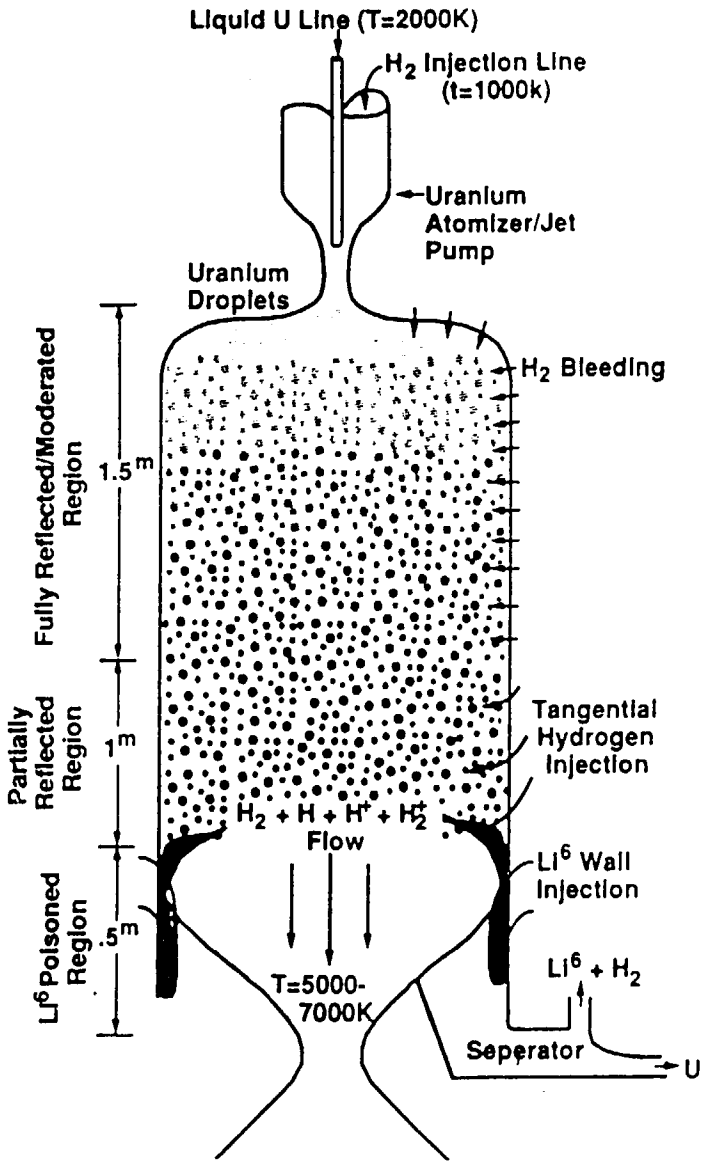


Figure 1

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE

EVOLUTION OF DROPLET CORE REACTOR DESIGN

1. COLLOID CORE CONCEPTS (Y.S. TANG ET AL. 1970)
   * U-C-ZR FINE PARTICLES CONFINED IN A VORTEX FLOW CAVITY
   * COMPACT CORE, T=3700K, ISP=1100S, T=20,000LB
   * VORTEX PROPERTIES OF COLLOID CORE REACTOR WERE DEMONSTRATED (L.A. ANDERSON ET AL., 1972)
   * VERY HIGH RATE OF U LOSS (100 G/S)
2. LIQUID CORE CONCEPT (J.P. MCGUIRK, 1972)
   * CORE CONTAINMENT USING CENTRIFUGAL FORCE (ROTATING AT 7000 RPM)
   * FORCING HYDROGEN TO BUBBLE THROUGH UC-ZRC LIQUID FUEL
   * T=4800K, ISP=1500S, T=9000LB
   * HIGH RATE OF URANIUM LOSS, LACK OF A RELIABLE MECHANISM FOR ROTATION AT 7000 RPM

Figure 3

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE

EVOLUTION OF DROPLET CORE REACTOR DESIGN

3. DROPLET CORE REACTOR (S. ANGHAIE 1988)
   * RECIRCULATION OF URANIUM INSTEAD OF CONFINEMENT
   * UTILIZATION OF VERY STABLE URANIUM LIQUID PHASE (@ 500 ATM T_{MELT} = 1400K, T_{BOIL} = 9500K)
   * FULL ENTRAINMENT OF DROPLETS SIGNIFICANTLY REDUCES THE FORCED EVAPORATION AND MINIMIZES THE URANIUM LOSS (LESS THAN 50 KG/MISSION)
   * ESTABLISHED METHOD OF TANGENTIAL INJECTION INDUCED VORTEX FLOW IS USED FOR WALL PROTECTION AGAINST URANIUM DROPLETS AND SUBSEQUENT SEPARATION.
   * MAXIMIZES HYDROGEN FLOW AREA AND RELAXES THRUST LIMITATIONS (2500<T<400,000LB)
   * NUCLEAR ENHANCED DISSOCIATION OF HYDROGEN INCREASES ISP (1500<ISP<3000S)

Figure 4

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE

VAPOR PRESSURE OF URANIUM AS A FUNCTION OF TEMPERATURE

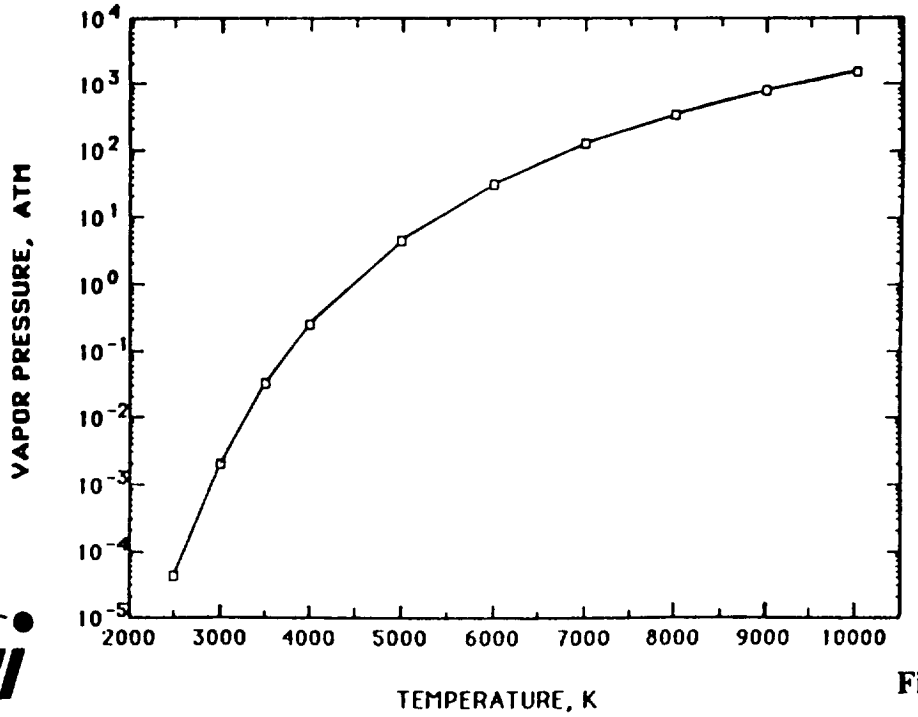
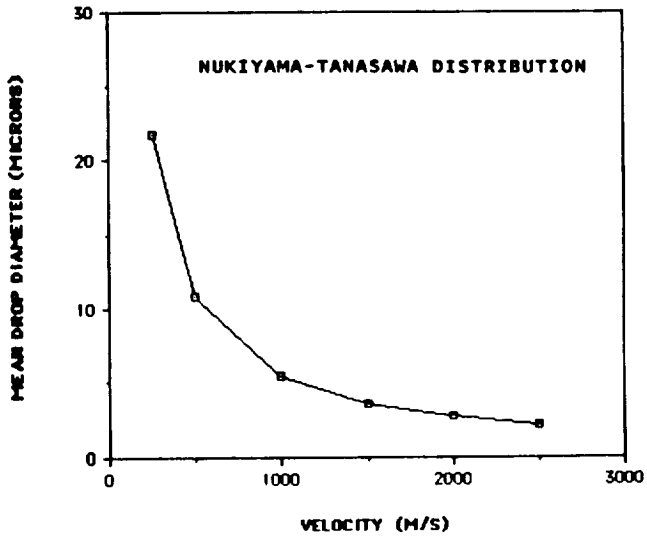


Figure 5

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE



AVERAGE URANIUM DROPLET SIZE AS A FUNCTION OF HYDROGEN FLOW VELOCITY IN THE NOZZLE SYSTEM

Figure 6

INNOVATIVE NUCLEAR SPACE
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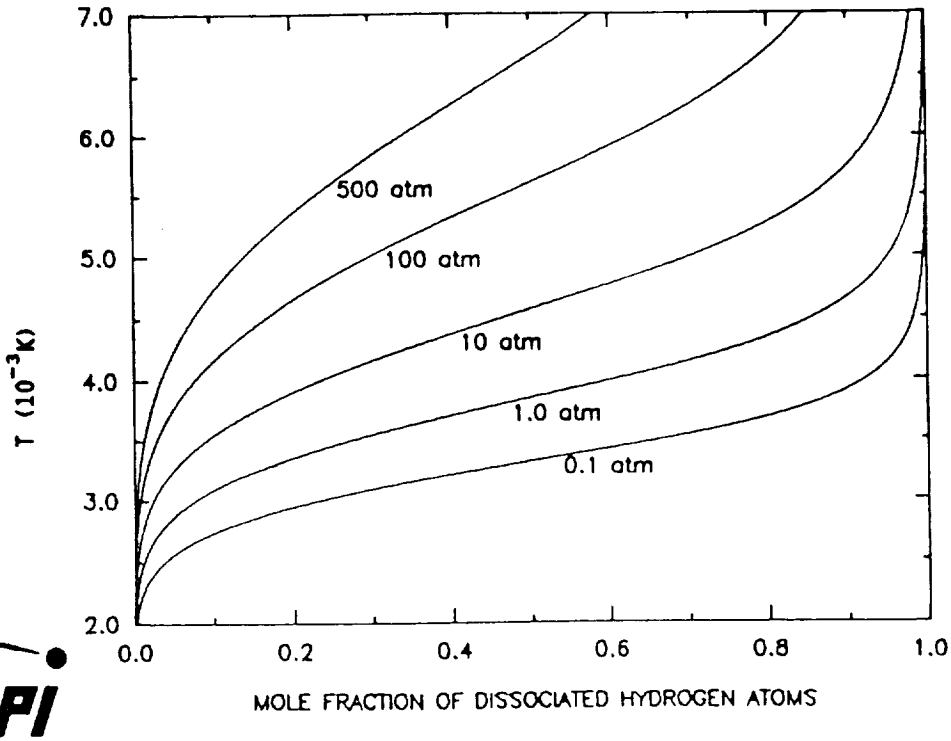

Figure 7

INNOVATIVE NUCLEAR SPACE
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NEW MATERIAL TECHNOLOGY

REQUIREMENTS: SUPERIOR THERMAL CAPABILITIES AND ULTRAHIGH TEMPERATURE MECHANICAL PROPERTIES

SINGLE CRYSTAL TUNGSTEN, W

SINGLE CRYSTAL TANTALUM, Ta

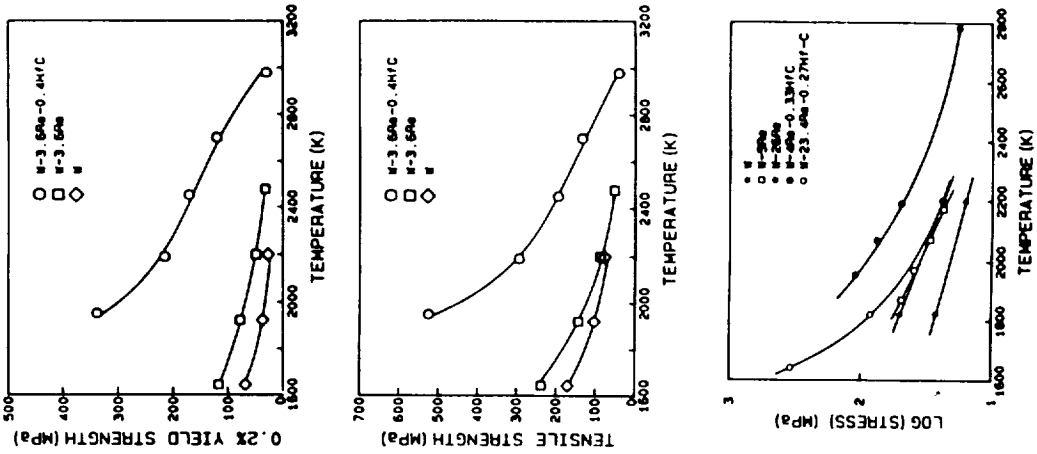
GLOSSY CARBON (~1% POROSITY)

W-Re-HfC ALLOYS (W-3.6Re-0.4HfC, W-4Re-0.33HfC, T_M ~ 3700K)

W-ThO_2 ALLOYS (W-1ThO_2, W-2ThO_2)

T-222 (Ta-10W-2.5Hf-0.01c)

Figure 8



COMPARISON OF THE YIELD STRENGTH, TENSILE STRENGTH AND CREEP STRENGTH OF W-BASE ALLOYS

Figure 9

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE

DROPLET CORE NUCLEAR ROCKET (DCNR)

1. DROPLET FUEL AND PROPELLANT ARE INTIMATELY MIXED.
   - ★ ENERGY TRANSFER SURFACE AREA DENSITY (>10^6 M^2/M^3)
   - ★ ABOUT 1/2 OF FISSION ENERGY IS DIRECTLY DEPOSITED TO PROPELLANT.
   - ★ DROPLET FUEL PROVIDES MORE THAN 3 ORDERS OF MAGNITUDE IMPROVEMENT ON HEAT TRANSFER AREA.
2. HIGH PROPELLANT TEMPERATURES AND FLOW RATES WITH VERY LOW FUEL LOSS

   HYDROGEN TEMPERATURES ~ 3000 TO 7000K
   HYDROGEN FLOW RATES ~ 1 TO 1000 KG/S
3. HIGH DEGREE OF NONEQUILIBRIUM DISSOCIATION OF HYDROGEN MOLECULES DUE TO FISSION FRAGMENTS

   ISP = 2000 S (@ T=6000K AND 20% DISSOCIATION/RECOMBINATION)
4. VERY HIGH THRUST-TO-WEIGHT RATIO. (NUCLEAR THERMAL ROCKET, RADIATION SHIELDS AND ASSOCIATED POWER GENERATION SYSTEM)

   THRUST-TO-WEIGHT RATIO = 5 AT 75 KLB (333KN), 1500 MWE
   1.6 (SHIELDED)
5. IMPROVED SAFETY FEATURES
   - ★ IN-ORBIT FUEL LOADING
   - ★ A LARGE PORTION OF RADIOACTIVE FISSION FRAGMENTS LEAVE THE CORE
   - ★ LOW URANIUM LOADING (ABOUT 20 KG IN CORE AND 100 KG TOTAL)

Figure 10

INNOVATIVE NUCLEAR SPACE
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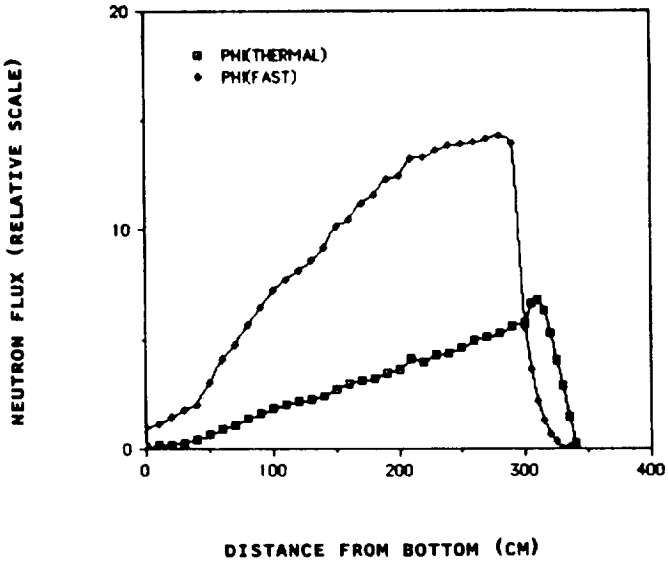

CROSS-SECTIONAL AVERAGE AXIAL FLUX DISTRIBUTION IN DCNR (E_{TH}<1.8EV, E_{FAST}>1.8EV)

Figure 11

INNOVATIVE NUCLEAR SPACE
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DROPLET CORE NUCLEAR ROCKET CHARACTERISTICS

* REDUCES MISSION DURATION TO LESS THAN 200 DAYS

* REDUCES HYDROGEN PROPELLANT CONSUMPTION RATE BY A FACTOR OF 2 TO 3

* SYSTEM DESIGN PARAMETERS

Isp	2000 SEC
ENGINE DIMENSIONS:	
REACTOR I.D./LENGTH	1/3 M
REACTOR O.D./LENGTH	2/4 M
ENGINE LENGTH	13 M
THRUST/WEIGHT (UNSHIELDED)	5
THRUST/WEIGHT (SHIELDED)	1.6

Figure 12

INNOVATIVE NUCLEAR SPACE POWER & PROPULSION INSTITUTE

CRITICAL TECHNICAL ISSUES

* MODELING OF TWO-PHASE FLOW DYNAMICS AND ENERGY TRANSFER
* DROPLET FUEL SEPARATION AND URANIUM LOSS
* HYDROGEN DRIVEN URANIUM SPRAY NOZZLE DESIGN
* RECIRCULATION OF LIQUID URANIUM
* MATERIALS COMPATIBILITY IN ULTRAHIGH TEMPERATURE LIQUID U, LIQUID AND VAPOR Li AND HYDROGEN ENVIRONMENTS (CORROSION, EROSION, INTERGRANULAR ATTACK...)
* ROCKET NOZZLE DESIGN FOR 6000 TO 7000K HYDROGEN ENVIRONMENT OPERATIONS

Figure 13