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PELLET BED REACTOR FOR NUCLEAR PROPELLED VEHICLES: I. REACTOR TECHNOLOGY

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Good afternoon. I am going to talk today about the pellet bed reactor concept. First, I would like to acknowledge my coauthors. Nick Morley is a graduate student now in the process of deciding whether or not to pursue his dissertation in nuclear propulsion. I would like also to acknowledge Bill Haloulakos from McDonnell Douglas. He kindly volunteered to do mission analysis associated with the pellet bed reactor, and he is going to present that analysis today.

Historically the pellet bed reactor concept was developed as part of the Multi-Megawatt Program (MMW). It was a joint project between SAIC and the University of New Mexico. The principle investigators on the project were David Buden and myself; one of the people who did the technical development is here also, Jim Mims from S-Cubed.

Figure 1 is a simple outline of the integration of the pellet bed in the rocket platform, and you can see the reactor, (a hot shield is inside the reactor), a shadow shield, and a bank of propellant tanks. Also, we have the Mars transfer vehicle and the crew compartment; the shield would be optimized between the shadow shield, the hot shield, and also the biological shield.

In this vehicle design we tried to satisfy the five REM per year reactor radiation requirement. This is what the reactor might look like (Figure 2). In the integrated nozzle, the coolant comes in and cools the structure. It also cools the reflector and the structure and then goes to the hot shield, flows down, cools the axial reflector, then flow in the annulus outside the core, flows radially through the core, and then axially down the center. The core is just one annulus. The dimensions for the core give you an idea of size, the diameter is about 70 centimeters and the height is about 1.3 meters. The advantage of this concept is that this kind of reactor is not neutronics limited, so you can increase the height-to-diameter ratio without really causing problems with neutronics.

The critical issue here is the thermal hydraulics. So by reducing the path of the flow we reduce pressure losses. By using pellets, which are about 1 cm diameter, we also increase the surface to diameter ratio.

To give you a point of reference, we can operate at about 3 megawatts per liter, compared to NERVA's 1.8 megawatts per liter. This is less than 4 to 4.3 megawatt per liter at which the particle bed would operate.

The fuel pellets (Figure 3) consist of a graphite matrix, with microspheres dispersed through the matrix. You can adjust the ratio of the fuel to the graphite in your design optimization of the neutronics. We use zirconium carbide coating here to reduce the diffusion of the graphite and interaction with the hydrogen. This is a major problem as some of you are aware. Also there is a problem with the losses of graphite from zirconium carbide. The zirconium carbide here doesn't provide any structural strength, just better compatibility with the hydrogen.

These are just our thoughts about how important the compatibility problem is (Figure 4). Most of the concepts we listened to this morning use hydrogen. There is a similar problem here with hydrogen. It's having graphite and hydrogen for a really long period of time. We didn't have any data that showed they would be compatible for a year or more.

We're using zirconium carbides because it could use a eutectic that would reduce the melting temperature of zirconium carbide by about maybe 20, 30 percent or something like 200-300 degrees. However, it's a good choice compared to niobium carbide because zirconium carbide doesn't lose graphite as fast or doesn't lose as much graphite in contact with hydrogen as niobium carbide.

By chemical vapor deposition, you can apply zirconium carbide close to the operating temperature. During operation you will not have any stress in zirconium carbide. However, the particle will be under compression at startup.

To show you some of the comparison, Figure 5 is the zirconium carbide and niobium carbide in a hydrogen atmosphere at constant temperature, and this graph shows you how much graphite you lose. These data were published by the Soviets at a meeting in May, and show that in the 3,000 to 6,000 second range, you can lose a lot of carbon from niobium carbide compared to zirconium carbide. But as to the effect of these carbon losses on zirconium carbide strength, I haven't seen anything to quantify that, but it remains an issue.

The microsphere is a trisosphere. Because of the fact that with nuclear thermal propulsion, we only operate at very high temperature, then we cannot use uranium-zirconium carbide as was proposed in the original particle bed. What I am proposing here (Figure 6) is using uranium carbide-tantallum carbide, (although I don't like it because of the neutronics, the high absorption concept here for tantallum), or uranium carbide-niobium carbide.

To my knowledge this technology needs to be developed; we know very little about it and it's just the typical try to design to have pyrolytic graphite. The graphite here reacts with niobium carbide, with uranium carbide-niobium carbide, also with uranium carbide and tantallum carbide, and for eutectic. The reduction in temperature here is about 200 degrees in each case. We can still operate at about 3,000 K, which is not the case with uranium-zirconium carbide.

The thickness of the pyrolitic carbon here is about 15 - 20 microns to absorb the damage that will be caused by the fission fragments, It is then surrounded by high density graphite, and also it has niobium carbide or tantallum carbide outer coating; this is really the pressure vessel for the microsphere. The idea here is to retain all the fission gases inside the sphere. The porosity in the fuel as well as in the pyrolitic carbon will provide the means to accommodate these fission gases without much increase in pressure. Of course, the design has yet to be done and optimization for the thickness of different layers have to be done.

An important issue will be how to coat these microspheres (Figure 7). As I said before, it has to be designed to accommodate the stresses due to the buildup of the fission fragments, particularly since you are talking now about five to ten atom percent burnup, which is a high burnup for this kind of microspheres.

Another option or alternative that we will be proposing today is to consider refueling in orbit; we believe that this concept provides the means to refuel in orbit. So you will have to make trade studies such as, designing the reactor to operate to a 5 atom percent burnup and refueling it versus designing the fuel for 10 atom percent burnup and not refueling it. I cannot tell you more about this because it is now in the process of getting patented.

You have seen this graph before (Figure 8), and we think that the operational condition would be in this range shown. And as I said, the zirconium carbide, uranium carbide-zirconium carbide seems out of question for nuclear thermal propulsion because you will not be able to get 3,000 degree Kelvin with it. It might be good for nuclear electric propulsion, but not here. So the only alternative you have is the niobium carbide and tantallum carbide; the temperature here is for the single phase. For the eutectic, just reduce that by roughly about 200 degrees Kelvin; so we are talking about, in this range, maybe 3,500 to 3,700 degrees Kelvin. So if you operate at an exit temperature of about 3,000 degrees Kelvin, the maximum fuel temperature would be 3,100, giving a margin of about 400 to 600 degree Kelvin below the melting temperature.

Figure 9 is just additional information about the different carbides or coatings that you can use to replace the niobium carbide. As I said, we know nothing about niobium carbide, but we do know about silicon carbide. Above 1,800 degree Kelvin you have this amoeba effect where the uranium will diffuse out of the kernel through the silicon carbide; silicon carbide is really out of question above 1,800 K (Figure 10 & 11).

At about 2,000 degrees, you have the same problem with zirconium carbide, so zirconium carbide should not be used above about 2,000 degrees Kelvin. This puts a lot of limitation on whether zirconium carbide would be the choice. And we don't know, with a similar scenario, what will happen with niobium carbide.

In my opinion, at the core of reactor design for nuclear thermal propulsion is the fuel material development. Without the fuel, we cannot build the system. There are a lot of issues dealing with that development that need to be investigated, ranging from compatibility to fabrication, to dealing with new material, with which we have not dealt before.

I will show you some of the results that General Atomic has published as part of their high temperature gas cooled reactors (Figure 12). In this case, horizontally you have uranium carbide in contact with uranium-zirconium carbide. Vertically is uranium content in weight percent. This is the interface, and as you see here, after operating for about 50 hours at about 2,100 Kelvin, the uranium diffuses up to about 45 microns into the zirconium carbide.

At the interface, the content of the uranium is close to 28 weight percent. This is a lot of uranium, because you will have fission, and also you will damage the zirconium carbide. This becomes worse if you operate either for a longer period of time or at a higher temperature.

Here it goes up to 70 percent if you increase the temperature by 200 degrees, so 70 weight percent will be uranium at the interface, and then it will penetrate up to about 1500 microns. If this is not a problem, I don't know what else would be a problem. So this is one issue.

The second issue is in the stress analysis (Figure 13). Recently, we did some work on the thermal stress analysis of the particle bed. In the beginning of the work we had to find out how much we know about the failure pressure of zirconium carbide. The scattering of the data, varies between 300 to 1,000 megaPascal. So to design this kind of microspheres, we really have to get better data on the structure and strength of these materials.

Now, going back to the pellet bed reactor, these are the parameters (Figure 14) that we used in our mission analysis today. The nominal power is 1,500 megawatts thermal. The dimensions for the core are shown. The power density is about 3 megawatts per liter. The diameter of the central channel is about 20 centimeters using hydrogen as coolant. The maximum fuel temperature is 3,100 degrees Kelvin, the maximum core exit temperature 3,000 degrees Kelvin, and the core inlet temperature is 120 degrees Kelvin. The inlet temperature to the reflector is about 70 to 80 degree Kelvin.

The coolant flow rate is 32 kilograms per second. This compares to NERVA's rate of about 24 kilograms per seconds, which makes for the difference in the specific power here. The specific mass for the reactor is 1 kilogram per kilowatt, excluding the shields, which is one ton. There are the two kinds of fuel proposed, pending an investigation, uranium-tantallum carbide -- uranium carbide-tantallum carbide, uranium carbide-niobium carbide. I couldn't find anything that would be better than these materials for these temperatures.

Why should we consider pellet bed reactor (Figure 15)? It is modular. You can build the reactor smaller or bigger. You can have more than one unit. The particle is self-supporting. I consider that an advantage, because it will enable refueling in orbit. We can get high thrust because of high specific power and also high specific impulse because we will be operating at about 3,000 degrees K. Then, it makes full use of the available technology for the fabrication of the particle, again pending knowing more about the fabrication and the high temperature material properties. But in the German-AVR Program we are building similar pellets. The only difference here is that the pellets are optimized for 1 centimeter in diameter, the pellets for the AVR were about 6 centimeters in diameter.

As I said, it provides the possibility for refueling in orbit, which would be a great advantage. I am not proposing a dual mode here, but if the option is to go with nuclear electric propulsion, you can use the same reactor design for that or, if the option is to go to nuclear thermal propulsion, the reactor design could also be used for that.

It is designed so that in a case of loss of flow, the conductive/radiative passive decay heat would be sufficient to cool the system, because of the high thermal conductivity of the graphite.

It has been designed for pulsed and continuous modes of operation. It also has a redundant mechanism for the control. The concept has two independent control mechanism, each of which would be sufficient to operate the system. We have the typical control drums on the periphery of the core and also we have safety rods. We think that it has a relatively low development cost. However, we have to quantify that.

As to the safety features (Figure 16), it satisfies being subcritical during water immersion, assuming that the water fills all the holes inside the core. It has two independent safety systems, 24 control drums and five safety rods, located about 19 centimeters from the center of the core. It could be refueled in orbit. It has passive decay heat removal. The design of the pellet, given that we must further investigate the material and properties, provides a safe containment of the fission fragments. It has a high height-to-diameter ratio, which provides a small cone angle for the shield; this is very important when you look to this to optimize the shield mass.

How long will development take (Figure 17)? My wild guess, is that it will take about 10 to 16 years to flight qualification, at the cost of about $3.1 billion. From what I have seen today, this doesn't look bad at all.

Well, I am running out of time, but you can read Figure 19. I think I covered all of these key issues. This is what I think of the status of technology (Figure 20), except for the fact that we know how to build these reactors. We have been doing that for so many years, as well as we know -- the best choice for shielding. The rest of the technology in between 1 and 3.

BIBLIOGRAPHY

Mohamed El-Genk
Pellet Bed Reactor Concept

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1. Alcoufee, R.E., F.W. Brinkley, D.R. Marr and R.D. O'Dell, "Users guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated Neutral-Particle Transport", Report No. LA-10049-M Rev. 1, UC-32, Los Alamos National Laboratory, Los Alamos, NM (1984).

2. Altseimer, J.H. et al "Operating Characteristics and Requirements for the NERVA Flight Engines", J. Spacecraft, 8(7):766-773 (1971).

3. Bennett, G. "Nuclear Thermal Propulsion Program Overview," NASA Nuclear Thermal Propulsion Workshop, Cleveland, OH 10-12 July, 1990.

4. Durham, F.P. "Nuclear Engine Definition Study Preliminary Report", LA-5044-MS, Vol. I-III, Los Alamos Scientific Laboratory (1972) Los Alamos, NM.

5. El-Genk, M.S., A.G. Parlos, J.M. McGhee, S. Lapin, D. Buden and J. Mims, "System Design Optimization for Multimegawatt Space Nuclear Power Applications", J. Propulsion and Power, (2)"194-202, 1990a.

6. El-Genk, M.S., N.J. Morley, and V.E. (Bill) Haloulakos, "Pellet bed Reactor for Nuclear Propelled Vehicles", NASA Nuclear Thermal Propulsion Workshop, Cleveland, OH 19-22 June 1990.

7. El-Genk, M.S. "Pellet Bed Reactor Concept for Space Propulsion", NASA Nuclear Electric Propulsion Workshop, Pasadena Convention Center, Pasadena, CA 19-22 June 1990.

8. Gordon S. and B.J. McBride. "Computer Program for Calculations of Complex Chemical Equilibrium Composites, Rocket Performance Evident Reflected Shocks and Chapman-Jouguet Detonations", NASA SP-273, NASA Lewis Research Center, Cleveland, OH, March 1976.

9. Haloulakos V.E. and C.B. Coehmer. "Nuclear Propulsion: Past, Present, and Future", McDonnell Douglas paper No. MDC H2642, Trans. 5th Symposium on Space Nuclear Power Systems, CONF-880122-SUMMS, Albuquerque, NM, 11-14 January 1988.

10. Nabielek, H. et al. "Fuel for Pebble-Bed HTRs", J. Nuclear Engineering and Design, 78:155-166, (1984).

11. Stansfield, O.M., F.J. Noman, W.A. Simon, and R.F. Turner. "Interactions of Fission Products and SiC in TRISO Fuel Particlea: Limiting HTGR Design Parameter", Report No. Ga-A17183-UC-77, General Atomis Technologies, San Diego, CA, U.S. Dept. of Energy, San Francisco, CA, 1983.

12. El-Genk, M.S., N.J. Morley, and V.E. (Bill) Haloulakos, "Pellet Bed Reactor for Nuclear Thermal Propelled vehicles", Proceedings of 8th Symposium in Space Nuclear Power Systems, 6-10 January 1991, Part 2, pp. 607.

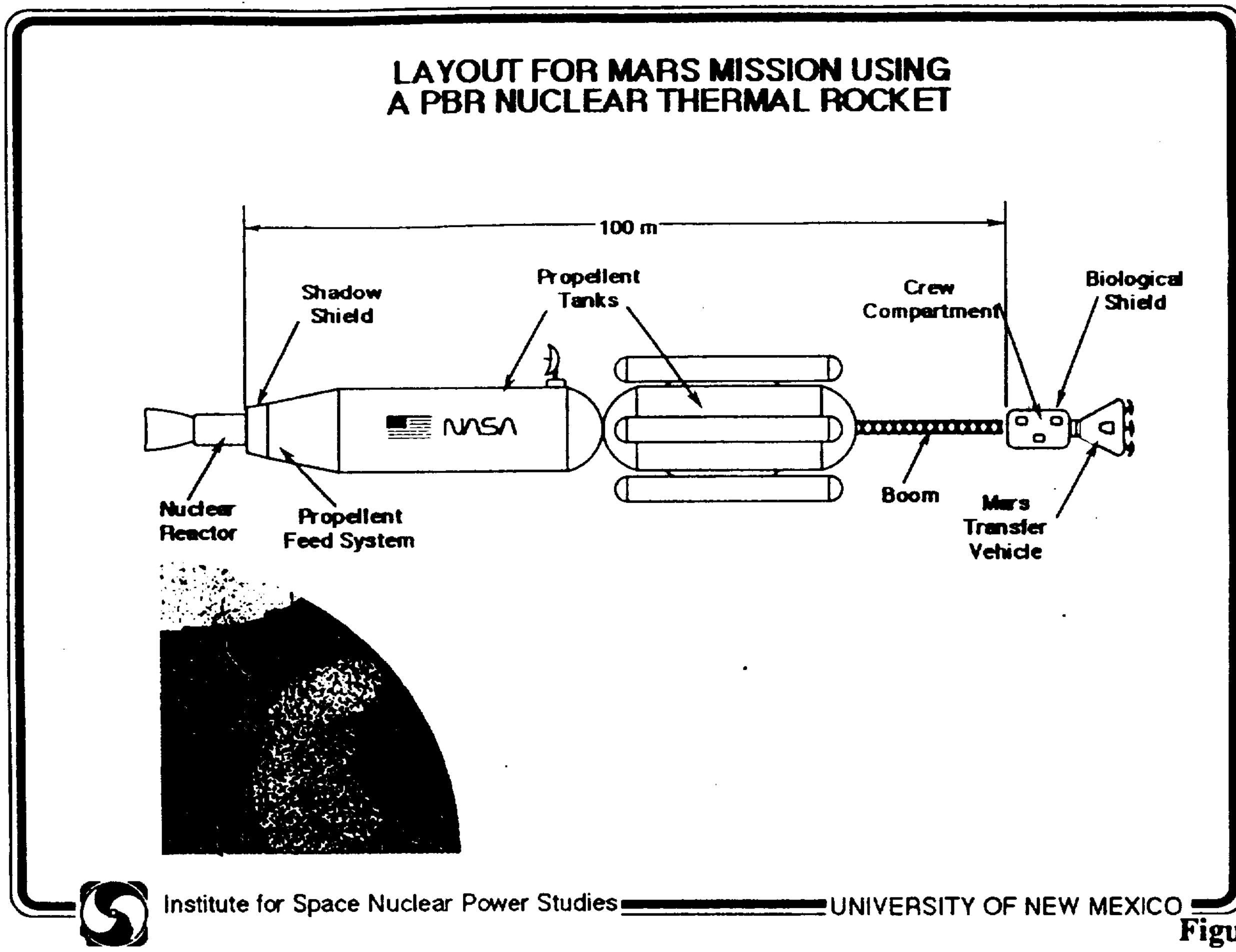

Figure 1

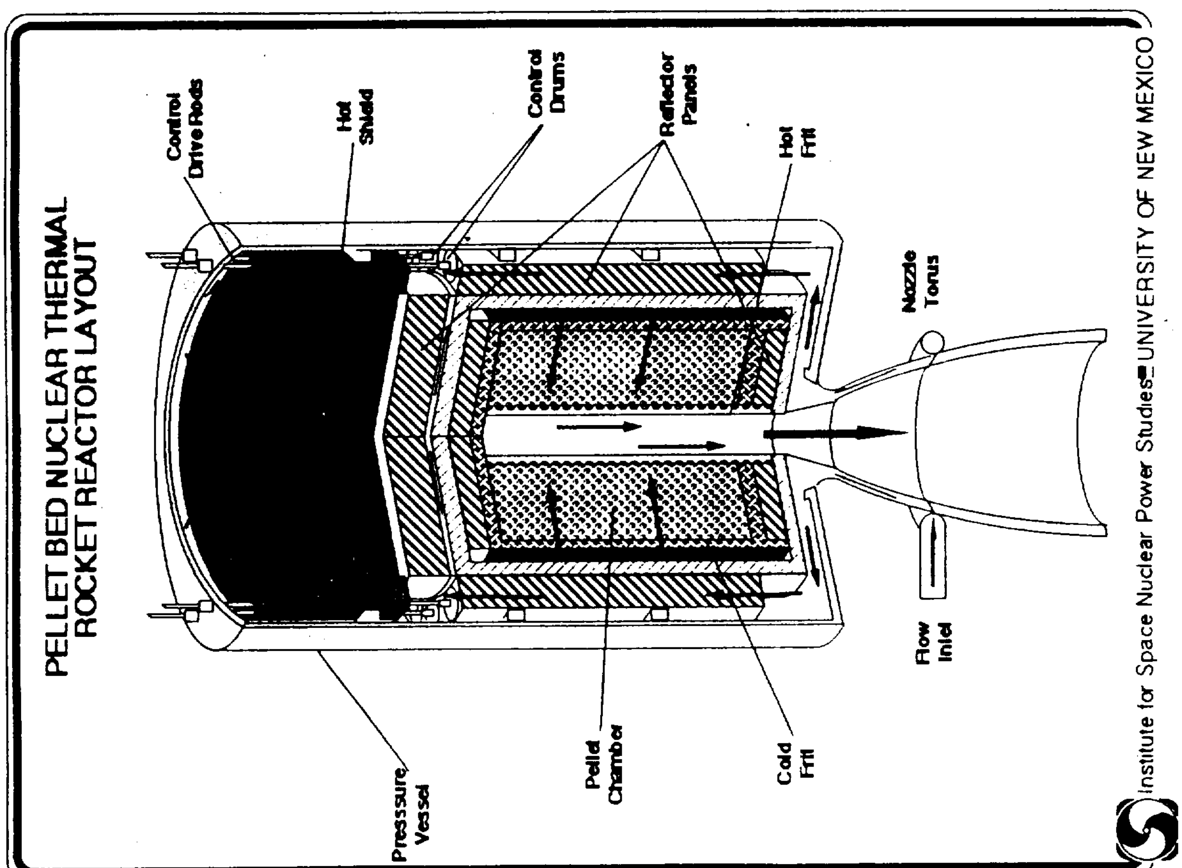

Figure 2

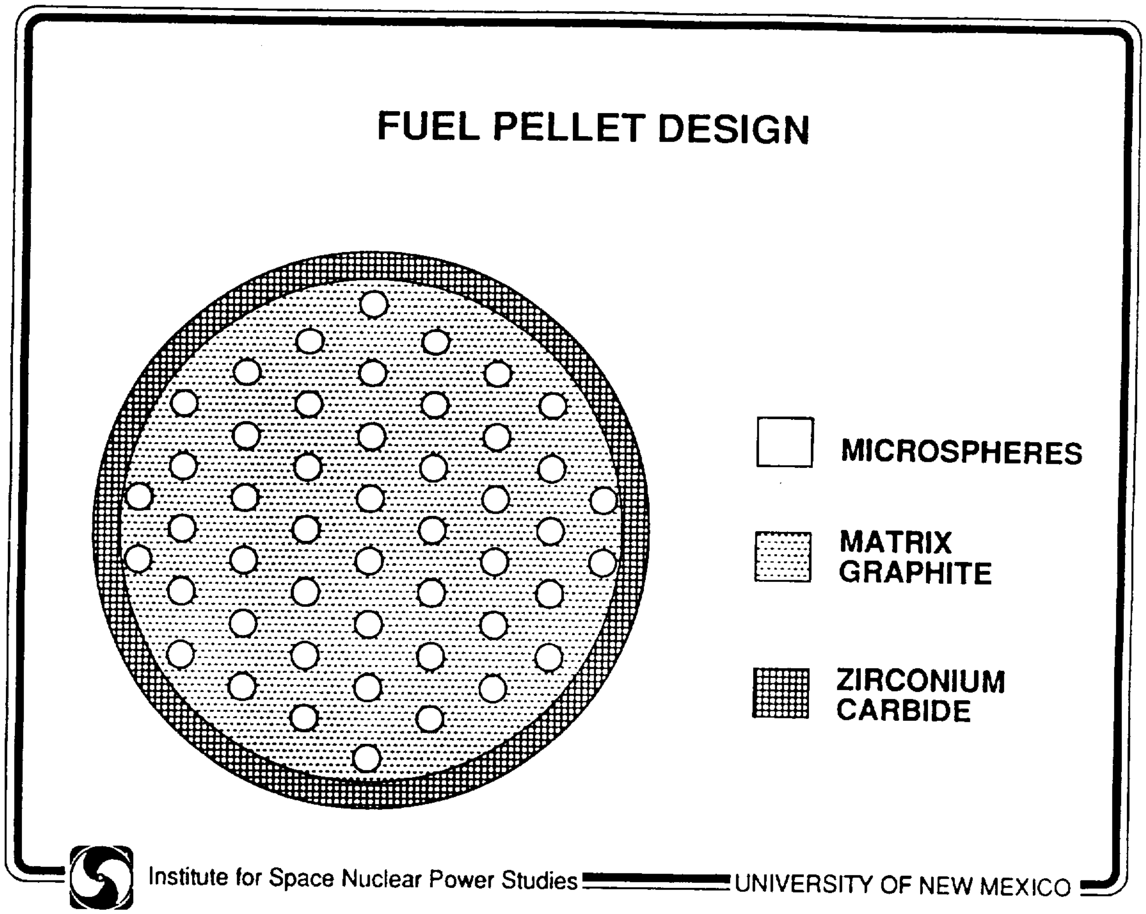

Figure 3

MATERIAL COMPATIBILITY

HYDROGEN-GRAPHITE REACTION

- HYDROGEN COOLANT REACTS WITH GRAPHITE AT HIGH TEMPERATURES TO FORM:
  - -- METHANE
  - -- OTHER HYDROCARBONS
- THESE REACTIONS CAUSE CONTINUOUS LOSS OF GRAPHITE FROM THE FUEL PELLETS.
- A SOLUTION TO SLOWDOWN THE GRAPHITE LOSSES IS TO COAT THE FUEL ELEMENTS WITH A THIN LAYER (FEW MICRONS THICK) OF ZrC.
- ZrC COATING IS A GOOD CHOICE BECAUSE:
  - -- HYDRIDING OF ZrC IS NEGLIGIBLE AT INTERMEDIATE -TO- HIGH TEMPERATURES (<2500K), BUT INCREASES WITH TEMPERATURE.
  - -- DIFFUSION COEFFICIENT OF GRAPHITE IN ZrC IS SMALL, HENCE SLOWING DOWN GRAPHITE LOSSES.
  - -- ZrC CAN BE APPLIED AT OR NEAR OPERATING TEMEPRATURE OF THE FUEL ELEMENTS, THUS ELIMINATING THERMAL STRESSES IN THE COATING DURING REACTOR OPERATION.
  - -- ZrC IS A BETTER CHOICE OVER NbC BECAUSE OF ITS EXCELLENT ADHESION PROPERTIES TO GRAPHITE; LOWER NEUTRON ABSORPTION; AND LOWER CARBON LOSSES AT HIGH TEMPERATURES IN HYDROGEN.

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Figure 4

VARIATION OF ZrC AND NbC COMPOSITION IN HYDROGEN

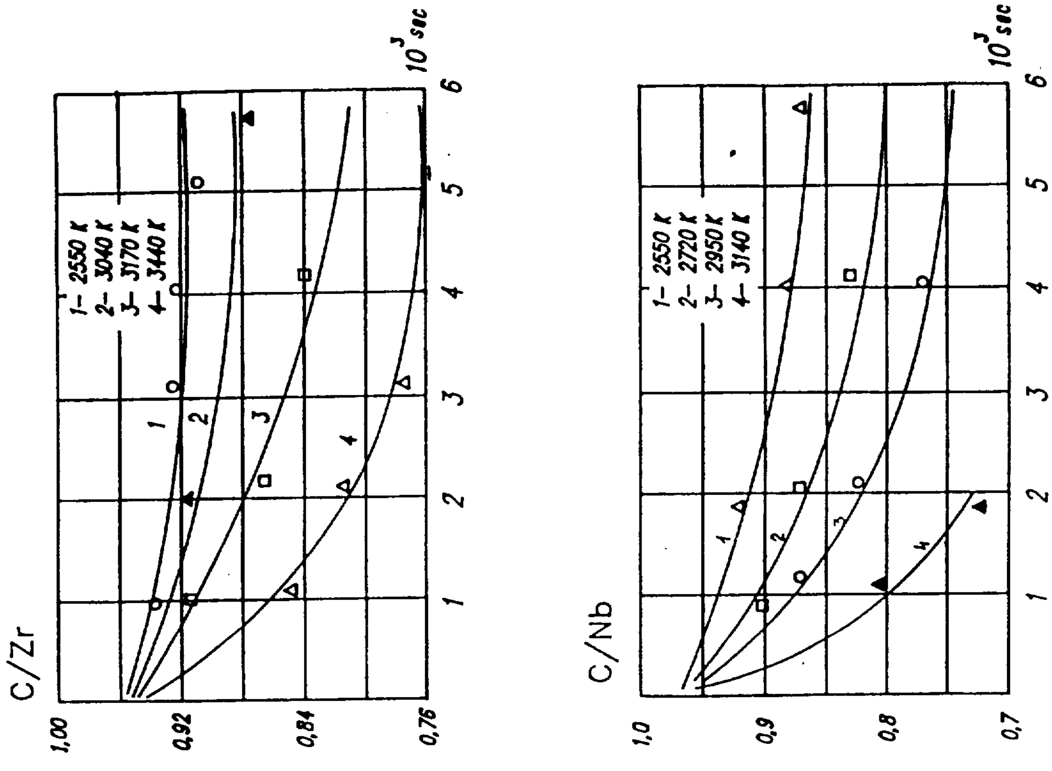


Figure 5

FUEL MICROSPHERE FOR PELLET BED NUCLEAR THERMAL ROCKET

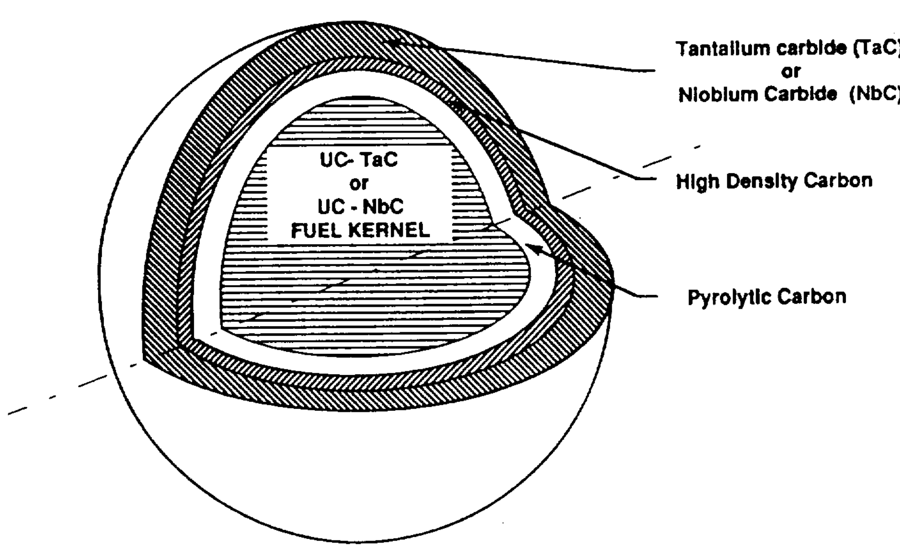


Figure 6

COATING AND FUEL MATERIALS IN MICROSPHERES

COATING DESIGN

IN DESIGNING A FUEL MICROSPHERE, IT IS IMPORTANT TO CHOOSE A COATING THAT HAS:

- COMPARABLE THERMAL EXPANSION COEFFICIENT TO THAT OF THE FUEL
- A THICKNESS GREATER THAN THE FISSION PRODUCT RECOIL RANGE
- STRONG ENOUGH TO ACCOMODATE STRESS DUE TO FISSION PRODUCT BUILDUP
- HAS HIGH THERMAL CONDUCTIVITY FOR REMOVING HEAT FROM THE FUEL MICROSPHERE

Figure 7

MELTING POINTS IN QUASIBINARY SYSTEMS UC-ZrC, UC-NbC, AND UC-TaC

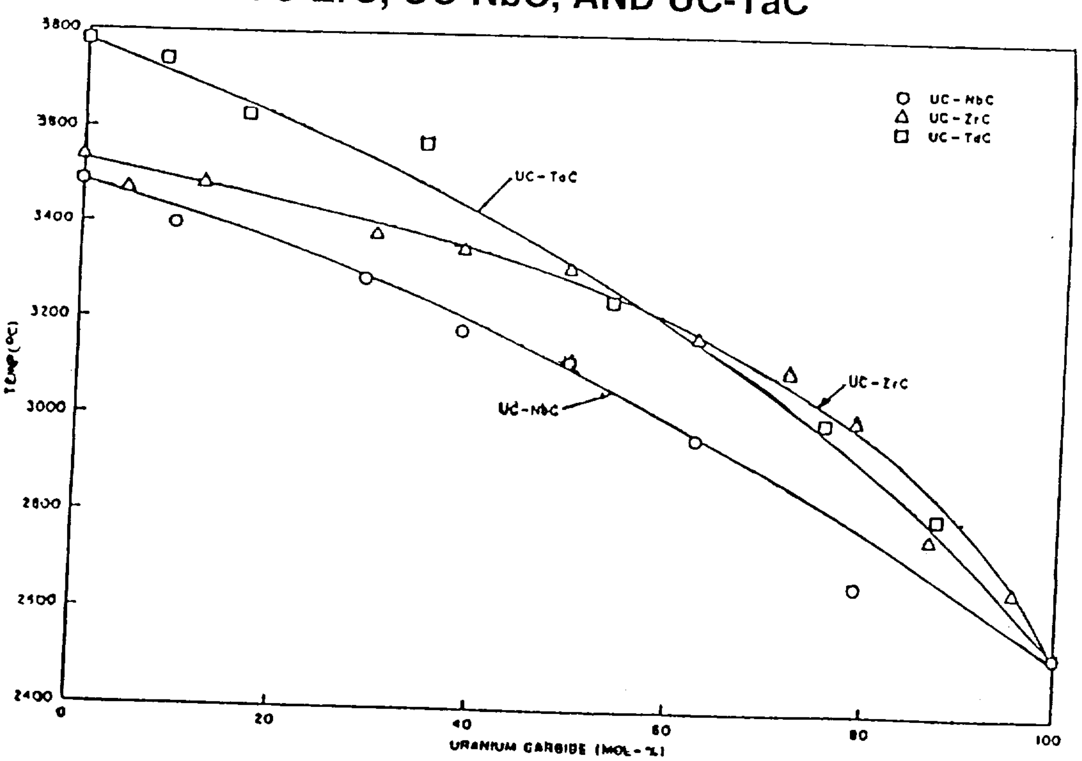


Figure 8

COATING PROPERTIES

COATING COMPOUND	DENSITY (g/cm^3)	THERMAL CONDUCTIVITY (W/cm K) @ 1600 K	FISSION FRAGMENTS RANGE (μ m)	THERMAL EXPANSION COEFFICIENT x 10^6 (K^{-1})
C	3.01	.357	10	3.0 - 5.07
SiC	3.21	.30	11	10.2
ZrC	6.40	.38	9	6.3 - 8.5
NbC	7.32	.721	7	7.1 - 9.0

Figure 9

MATERIALS COMPATIBILITY (CONTINUED)

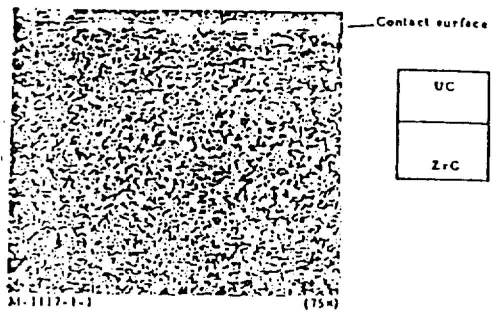
(2) DIFFUSION OF U THROUGH ZrC COATING

- THERE HAS BEEN EVIDENCE TO SHOW THAT THE UC FUEL, WHEN HEATED ABOVE 2073 K URANIUM WILL MIGRATE THROUGH THE KERNEL AND INTO THE ZrC LAYER . THIS MIGRATION WILL CAUSE FISSIONING IN THE ZrC LAYER LEADING TO ITS DESTRUCTION AND FAILURE OF FUEL MICROSPHERES.

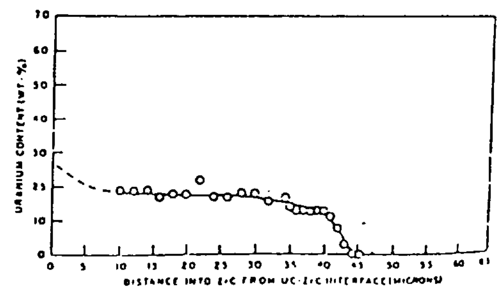
- THE RATE OF URANIUM MIGRATION AND ITS PENETRATION DISTANCE INTO THE ZrC COATING IS A STRONG FUNCTION OF TEMPERATURE AND THE TIME-AT-TEMPERATURE.

Figure 10

MIGRATION OF U FROM UC FUEL INTO 45 MICRONS OF ZrC WHEN IN CONTACT FOR 50 HOURS AT 2073 K



ZrC contacted with UC at 1800° ±20°C for 50 hr. Note that there is no apparent change in microstructure.



Electron-microprobe trace of uranium penetration into ZrC

Figure 11

MIGRATION OF U FROM U FUEL IN 1300 μm LAYER OF ZrC WHEN IN CONTACT FOR 30 HOURS AT 2273 ± 20 K (CONTINUED)

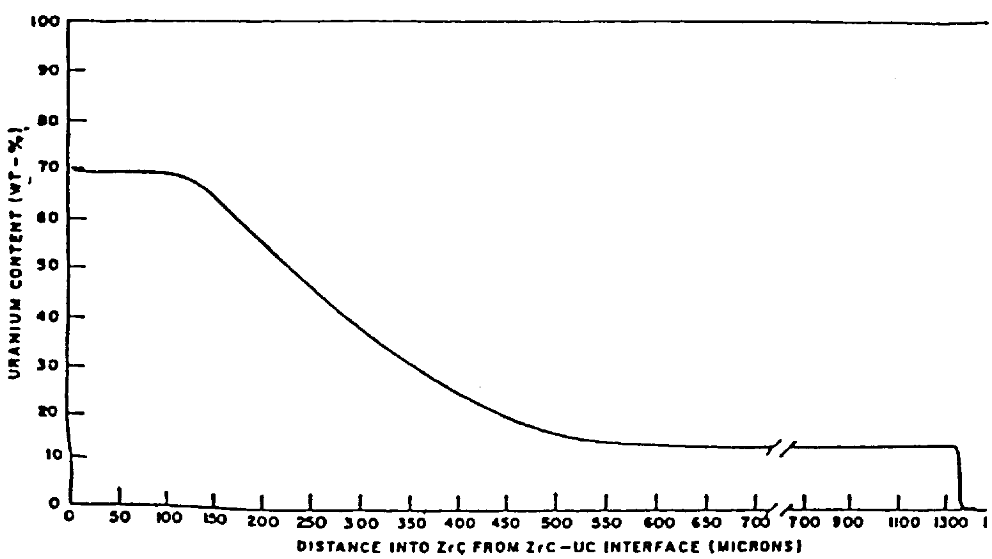


Figure 12

STRESS ANALYSIS OF MICROSPHERES

- TOTAL STRESS INDUCED IN MICROSPHERES = STRESS DUE TO BUILDUP OF FISSION GASSES, VOLATILES, AND SOLID FISSION PRODUCTS +THERMAL STRESS

- STRESS DUE TO FISSION PRODUCTS BUILDUP:
  - ACCOMODATION OF SOLID FISSION PRODUCTS REDUCES POROSITY OF THE FUEL MATRIX
  - FUEL CONSUMPTION BY FISSION INCREASES THE POROSITY OF THE FUEL MATRIX
  - THE NET POROSITY IN BOTH THE FUEL AND LOW DENSITY GRAPHITE COATING DETERMINE THE PRESSURE BUILDUP IN THE FUEL MICROSPHERES AS A FUNCTION OF BURNUP AND OPERATING TEMPERATURE
  - PRESSURE BUILDUP IS PROPORTIONAL TO THE STRESS INDUCED ON THE COATING

- THERMAL STRESSES ARE SMALL SINCE THE COATING PROCESS OF THE MICROSPHERES WILL BE PERFORMED AT ALMOST THE SAME TEMPERATURE AS THE FUEL OPERATING TEMPERATURE

Figure 13

PELLET BED REACTOR CONCEPT/NTP

CORE PARAMETERS

Rated Reactor Power (MWt)	1,000
Core Diameter (m)	0.8
Core Height (m)	1.3
Reactor Core Power Density (kW/cm3)	3.0
Diameter of Central Coolant Channel (m)	0.2
Coolant	Hydrogen
Maximum Fuel Temperature (k)	3,100
Maximum Coolant Exit Temperature (k)	3,000
Core Inlet Temperature (k)	120
Reflector Inlet Temperature (k)	70-80
Coolant Flow rate (kg/s)	32
Specific mass of reactor (excluding shield)* (kg/kWt)	1.0
Fuel Type [m·pt·(k)]	UC-TaC (2,800-3,670**±50) UC-NbC (2,800-3,570**±50)

* Compared to about 3.0 kg/kWt in Rover Program.
** M·pt in equilibrium with carbon; single phase UC-TaC has a higher melting point.

Figure 14

PELLET BED REACTOR CONCEPT/NTP

SAFETY FEATURES

- Subcritical water immersion and compaction.
- Two independent control systems, each capable of maintaining safe operation of the Reactor.

  --24 Control drums (only 20 are sufficient for reactor shutdown).
  --5 Safety Rod Drivers in the core.

- Reactor could be fueled in low earth orbit .
- Passive decay heat removal by radial conduction/radiation to space.
- Fuel pellet design provides for safe containment of fisson products, low thermal gradient (<100 K/cm), and structural integrity.
- High height/diameter ratio of the core provide for small cone angle, thus lower shield mass.
- Orbit Refueling.

Figure 16

WHY PELLET BED REACTOR CONCEPT?

- Modular
- High Specific Power
- High Thrust and Specific Impulse
- Make full use of available technology base (NERVA-German AVR).
- Long lifetime; provide for possibility of in-orbit refueling.
- Could be coupled to any dynamic conversion system of choice (Stirling, K-Rankine, Direct Brayton Cycle) for NEP option.
- High heat capacity and passive decay heat removal.
- Could be used both for pulsed and continuous modes of operation.
- Redudancy in the reactor control mechanism.
- Low Development Cost

Figure 15

PELLET BED REACTOR CONCEPT/NTP

COST ESTIMATE TO BRING TECHNOLOGY TO READINESS BY 2006 TECHNOLOGY FREEZE

PHASE	MINIMUM TIME (YRS)	COST ($M)
Conceptual Design and Technology Issue Resolution	3-5	100
Preliminary design and Component Development	5-7	800
System Ground Demonstration	1-2	1,000
Flight Qualification	1	1,200
TOTAL	10-16	2,100

Figure 17

PELLET BED REACTOR CONCEPT/NTP

KEY FIRST YEAR ACTIVITIES

ESTABLISH ENGINE SYSTEM MODEL

- Operation parameters (flow rate, temperature and pressure)
- Weight
- Critical Mass
- Thrust and Isp
- System redundancy and modularity

SHIELDING AND SAFETY ANALYSIS

- Optimization of biological shield mass
- Criticality Calculations
- Orbit refueling options
- Post-accident heat removal
- Fuel design

ASSESSMENT OF MATERIAL AND FUEL FABRICATION CAPABILITIES

- Fuel Fabricability
- Compatibility with structure materials and hydrogen
- Development of irradiation testing program for fuel burnup up to 10 at.% @ ≥3000 K.

INTEGRATION STUDIES

- Spacecraft-reactor system integration
- Single versus multiple engine option.
- Gas effluent interaction with vehicle structure.

Figure 18

PELLET BED REACTOR CONCEPT/NTP

KEY ISSUES

- Development of high temperature fuel and demonstrate its reliability at high burnup (up to 10 at .%) and high temperature >3000 K.
- High temperature materials compatible with hydrogen.
- High temperature instrumentation.
- Development and demonstration of MMW thrusters with lifetime up to 2 years at up to 3500 K.
- Environmental issues (e.g. CO_2 Mars atmosphere, creep strength at high temperature).
- Autonomous operation and fault detection technology.

Figure 19

PELLET BED REACTOR CONCEPT/NTP

PRESENT TECHNOLOGY LEVEL

TECHNOLOGY	READINESS LEVEL
Fuel	2
Reactor Design	4-5
Core & Structure	3
MW Thruster	1
Reactor Control	3-4
Instrumentation	2-3
Autonomy and Fault Detection	1-2
Shielding	5-6

Figure 20