CONF-850103--14

JAN 29 1986

BNL 37407

HIGH POWER DENSITY REACTORS BASED ON DIRECT COOLED PARTICLE BEDS*

J. R. Powell and F. L. Horn
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973
(516) 282-2440

BNL--37407

DE86 005679

ABSTRACT

Reactor based on direct cooled HTGR type particle fuel are described. The small diameter particle fuel is packed between concentric porous cylinders to make annular fuel elements, with the inlet coolant gas flowing inwards. Hot exit gas flows out along the central channel of each element. Because of the very large heat transfer area in the packed beds, power densities in particle bed reactors (PBR's) are extremely high resulting in compact, lightweight systems. Coolant exit temperatures are high, because of the ceramic fuel temperature capabilities, and the reactors can be ramped to full power and temperature very rapidly. PBR systems can generate very high burst power levels using open cycle hydrogen coolant, or high continuous powers using closed cycle helium coolant. PBR technology is described and development requirements assessed.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

---

*Research carried out under the auspices of the U. S. Department of Energy under Contract No. DE-AC02-76CH00016 from the U. S. Air Force Rocket Propulsion Laboratory.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CW SYSTEM DEPLOYMENT

Radiator Features

- Stainless Steel
- Water Heat Pipe Fluid
- 300 Individual Elements
- Disconnect Attachment
- Central Helium to Heat Pipe Heat Exchanger

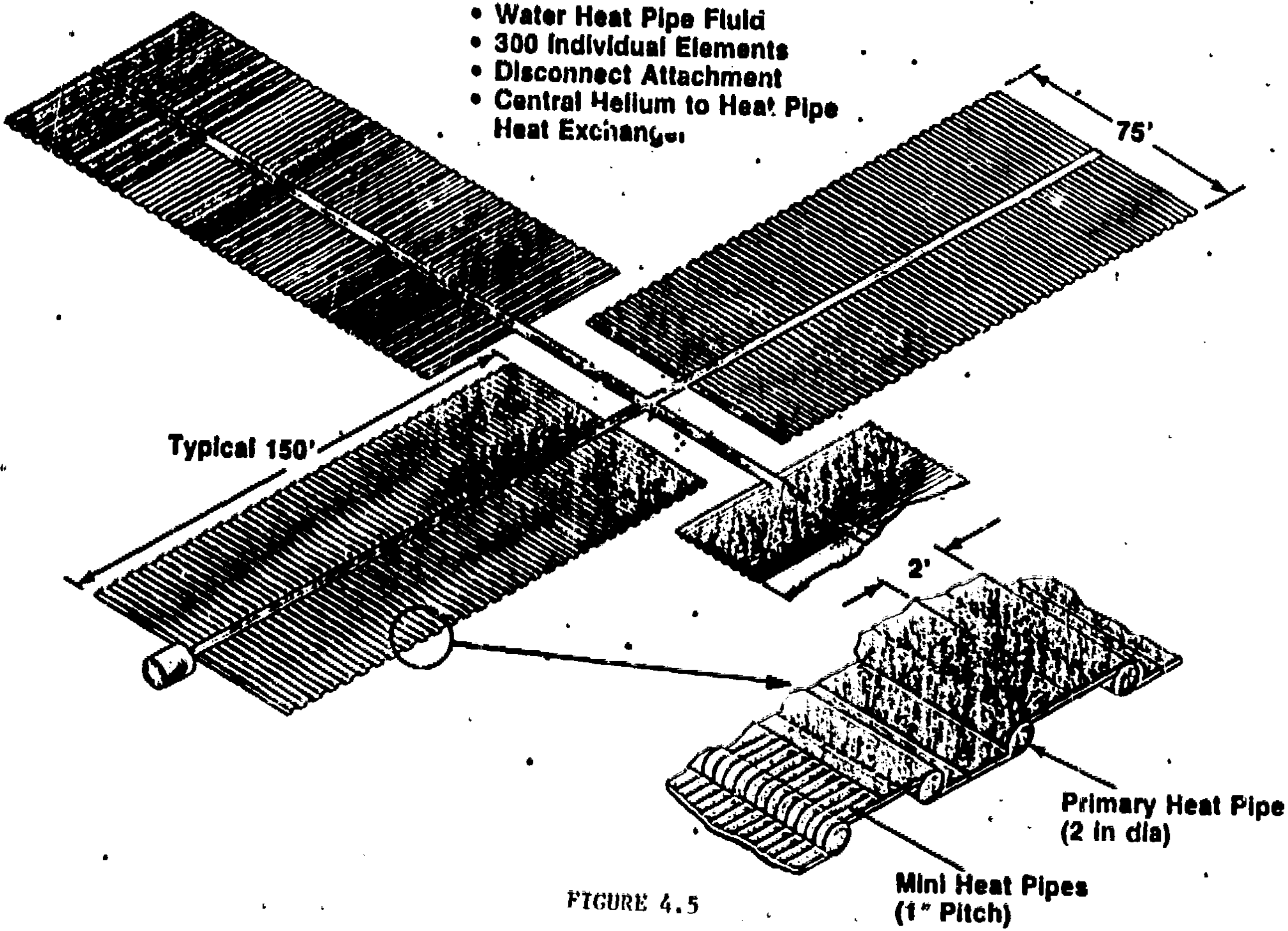

FIGURE 4.5

INTRODUCTION

Particle Bed Reactors (PBR) are very attractive for space based power systems. The PBR uses fuel elements consisting of annular packed beds of small diameter HTGR type fuel particles (typically about 500 microns in diameter). Inlet coolant gas flows radially inwards through each annular bed (Figure 1.1) element, emerging as a hot gas stream from the central channel.

A number of fuel elements, typically 19 or 37, is assembled to form the reactor core. For most applications, beryllium or metal hydride moderator is placed between the fuel elements, resulting in a thermal spectrum. For high power CW applications the moderator is eliminated, leaving only close packed fuel elements. Here the reactor has a fast spectrum.

Typically, PBR fuel elements have diameter of 2 to 3 inches, and core diameters in the range of 1 to 2 feet.

The extremely large heat transfer area in the packed bed (on the order of 100 cm^2/cm^3 of bed) and the small fuel particle size results in three major benefits:

1. Very high power densities.
2. Small temperature differences between fuel and coolant.
3. Minimum thermal stress and shock in the fuel.

Thermal power densities in the packed bed can be 10 $kilowatts/cm^3$ and higher, because of the large heat transfer area. The temperature difference between the fuel particles and coolant is small, even at high power densities, on the order of a few tens of degrees kelvin.

The small particle size results in low thermal stress and fast start ability. Tests have demonstrated the capability of packed beds to repeatedly withstand temperature changes on the order of 1000 kelvin per second without damage, allowing reactors to startup very rapidly.

The power densities and reactor startup capabilities outlined above for PBRs cannot be matched by reactors with conventional fuel pin elements. Conventional reactors simply do not possess sufficient heat transfer area, and the large element size dictates a slow rate of temperature change to prevent excessive thermal stress and cracking.

In addition, the fuel particles are composed of materials that can withstand extremely high temperatures — in excess of 2000 K for short term (hours) intermittent power systems, and in excess of 1500 K for long term (years) continuous power systems.

Finally, fission products are completely retained inside the particle, even for long term applications. A minor portion of the particles can fail after long term (years) exposure, letting a small fraction of fission products escape. The failure rate is very low, however. Typically less than 1 particle in 10^4 fails; with improved quality control, failure rate can probably be reduced to 1 in 10^5.

PARTICLE BED REACTORS

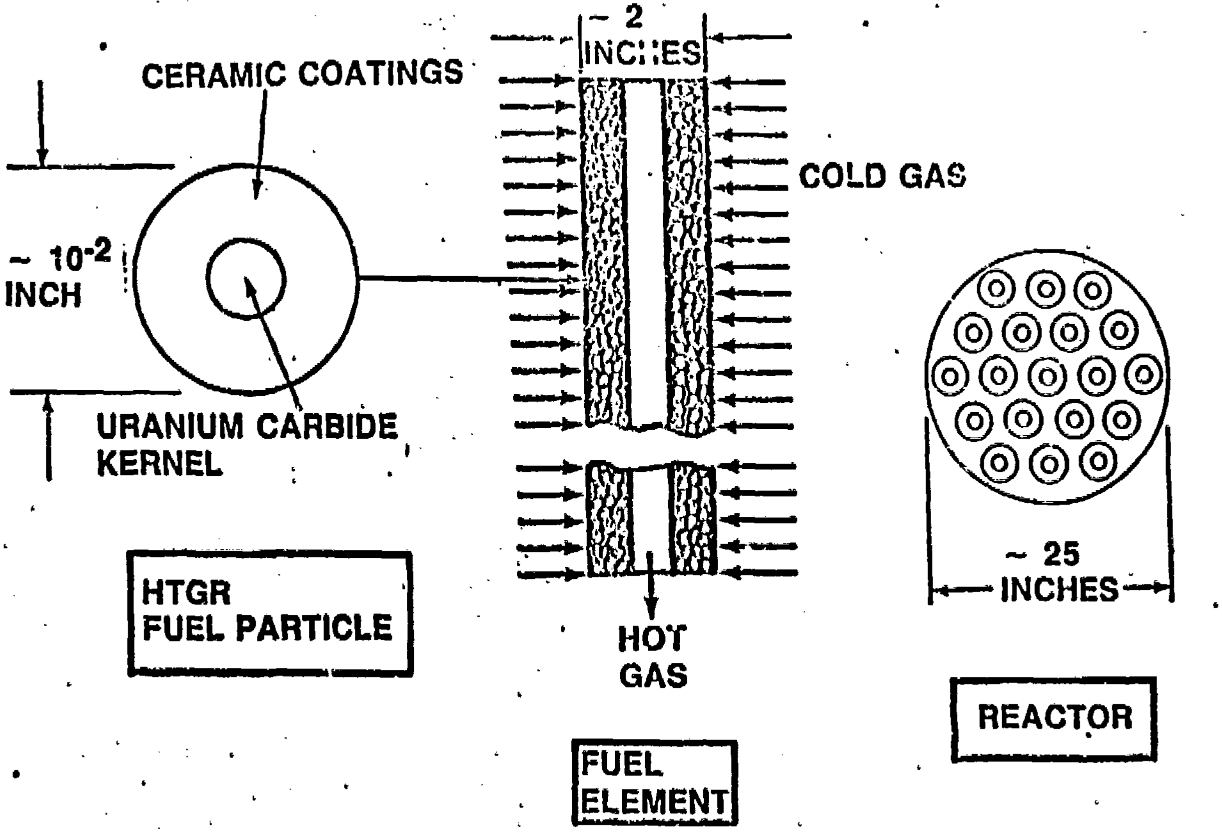

FIGURE 1.1

0347-001

Figure 1.2 shows the general types of PBR space power systems. These systems are discussed in more detail in the following sections. The important point is that these systems, though very different in power level and operating time, essentially share a common reactor technology. For example, the fuel particle coating may be different for continuous and open cycle systems, but the fabrication techniques are basically identical. Construction of the various reactor systems is very similar.

The main differences between systems are in the power conversion and radiator components.

PARTICLE BED TECHNOLOGY

Figure 2.1 shows a detailed view of the particle bed fuel element. The cool incoming gas first passes through channels in the moderator matrix around the elment, removing neutron and gamma heat deposited in it.

If beryllium is used, cooling channels can be cut directly in the moderator structure. If a metal hydride moderator is used, for example zirconium hydride or lithium-7 hydride, it must be canned to prevent hydrogen loss to the coolant. The canned moderators would be sectionalized, with grooved surfaces between the sections serving as the coolant channels.

The inlet coolant first flows to a thin (approximately 1 millimeter in thickness) annular plenum around the outer surface of the fuel element then flows radially inwards through the element.

The fuel particles are packed between two concentric porous cylinders. These allow gas to readily flow through, but firmly hold the particles in place. There is no motion of the particles and no rubbing or abrasion.

The cylinders, termed "frits," have a multitude of small holes on the order of 100 microns in diameter. The particles are larger, typically about 500 microns in diameter. Gas flows freely through the frits and packed particle bed, without obstruction.

Both metallic and non-metallic frits are possible, and they can be manufactured by various techniques. The frit can be fabricated by powder metallurgy techniques. Powder would be first pressed into a porous cylinder, followed by partial sintering at high temperature and pressure. Both metallic and non-metallic frits are routinely made for the chemical industry by this method.

FIGURE 1.2

Particle Bed Reactor Power Systems

PARTICLE
BED
REACTORS

Moderate Continuous Power

- Power to ~1 megawatt(e)
- years lifetime
- He or He/Xe cooled closed cycle
- Deployable heat pipe radiators
- Existing reactor and power conversion technology
- Thermal reactor

Burst Power

- Very high power
- Fast start
- H_2 cooled open cycle
- Multiple or single pulse
- Operating time determined by H_2 supply
- Thermal reactor

Multi-Megawatt Continuous Power

- High Power
- years lifetime
- He or He/Xe cooled closed cycle
- Space erectable heat pipe radiators
- Existing particle fuel
- Turbine and radiator require development
- Fast reactor

Bimodal Power

- Single reactor
- Operates in He/Xe continuous closed or H_2 open cycle burst mode
- Very high power in burst mode
- Moderate power in continuous mode
- Thermal reactor
- Switches modes in several seconds
- Separate power conversion units for different modes

BASELINE FUEL ELEMENT & MODERATOR BLOCK

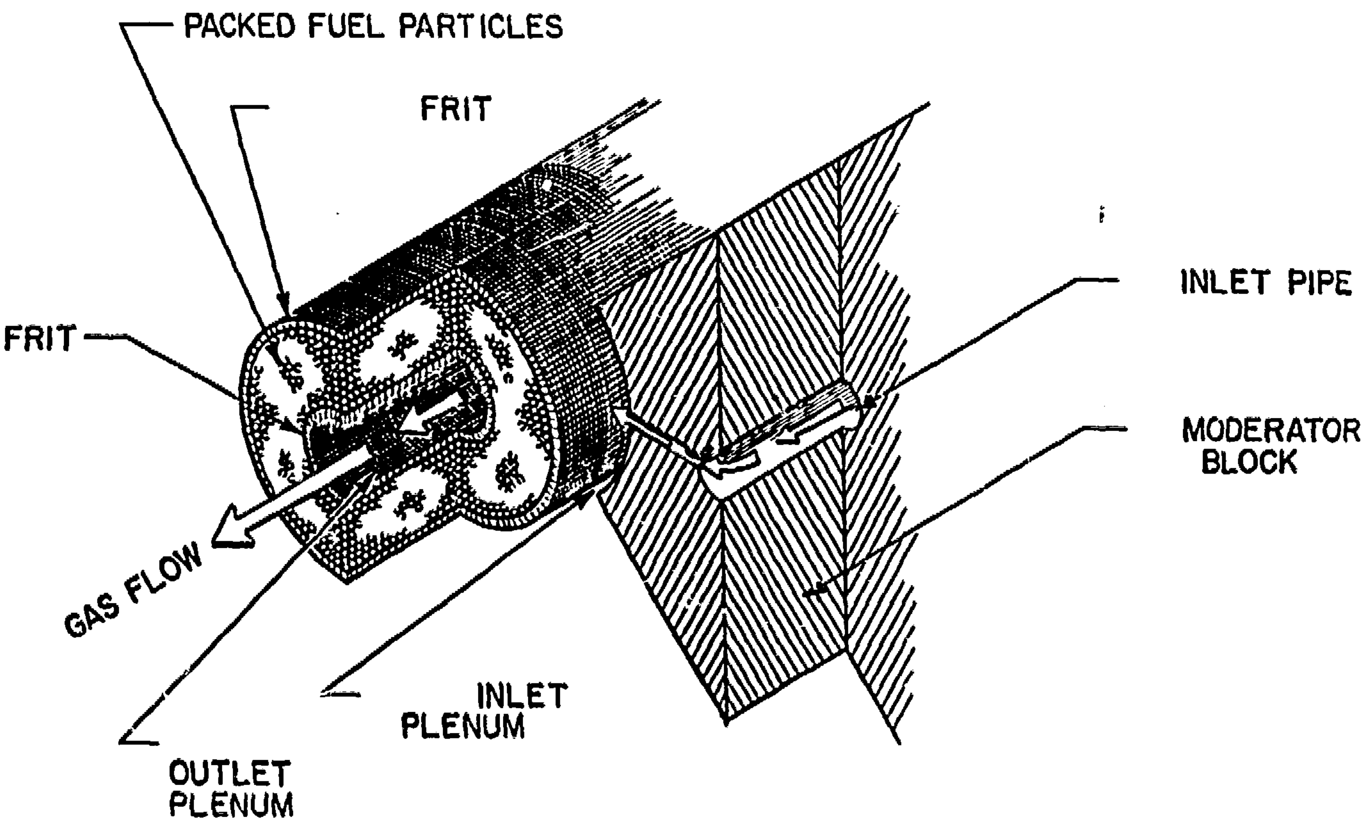

FIGURE 2.1

Another technique suitable for metallic frits is to wind several layers of wire on a mandrel cross winding the layers to obtain the desired porosity. Partial sintering at elevated temperature and pressure then produces a rigid, low pressure drop structure with the strength of the parent metal.

A third technique, suitable for both metallic and non-metallic frits, is to fabricate a solid non-porous cylinder of the appropriate thickness, and then drill the desired pattern and size of holes through the wall. Various drilling methods can be used, including lasers, mechanical drill, and spark discharge machining.

For most PBR applications, both open and closed cycle, the cool outer frit can be stainless steel or Inconel. Such frits are routinely fabricated, and have high strength and excellent radiation damage resistance. For open cycle power systems, cool frits will operate at near ambient (approximately 300 K) temperatures. For the closed cycle, multi-megawatt power systems, cool frits will operate at a high temperature, on the order of 900 K. This is well within the capability of stainless or Inconel.

For short term applications where minimum critical mass is desired, the cool outer frit can be made of low cross section materials such as beryllium, zirconium, or aluminum.

Cool frit thickness is typically 2 to 3 millimeters. Because of the small ΔP in the element, mechanical stress in the frit is low, several hundred psi at most, and compressive in nature. These stress levels are far below the yield stress, which is on the order of 10^5 psi.

The hot frit operates at the exit coolant temperature, and its material and operating temperature depend on the application. For continuous power outputs up to about 1 megawatt, helium temperature is approximately 1100 K. Inconel hot frits appear excellent for these systems. For burst power systems, rhenium hot frits appear very attractive. Tests at 2000 K have demonstrated that rhenium is unaffected by hydrogen for exposure periods of 10 hours — longer than actual systems are likely to operate. Operating mechanical stress in the hot frit is very low, approximately 100 psi, and compressive in nature. This stress level is two orders of magnitude below the yield stress of rhenium. 2000 K is probably an upper limit for exit temperatures in burst power systems — not because of the particle bed reactor, which can operate at higher temperatures, but because of turbine material limitations.

Rhenium hot frits are also attractive for bimodal systems. In addition to short term exposure to hydrogen, the bimodal hot frit must withstand long term exposure (years) to helium or helium-xenon. These gases are inert, but may contain trace impurities (i.e. oxygen or H_2O) that attack refractory metals. However, initial long term tests (150 hours) of rhenium in impure helium do not show any degradation, even at high impurity levels.

The hot frit in bimodal systems operate at approximately 2000 K in the short term open cycle, H_2 cooled mode, and at approximately 1100 K in the long term closed cycle, He cooled mode.

Finally, rhenium hot frits also appear attractive for continuous multi-megawatt power systems. In these systems, the hot frit is exposed to helium or helium-xenon (with possible impurities) at approximately 1500 K for years.

The operating stress in the rhenium hot frit for the bimodal and continuous power systems is very low, approximately 100 psi, which is far below allowable creep stresses.

There are a number of hot frit options that can be used in place of rhenium, if necessary. Silicon carbide is an attractive possibility, for example. It has excellent radiation damage properties, good resistance to high temperature hydrogen, and will not react with trace impurities in helium. Porous SiC frits are presently manufactured; solid cylinders can also be drilled to form hot frits.

Graphite frits are another interesting possibility. Zirconium carbide or other types of coatings would provide hydrogen protection in open cycle systems (as was done for the ROVER fuel elements); uncoated graphite would be suitable for pure closed cycle systems.

In general, there is a wide range of promising candidate hot frit materials and configurations, and it does not appear that this is a go-no-go issue.

Figure 2.2 shows present commercial types of HTGR fuel particles. The bottom particle is a "burner" particle, with a central kernel of highly enriched (93.5% U^{235}) fissile fuel. The kernel can be uranium oxide, carbide, or oxy-carbide.

Surrounding the fissile kernel is a porous layer of pyrographite, followed by several layers of pyrographite and silicon carbide. Fission product gases (i.e. krypton and xenon) collect in voids in the porous layer and kernel. The outer layers of the particle act as a minature pressure vessel, holding all of the fission products (including the gases) inside the particle. Particle failure rate is extremely low, about one in 10^4, even at very high burnup (e.g. 50%) of the central kernel. [With more stringent quality control of particle, the failure rate could be substantially reduced, possibly to one in 10^5].

In HTGR's, the burner particles are imbedded in large blocks or balls of graphite, which are then handled as the fuel elements. Heat generated in the particles flow out through the graphite blocks or balls to the coolant.

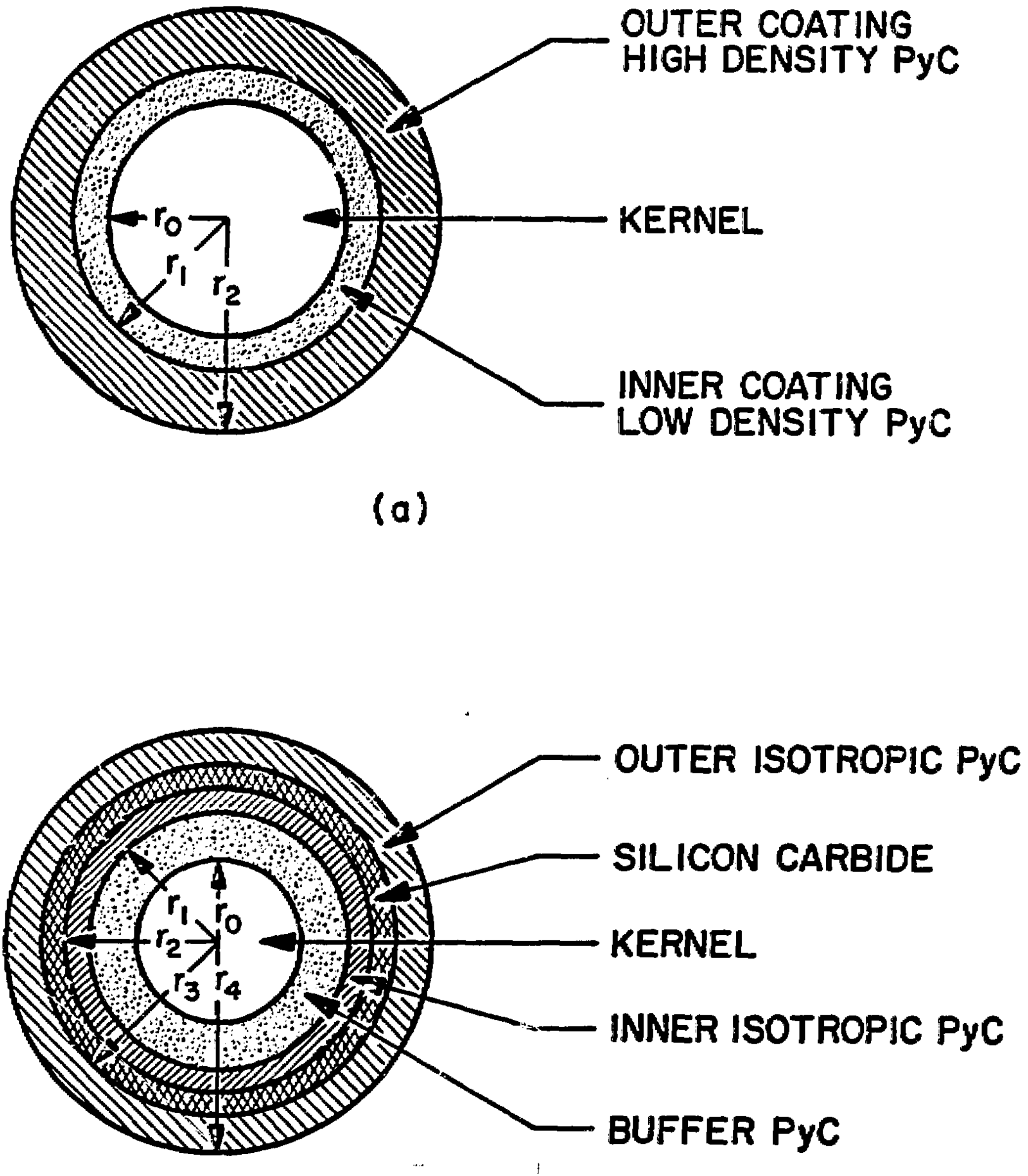
OUTER COATING
HIGH DENSITY PyC
KERNEL
INNER COATING
LOW DENSITY PyC
r_0
r_1
r_2
(a)
OUTER ISOTROPIC PyC
SILICON CARBIDE
KERNEL
INNER ISOTROPIC PyC
BUFFER PyC
r_0
r_1
r_2
r_3
r_4

FIGURE 2.2

(b)

Fission product release is prevented by the particle layers, not the graphite matrix. The PBR should retain fission products as well as HTGR's. The principal difference between them is the much larger heat transfer area per unit volume in the PBR, due to the elimination of the graphite matrix.

The top particle in Figure 2.2 is an HTGR "breeder" particle. It has a large kernel of thoria (ThO_2), overlaid with a porous layer of pyrographite (PyC) followed by a full density layer of PyC. In the HTGR, breeder particles are imbedded in the graphite matrix together with burner particles. Neutrons captured in thorium breed U^{233}, which then burns in-situ to sustain reactivity and improve neutron economy.

Fission product release and internal gas pressure in the breeder particle is low, so large kernel and thin coating layers can be used.

PBR's are fully enriched and do not breed. However, pure open cycle systems have very low burnup (<0.1%) and can use simple particles. To resist high temperature hydrogen, the particle coating should be a refractory carbide, such as zirconium carbide. Such particles, though not yet used commercially, have undergone extensive development and testing with excellent results.

For pure open cycle systems, the inner porous pyrographite layer is probably not needed, and a single zirconium carbide coat should suffice. ZrC particles of the same size as actual fuel particles were exposed to 2000 K hydrogen for 10 hours. No weight loss could be detected (limits for detection were <0.1%). ZrC coated fuel particles thus are a very attractive candidate for open cycle PBR's.

ZrC coated particles are also a leading candidate for bimodal systems. Burnup will be several percent, so that a porous inner layer or a porous kernel is probably required to prevent excessive pressure buildup. ZrC coated particles have been tested at high burnup (approximately 50%) and high temperature (approximately 1800 K) for approximately 6 months. Results were good, with low particle failure rate.

Conditions on bimodal particle fuel are not appear as stressing as the already achieved performance. The particles operate at relatively low temperatures (approximately 1100 K) for years in helium, with relatively low burnups (several percent). When the system switches to the high power H_2 cooled mode, the operating temperature increases to approximately 2000 K, but the exposure time is extremely short. It appears likely that ZrC coated particles will be satisfactory.

Present commercial type HTGR fuel particles are suitable for the closed cycle continuous PBR power systems. For power levels up to about 1 MW(e), maximum particle temperature is 1150 K (1600 F), well below present demonstrated fuel capability. For multi-megawatt systems, outlet particle temperature is approximately 1500 K, comparable to the maximum particle operating temperature now experienced in HTGRs.

The 1150 K regime is compatible with existing superalloy turbine technology, but the higher (1500 K) regime will require development of ceramic turbines. The switch to the higher temperature regime is dictated by the need to minimize radiator area. For the lower temperature PBR cycle optimum system weight is achieved with a specific radiator area of about 1 m^2/KW(e). Increasing turbine inlet temperature to 1500 K reduces optimum specific radiator area to 0.3 m^2/KW(e). [For comparison, the specific radiator area of SP-100 is 0.6 m^2/KW(e)].

For sub-megawatt applications, the radiator area appears acceptable, and compatible with a folding deployable radiator. For multi-megawatt applications, however, deployable radiators probably are not practical. At these high power levels the Grumman space constructable radiator (discussed in a subsequent section) appears necessary.

The 1150 cycle would use the deployable heat pipe radiator with stainless steel/water construction materials, while the 1500 K cycle would use the space constructable radiator with liquid metal heat pipes. There is incentive to go to higher cycle temperatures, to further reduce radiator area. Present HTGR fuel probably is not adequate for such operation, however.

Zirconium carbide coated particles, similar to those currently being developed and tested for commercial applications, appear promising for higher temperature PBR's. Operation at 1800 K has been demonstrated. Ultimately, temperature capabilities of approximately 2000 K may be achievable for long term continuous power systems.

PBR thermal hydraulic technology comprises three areas:

1. Power density capability in packed beds.
2. Coolant flow and power distribution control.
3. Ramp temperature/power capability.

A variety of experiments and analyses have been carried out of PBR packed bed heat transfer. Using high temperature electrically heated particle beds, steady state power densities of 1 megawatt per liter have been demonstrated with low pressure (1 atm) helium coolant. Transient blown down experiments at higher coolant pressure (1000 psi Helium), have demonstrated power densities of approximately 10 megawatts per liter in high temperature particle beds.

Experimental pressure drops and film ΔT's (between coolant and particles) agree with experimental predictions. Typically, pressure drops are on the order of 1 atmosphere and film ΔT's about 100 K in high power density operation.

Figure 2.3 shows predicted pressure drop and film ΔT in a typical PBR fuel element as a function of power density [This element is for an Orbit Transfer Vehicle application, using direct nuclear thrust]. As shown by Figure 2.3 power densities of 10 kilowatts/cm^3 (10 megawatts per liter) or more can be achieved without excessive pressure drop or ΔT.

Coolant and power distribution control are interdependent. In order to minimize local exit temperature variations, coolant flow must be controlled to match local volumetric heat generation rate. This minimizes hot channel factors, so that peak coolant outlet temperatures are close to the mean.

Core power distribution can be made flat by zoning of the fuel loadings in the PBR fuel elements. The fuel particles are mixed with inert particles of the same size and composition to give the desired local loading. Two dimensional neutronic analyses indicate that a four zone loading pattern achieves peak to average power ratios below 1.1/1, both radially and axially.

Coolant flow can be controlled to compensate for radial variation in power density using simple orificing methods (Figure 2.4A). To compensate for axial variations in power density, coolant flow resistance through the outer cool frit is locally controlled (Figure 2.4B). The cool outer frit is made to have the major portion of total core ΔP by minimizing pore area and size. By appropriately changing local flow resistance, the correct amount of coolant then flows through the packed bed.

Local control of flow resistance is readily achieved for drilled frits by varying number of holes. Where high flow is desired, there is a relatively large number of per unit area. Where low flow is desired, there is a smaller number per unit area. For sintered powder or wire frits, pores can be sealed, using E-beam welding or other methods, to give the desired local flow area.

Thermal-hydraulic studies of PBR elements indicate that good flow and temperature control can be achieved even without power distribution flattening. With flattening, hot channel factors should be very close to one.

The third thermal-hydraulic area is rapid power ramps. Packed bed elements (electrically heated and helium cooled) were ramped from 300 K to approximately 1700 K in 2 to 3 seconds without damage to either the particles (700 micron diameter HTGR breeder particles) or the stainless steel frits. This was done repeatedly for dozens of cycles. Particles and frits showed no cracking or other damage.

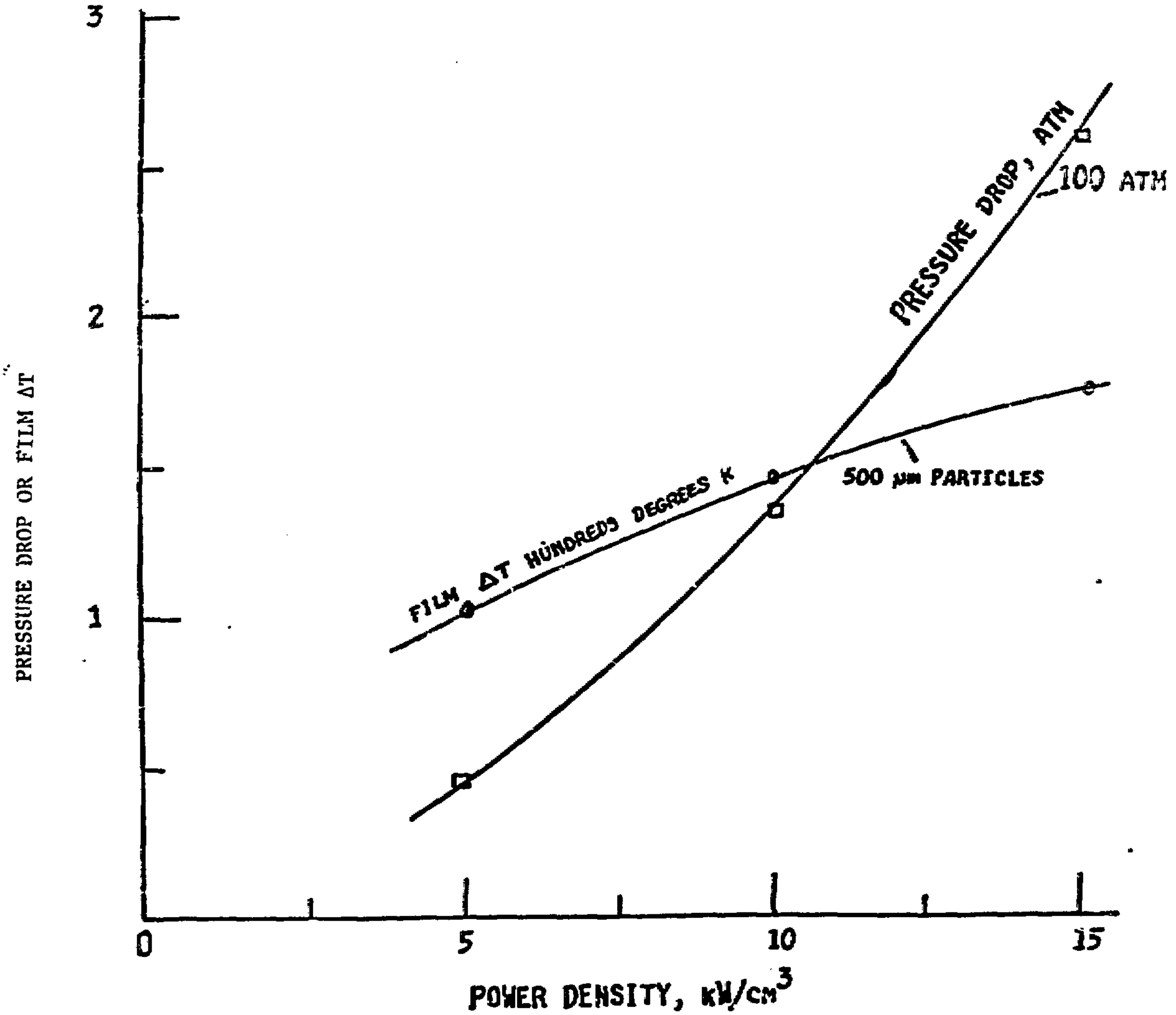
PRESSURE DROP OR FILM ΔT
3
2
1
0
5
10
15
POWER DENSITY, kW/cm^3
FILM ΔT HUNDREDS DEGREES K
PRESSURE DROP, ATM
100 ATM
500 μm PARTICLES

FIGURE 2.3

ORIFICE CONTROL OF COOLANT FLOW

RADIAL POWER VARIATION

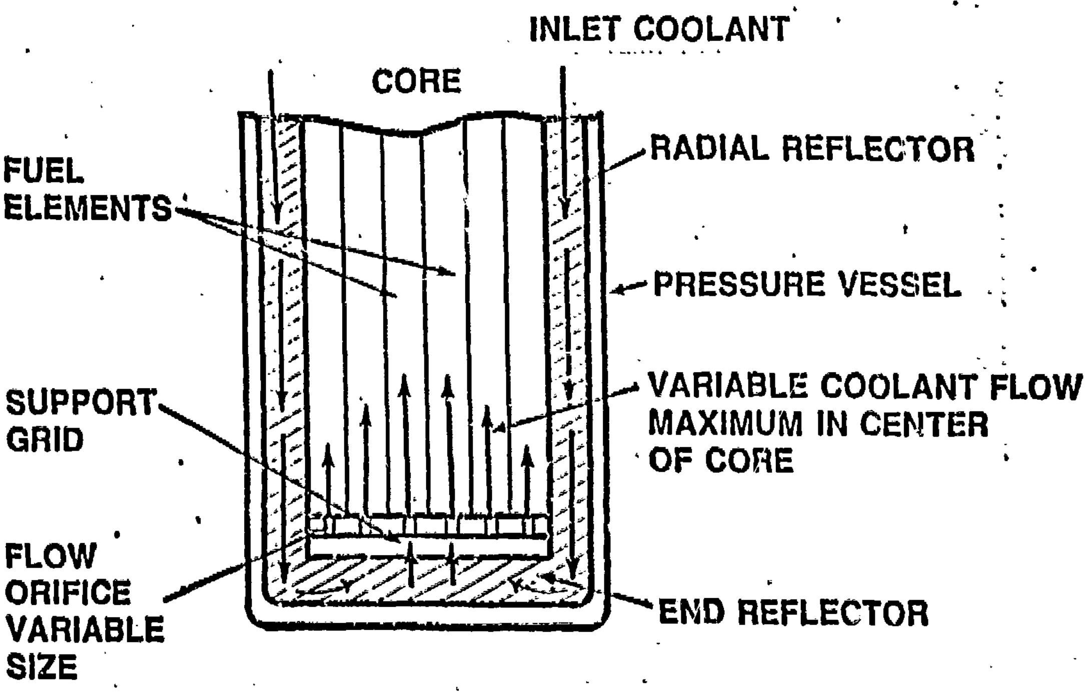

FIGURE 2.4A

0347.008

ORIFICE CONTROL OF COOLANT FLOW

AXIAL POWER VARIATION

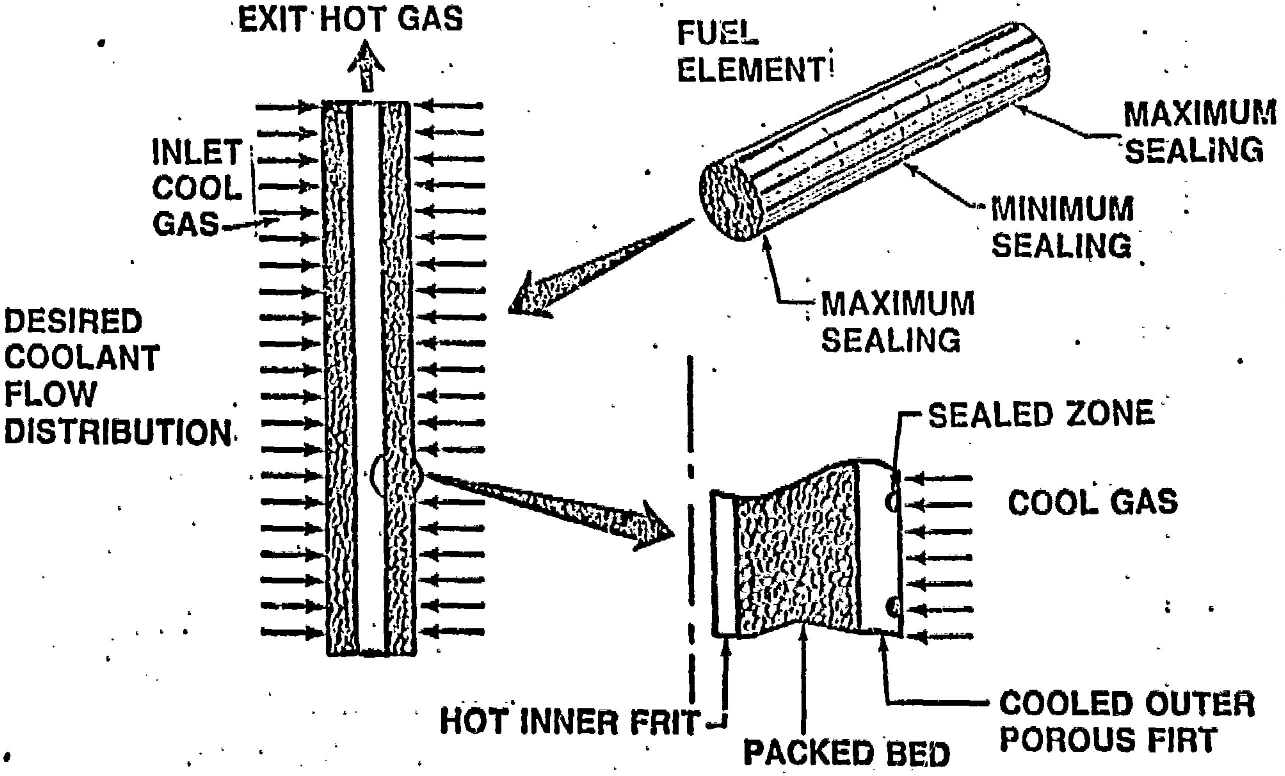

FIGURE 2.4B

0347-007

High power density and ramp rate capabilities relate to the open cycle and bimodal reactors. For closed cycle reactors, power densities are much lower (100 watts/cm^3), and are determined by fuel burnup capabilities, not thermal hydraulics. Power is constant, and startup would be done slowly.

OPEN CYCLE AND BIMODAL SYSTEMS

Pure open cycle and bimodal reactors are similar in design and operation. In both, the reactor is sized by the burst power requirement. Their high power turbine and generator operate at similar conditions. Both require a large hydrogen supply tank.

The principal difference is the additional power conversion and radiator equipment for closed cycle operation. This equipment is much smaller and ligher than the high power equipment.

Neutron fluence exposure is negligible for pure open cycle operation, but significant for bimodal operation. In addition, materials in bimodal systems will be exposed to high temperature helium or helium-xenon for years, and the effects of trace impurities (e.g. H_2O, O_2, H_2, etc.) must be considered.

Both systems use zirconium carbide coated fuel particles, and stainless steel cold frits. Bimodal reactors probably would use zirconium hydride moderator because of its excellent radiation damage properties and high temperature capability. Pure open cycle reactors could use zirconium hydride, but might choose beryllium metal or lithium-7 hydride for lighter weight.

Rhenium hot frits are preferred for both systems; however, tests of rhenium under long term exposure to helium and radiation need to be carried out for bimodal operation.

The pure open cyle reactor would probably use an aluminum pressure vessel to minimize weight; the bimodal reactor would need a stainless or Inconel vessel because of the much higher coolant inlet temperature.

Figure 3.1 shows a typical bimodal reactor. Inlet coolant (H_2 in open cycle, helium-zenon in closed cycle) flows through the reflector to the inlet plenum, and then through the moderator. It then flows through distribution holes to the thin annular plenums around each element, radially inwards through the packed fuel bed to the hot frit, and exits as hot gas along the central channels to the outlet plenum. From the plenum it flows to the turbine.

Figure 3.2 shows a bimodal reactor system packaged for shuttle launch. The principal components are:

BIMODAL REACTOR

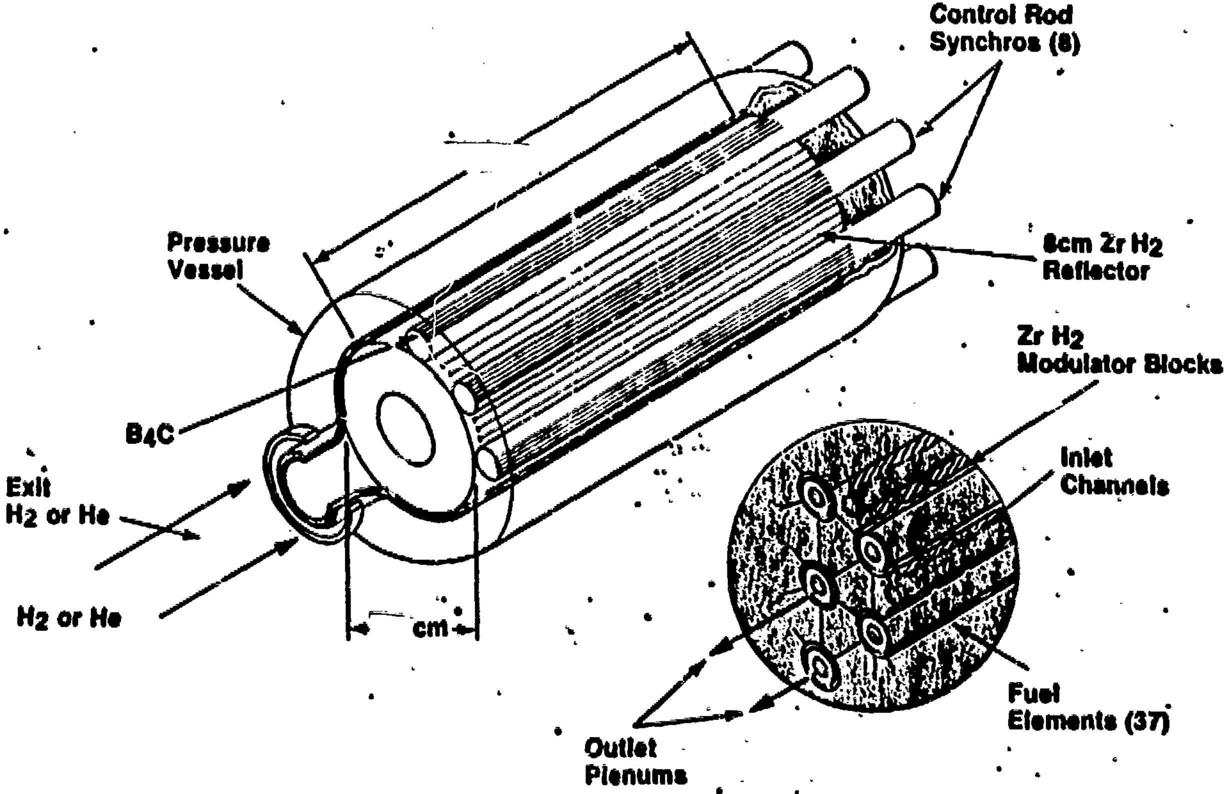

FIGURE 3.1

PACKAGED BIMODAL POWER SYSTEM

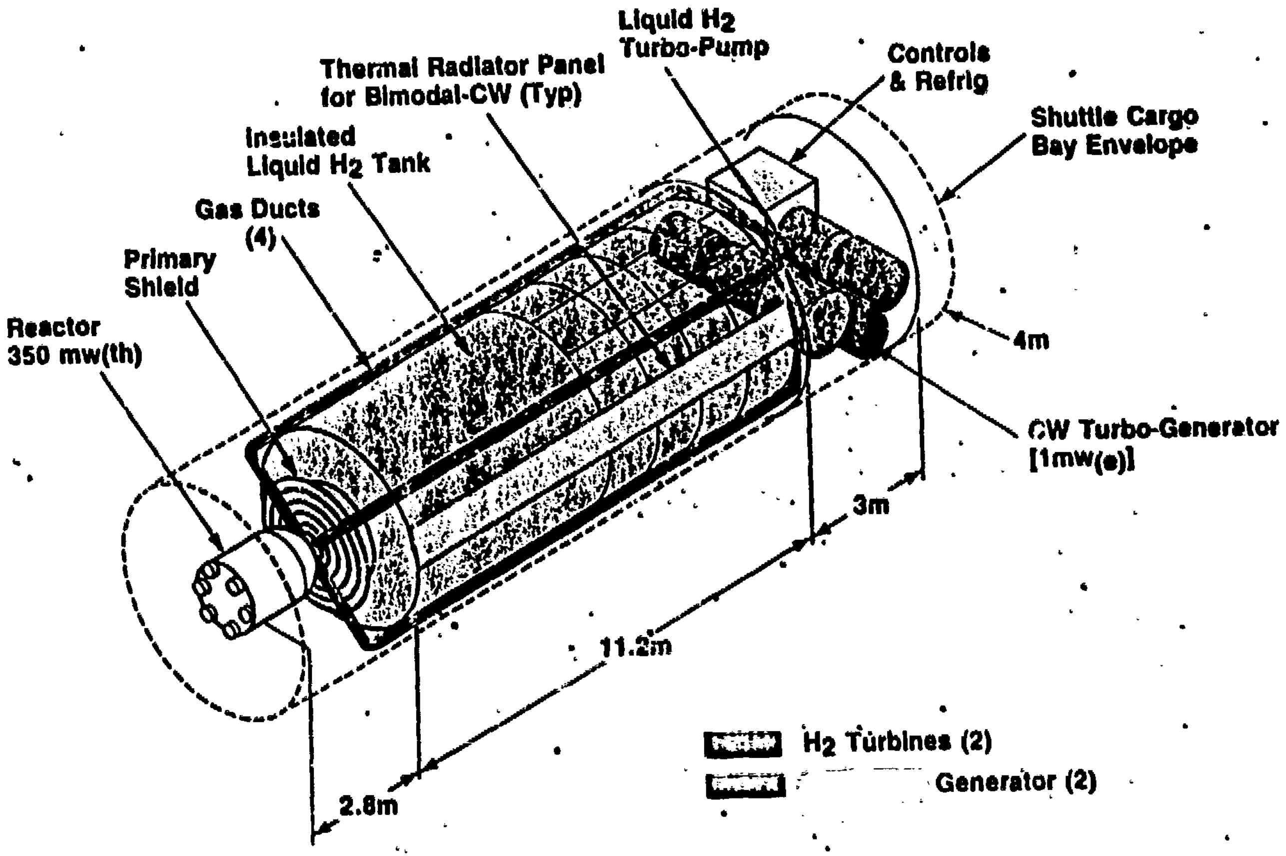

FIGURE 3.2

- reactor
- shield
- liquid H_2 supply tank
- high power turbine/generators (open cycle burst mode)
- moderate power continuous turbine/generator and compressor (closed cycle mode)
- thermal radiator (one panel is shown on the H_2 tank. Thermal insulation between the radiator and the H_2 tank is not shown)
- controls

The launch package is compatible with shuttle volume and weight limits. Operating time in the burst mode is determined by the amount of stored liquid H_2; run time is extended by adding extra tankage. Continuous power levels to approximately 1 megawatt(e) for years with the bimodal system can be achieved. Burst power levels will be considerably larger.

The open cycle portion of the system is shut off from the normally operating closed cycle portion by an isolation valve. Upon demand, this valve is quickly opened. The reactor is then quickly ramped to high power, and hydrogen coolant starts to flow through the reactor, replacing the helium or helium-xenon closed cycle coolant.

The transition to burst power could either be irreversible (one-time) or reversible (i.e., move back and forth between open and closed cycle operation). If irreversible transitions are acceptable, the isolation valve can be a simple blowout diaphragm. If reversible transitions are required, mechanical or freeze valves are potential options.

Garrett has carried out conceptual design studies of H_2 turbines for burst power. Such turbines appear practical. They will be multi-stage, have a high pressure ratio (e.g., 50/1), operate at high inlet temperatures (approximately 2000 K), and achieve good thermal to electric efficiencies (approximately 50%). Unit weights are low and size is compact.

Turbines with uncooled blades appear practical. Ceramic (SiC) or carbon-carbon blades are promising options, based on the existing extensive development work on high temperature turbines. As a backup, turbines with hydrogen cooled superalloy blades could be used. Multi-megawatt turbines were tested by General Electric in the early 1960's at turbine inlet temperatures up to 2500 K with excellent results.

Lightweight, compact superconducting generators are being developed by the Aeropropulsion Laboratory (APL) with full scale tests of their prototype scheduled in approximately one year. Studies by APL indicate that the same technology can be scaled to higher powers if desired.

Closed cycle power conversion and radiator equipment for the bimodal system is similar to that for the Class 1 CW systems discussed below.

CONTINUOUS POWER SYSTEMS

As discused in Section 2, continuous power (PBR) systems are divided into two classes:

- Class 1 - power levels from 10 KW(e) to approximately 1 megawatt(e)
- Class 2 - multi-megawatt

Class 1 systems use 1600 F superalloy turbines similar to the Garrett turbine that demonstrated successful operation for 41,000 hours (NASA engine B). Existing turbo-generator equipment could be used to 30 KW(e) (single unit), and a joint design of this system has been carried out. Parameters are summarized in Figure 4.1; a cross section of the PBR reactor is shown in Figure 4.2

The reactor fuel and materials are all off the shelf, as is the turbine, compressor, and generator. The radiator would use demonstrated Grumman heat pipe radiator construction with stainless steel and water, instead of the present aluminum/ammonia construction.

The complete 30 KW(e) system, together with its folded radiator, would be stowed in a 10 foot long section of the shuttle cargo bay, and could be deployed as a single unit with its attached payload.

The existing generator is limited to 30 KW(e) by field saturation. With redesign, power output could be increased to 150 KW(e) (single unit) while retaining the same turbine, compressor and reactor. Higher power outputs could be achieved with multiple turbo-generator present units, or a redesigned larger capacity unit.

Class 1 PBR's could operate in space in 4 to 5 years. There does not appear to be any fundamental development requirements or issues to be resolved. Weight and volume performance appear good. Overall system weights are approximately 30 kg/KW(e) in the 100 KW(e) regime. Unit weights are less at higher power levels.

For power levels above 1 megawatt(e), Class 2 systems are desirable to reduce radiator area and weight. This can be achieved by higher turbine inlet temperatures (1500 K instead of 1150 K).

It is also necessary to shift from a thermal reactor to a fast reactor construction, because of the increased burnup. Optimum cycle efficiency for Class 2 systems is approximately 20% (thermal to electric).

Figure 4.3 shows a Class 2 PBR designed for continuous power generation. It is similar in size and construction to the bimodal PBR (Figure 3.1) except that the moderator has been removed and replaced with packed bed fuel elements. Incoming gas flows in the spaces between the close-packed elements, rather than through the moderator blocks. The coolant still flows radially inwards through each element, and exits along the central channel.

FIGURE 4.1

Parameters for 30 KW(e) Closed Cycle Particle Bed Reactor System

Gas Composition	He/Xe (MW=40)
Turbine/Radiator/Compressor Inlet Temperature	1600/575/200 °F
Thermal/Electrical Power	100/30 KW
Turbine/Compressor Inlet Pressure	101/49 psia
Recouperator Effectiveness	0.90
Core Diameter/Length	35/35 cm
Particle Bed Power Density	0.012 KW/cm^3
Uranium Loading (U^{235}, 93.5% enriched)	6 kg
Fuel Burnup (7 years)	4.5%
Core Pressure Drop	3 psia
ΔK Central Margin	0.08
ΔK, BOL to EOL	0.02
K_{eff}, EOL, Drums Out	1.01
K_{eff}, BOL, Drums Outs and Safety Rods In	0.35
Neutron Fluence (>100 KeV), 7 years	9×10^{20} n/cm^2
Fuel Element OD/ID/Length	4.4/1.0/35 cm
Radiator Area	30 m^2
Reactor/Power Conversion/Radiator Weight	350/650/800 kg

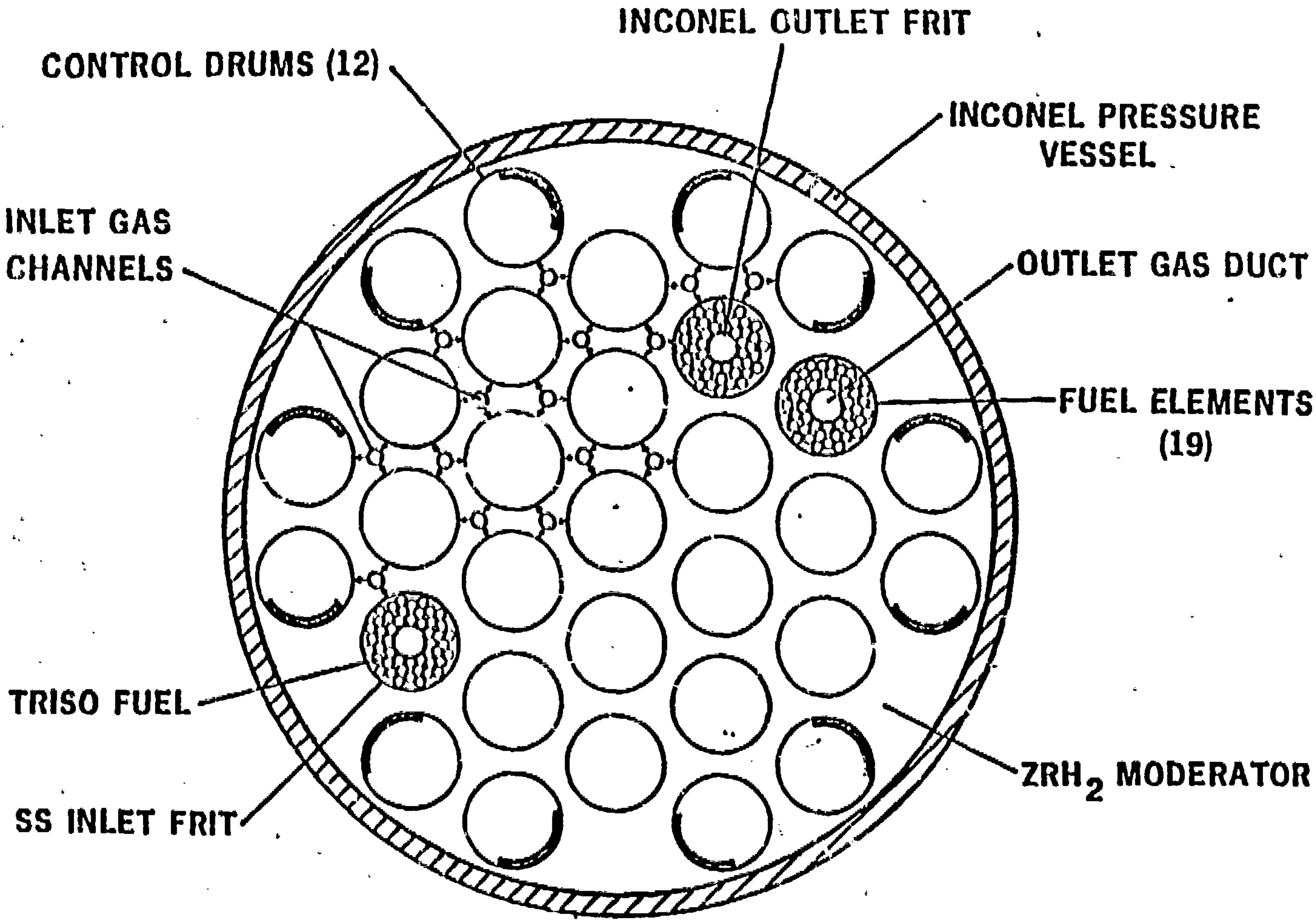
INCONEL OUTLET FRIT
CONTROL DRUMS (12)
INCONEL PRESSURE VESSEL
INLET GAS CHANNELS
OUTLET GAS DUCT
FUEL ELEMENTS (19)
TRISO FUEL
ZRH$_2$ MODERATOR
SS INLET FRIT

FIGURE 4.2

CW REACTOR

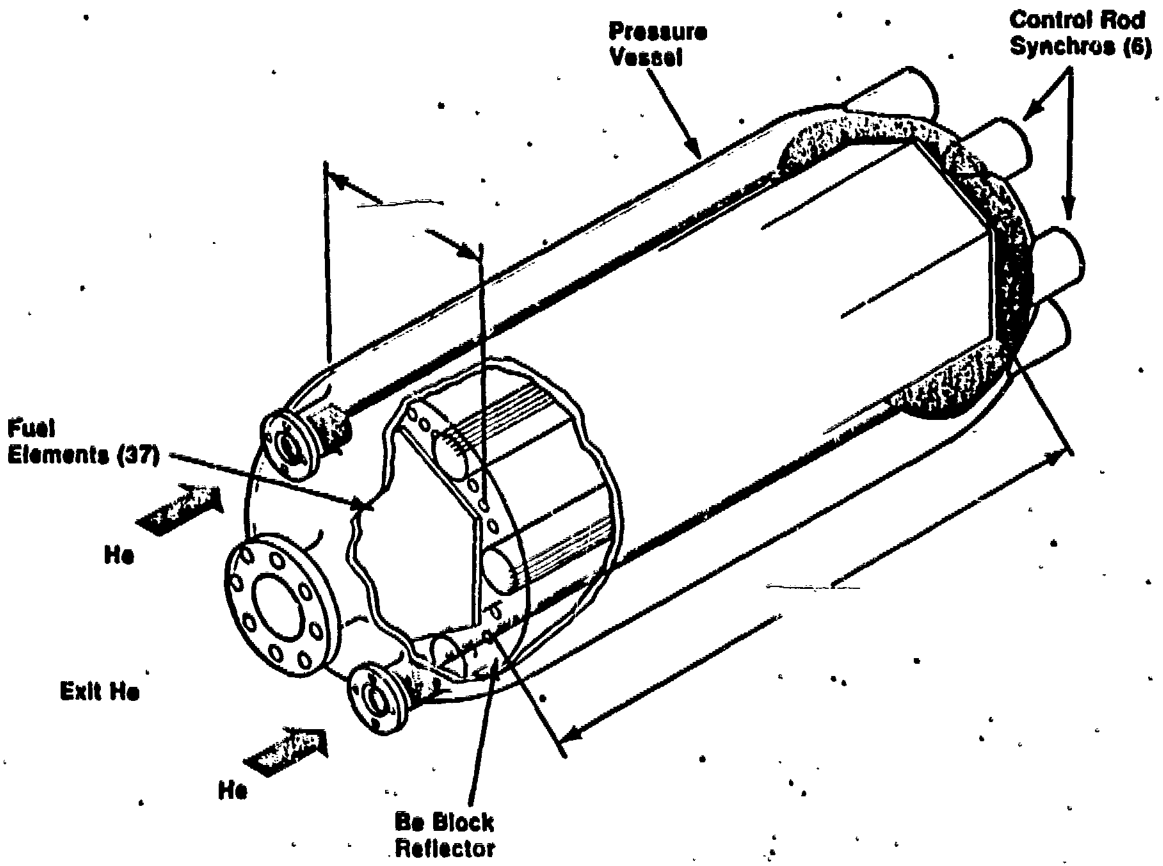

FIGURE 4.3

Studies of Class 2 PBR's show that flat power distribution (both axially and radially) can be achieved. Peak to average power ratios below 1.1 can be achieved with graphite reflectors, for example. Furthermore, the peak to average ratio, and the power distribution remain virtually unchanged over the reactor operating life. It does not appear necessary to add burnable poisons.

Because of the large radiator area, it does not appear feasible to use deployable construction. Instead, the space-erectable construction proposed by Grumman, and being developed for the space-station, would be used. In this concept, modular heat pipe radiator fins, each 2 feet in width and 50 feet long, would be inserted by the shuttle manipulator arm into a common heat transport "spine". Heat would be conducted across the thermally bonded joint to each fin, which then radiates to space. The fins are independent, and failure of a fin would not affect the rest of the radiator assembly.

Figure 4.4 shows the power system packaged for the shuttle. The heat pipe radiator fins are stacked in a pallet. Upon achieving orbit, they are withdrawn and inserted into an extended "Astromast" type heat transport line to form the complete array (Figure 4.5).

Vacuum chamber tests of the constructable radiator have been successfully carried out. Assembly tests of the constructable radiator using the shuttle manipulator arm will be carried out in space in late 1986.

SUMMARY AND CONCLUSIONS

PBR systems appear promising for both continuous and burst power applications. Because of the very large heat transfer area in packed beds, the PBR can operate at much higher power densities and lower weights than other reactors, and can start and stop very rapidly. Coolant outlet temperatures are very high, because of the high temperature fuel particles and materials used, and because of the small temperature differences (tens of degrees) between coolant and fuel. Fission products generated in the particles are fully retained in the particle, and there is virtually no particle failure.

PBR fuel is well developed for the applications considered. It has excellent resistance to high temperature hydrogen and helium, and existing particle materials appear satisfactory.

Existing materials appear suitable for moderators, cold frits, and pressure vessels. Hot frit materials will require some development for burst power and multi-megawatt continuous power application.

Power conversion and radiator technology is virtually off the shelf for continuous power systems up to approximately 1 megawatt. For the higher power continuous sytems, ceramic turbines and high temperature radiator technology development will be required. For the very high burst power systems turbine development will be necessary, with carbon-carbon or ceramic blading. Compact superconducting generators are being developed, but require scaling to higher power levels.

CW SYSTEM PACKAGING

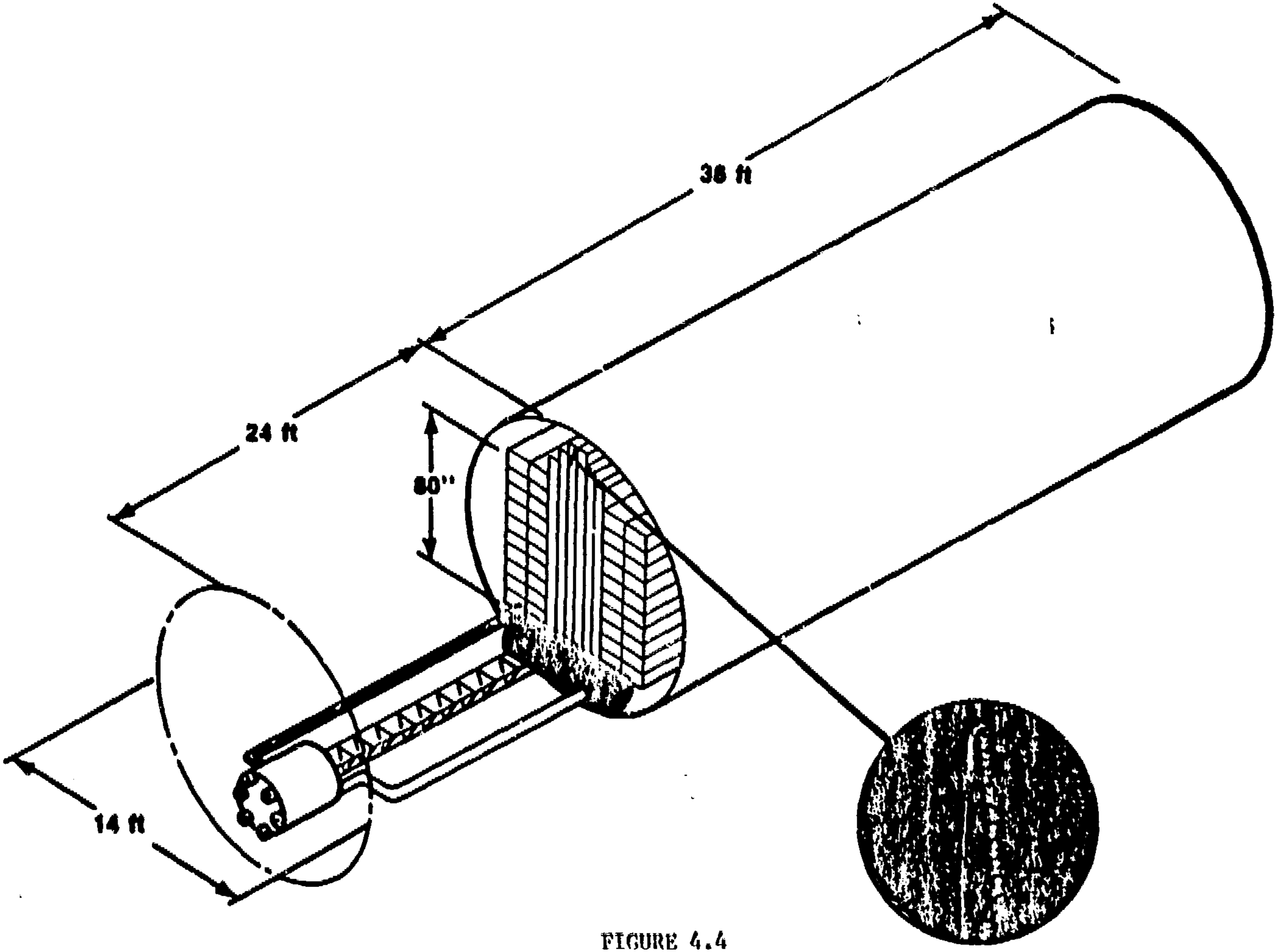

FIGURE 4.4