Appendix A

GAS AND PEBBLE BED REACTORS AND THEIR FUELS

A. 1. MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR

In an effort to keep up with increasing need for electrical power, the U. S. is researching new designs for generating electricity from nuclear power. Smaller, safer, and simpler reactor designs, which may be built independently or as modules in a larger complex, would enable generating capacity to be added as required.

These modern small reactors for power generation are expected to have greater simplicity of design, economy of mass production, and reduced siting costs. Many are also designed for a high level of passive or inherent safety in the event of malfunction. Inherent safety depends only on physical phenomena such as convection, gravity or resistance to high temperatures, not on functioning of engineered components.

A U. S. Department of Energy report in 2001 considered nine designs that could possibly be deployed by 2010. Two designs that use high temperature helium to drive turbines directly will be discussed in this section: the Gas Turbine - Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR).

A. 1.1. Description of the MHGTR

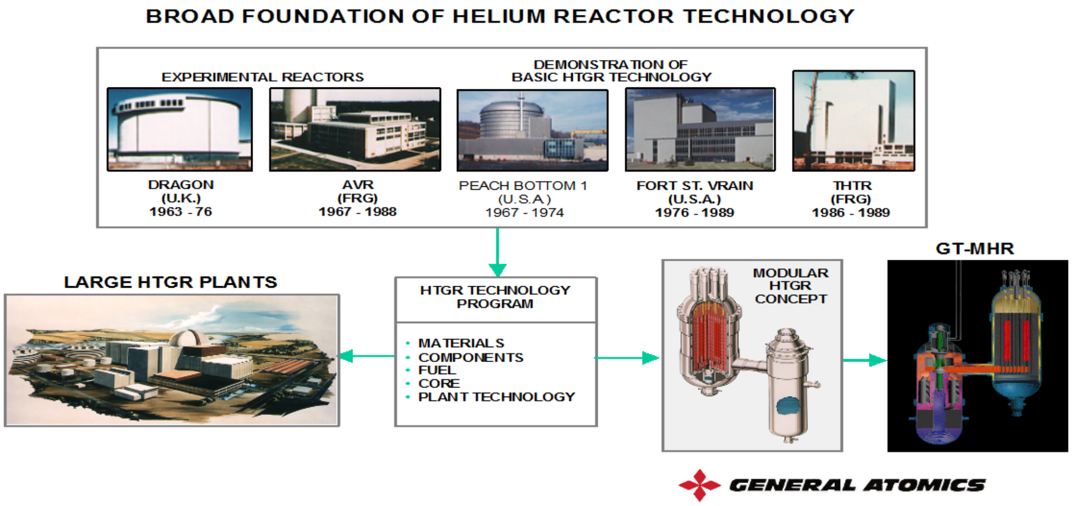
The following information was extracted from a 2001 presentation at the MHTGR Technology Course for NRC/DOE by Arkal Shenoy, Director of the Modular Helium Reactor Group at General Atomics and from the University of California at Berkeley, Nuclear Engineering Web page http://www.nuc.berkeley.edu/designs/mhtgr/concept.html.

The modular high-temperature gas-cooled reactor (MHTGR) is an advanced power plant concept that has been under design definition since 1984. The MHTGR design utilizes basic high-temperature gas-cooled reactor features of ceramic fuel, helium coolant, and a graphite moderator.

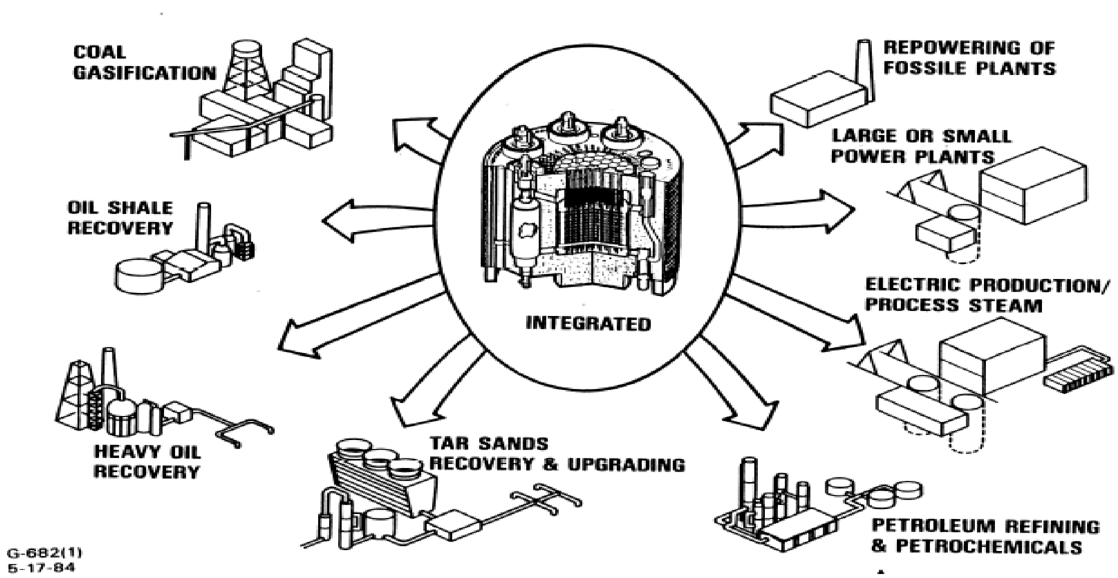
The geometric arrangement of the reactor vessels, the core, and the heat removal components has been selected to exploit the inherent characteristics associated with high temperature materials. The design utilizes passively safe features, which provide a higher margin of safety and investment protection than current generation reactors. The design has been evaluated to be economically attractive relative to modern coal-fired plants. The design and development program is a cooperative effort by the U. S. government, the utilities, and the nuclear industry.

The technology is based upon experiences with earlier gas-cooled reactors and has potential applications for a variety of industries.

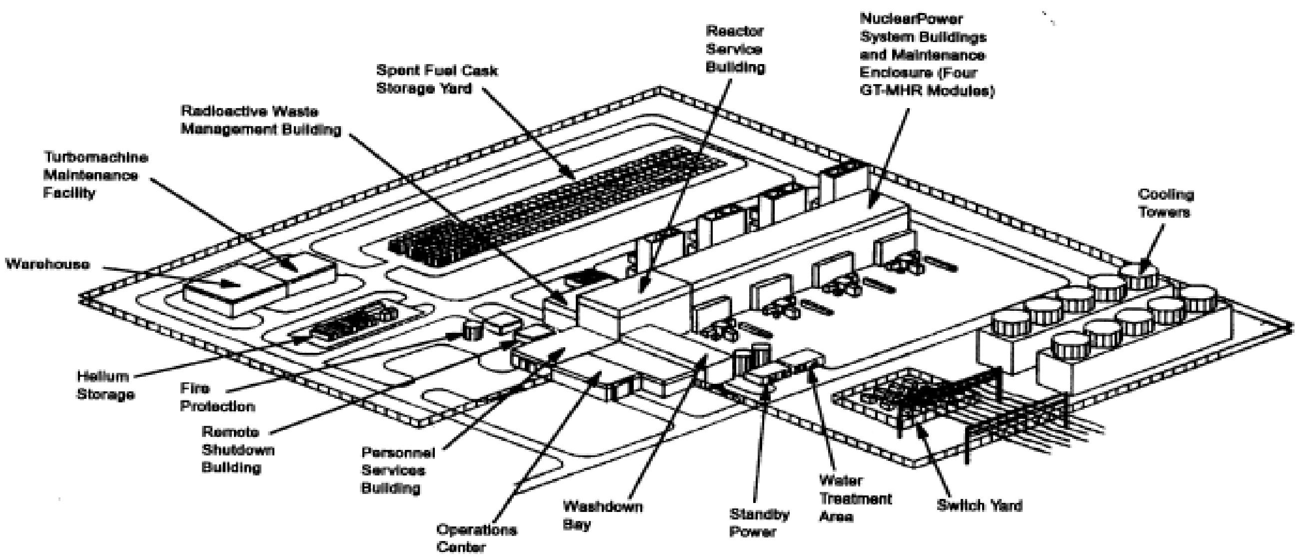
U.S. AND EUROPEAN TECHNOLOGY BASES FOR MODULAR HIGH TEMPERATURE REACTORS



POTENTIAL APPLICATIONS OF HTGR



The typical MHTGR plant includes an arrangement of four identical modular reactor units located in a single reactor building. Each reactor module is housed in adjacent, but separate, reinforced concrete structures located below grade and under a common roof structure. The below-grade location provides significant design benefits by reducing the seismic amplifications typical of above-grade structures and by providing confinement.



Almost all components and systems of each module, which are required to meet regulatory requirements, are independent of other modules and are localized within the individual concrete structures. These include plant protection and decay heat removal systems.

The reactor components are contained within three steel vessels: a reactor vessel, a steam generator vessel, and a connecting cross vessel. The reactor vessel is approximately the same size as that of a large boiling water reactor and contains the core, reflector, and associated supports. A shutdown heat exchanger and a shutdown cooling circulator are mounted on the bottom of the reactor vessel. Top mounted penetrations house the control rod drive mechanisms and the hoppers containing boron carbide pellets for reserve shutdown. The penetrations are also used as access for refueling and inspection.

The heat transfer during power operation or normal core decay heat removal operation is accomplished by helium which is heated as it flows down through the core. It is collected in a plenum below the core and flows through a coaxial hot duct inside the cross vessel to a once-through helical bundle steam generator.

After flowing downward over the steam generator tubes, the cool helium flows upward in an annulus between the steam generator vessel and a shroud leading to the main circulator inlet. The main circulator is a submerged electric motor-driven single stage axial compressor with active magnetic bearings. The helium is discharged from the circulator and flows through the annulus of the cross vessel and hot duct and then upward to the top plenum over the core. In order to meet availability and maintenance requirements, a separate shutdown cooling system is provided as a backup to the primary heat transport system. The heat removal systems allow hands-on plant maintenance to begin within 24 hours after plant shutdown.

A reactor cavity cooling system (RCCS) is located in the below grade concrete structure external to the reactor vessel to remove plant residual heat. This system is totally passive and provides the alternative safety related heat sink if the forced cooling systems are inoperative. The heat is transferred by means of conduction, convection, and radiation from the core to the RCCS. This system has no controls, valves, circulating fans, or other active components. The RCCS is the only safety related heat removal system utilized by the MHTGR.

The reactor core and the surrounding graphite neutron reflectors are supported on a steel core support plate at the lower end of the reactor vessel. The reactor core primarily contains graphite fuel blocks that are hexagonal in cross-section. The fuel is in the form of coated particles of low enriched fissile uranium oxycarbide and fertile thorium oxide. The fuel particles are bonded together in fuel rods which are contained in sealed vertical holes in the fuel blocks. These fuel blocks are stacked in columns to make up an annular-shaped core. Unfueled graphite blocks form the center of annulus, and surround the active core to from the reflector. The annular shape of the core has been selected to enhance the heat removal capabilities in the event of a loss of all forced cooling.

The MHTGR utilizes a once-through fuel cycle; that is, it does not rely on recycling of spent fuel. Each module is refueled once every 20 months. The refueling is accomplished with the reactor shutdown and depressurized, utilizing a refueling machine accessing the fuel elements through the appropriate control rod penetrations in the top of the reactor vessel. The spent fuel is transported to the spent fuel storage pool for temporary storage before shipping to final storage offsite.

Thermal energy from the four reactor modules is delivered to two steam turbine generators to produce 538 MW(e) net, of electric power. The turbine plant is similar to a modern fossil-fired plant except that the MHTGR plant utilized a nonreheat steam cycle. A mechanical draft cooling tower rejects the condenser heat load to the atmosphere.

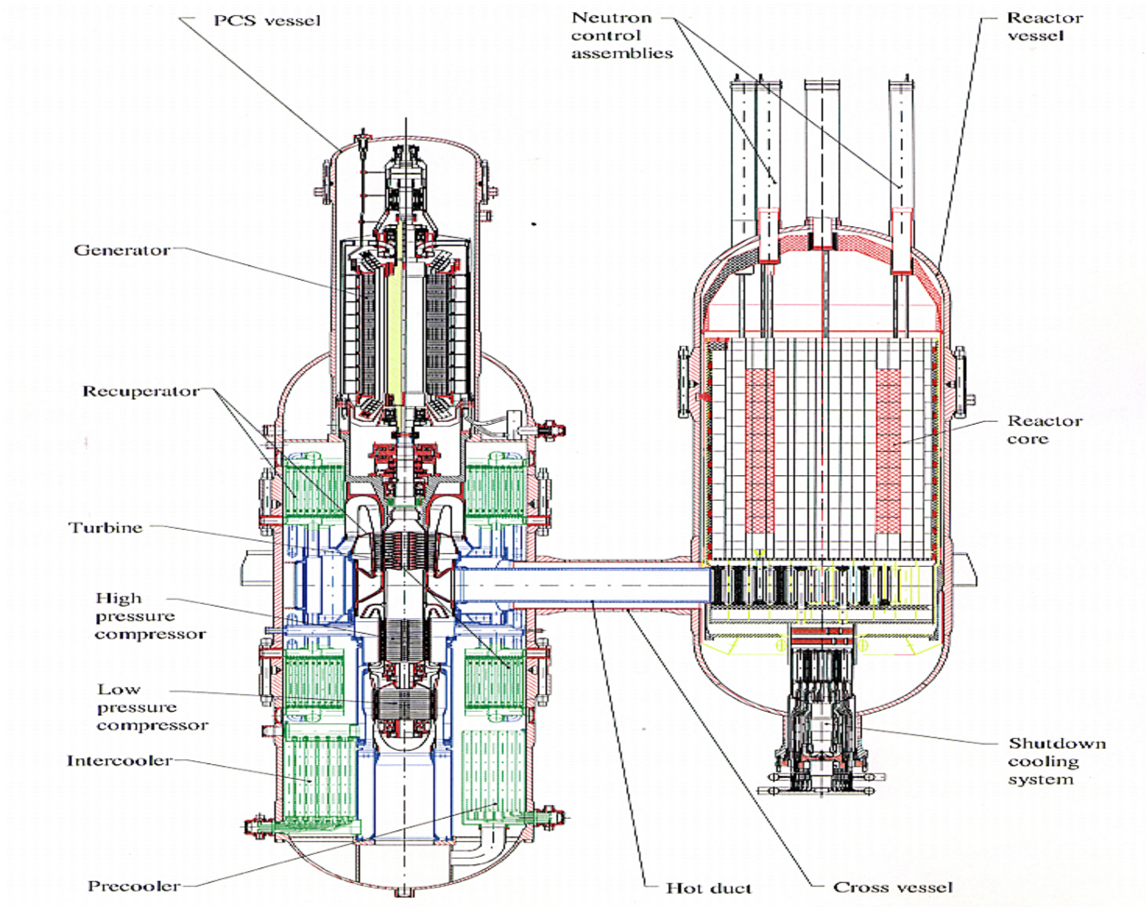
A. 1.2. Gas Turbine - Modular Helium Reactor

The Gas Turbine - Modular Helium Reactor (GT-MHR) is a concept currently under preliminary design of a prototype in Russia for the disposition of Wpu. General Atomics, Minatom, Framatome, and Fuji Electric are teaming to design this next generation reactor. The GT-MHR:

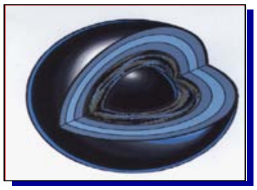
- Utilizes inherent characteristics
    - Helium coolant - inert, single phase
    - Refractory coated fuel - high temp capability, low release
    - Graphite moderator - high temp stability, long response times
- Utilizes existing technology, successfully demonstrate components and experience
- Develops simple modular design: small unit rating per module; silo installation
- Develops passively safe design
    - Annular core, large negative temperature coefficient
    - Passive decay heat removal system
    - No powered reactor safety systems
    - No operator action required
    - Insensitive to incorrect operator action
- Specifications:
    - Electrical output 286 MW(e) per module, efficiency = 48%
    - Four identical reactor modules located below grade
    - Each module includes Reactor System and Power Conversion System
- Reactor System Design–600 MW(t), 102-column annular core
    - Hexagonal prismatic blocks similar to FSV
    - TRISO ceramic particle fuel
    - Redundant reactivity control system
- Power Conversion System design
    - Generator, turbine, and two compressor sections on a single shaft
    - Magnetic bearings
    - Plate-fin recuperator
    - Cross-counterflow, water-cooled precooler and intercooler
    - Incorporates passive safety by design
- Fission products retained in coated particles
    - High temperature stability materials
    - Refractory coated fuel
    - Graphite moderator
- Worst case fuel temperature limited by design features
    - Low power density
    - Low thermal rating per module
    - Annular core
    - Passive heat removal—core can’t melt
- Core shuts down without rod motion

GT-HTR Combines Meltdown-Proof Advanced Reactor and Gas Turbine

Power Level 600 MWt



Ceramic Fuel Retains Its Integrity Under Severe Accident Conditions



Pyrolytic Carbon
Silicon Carbide
Porous Carbon Buffer
Uranium Oxycarbide

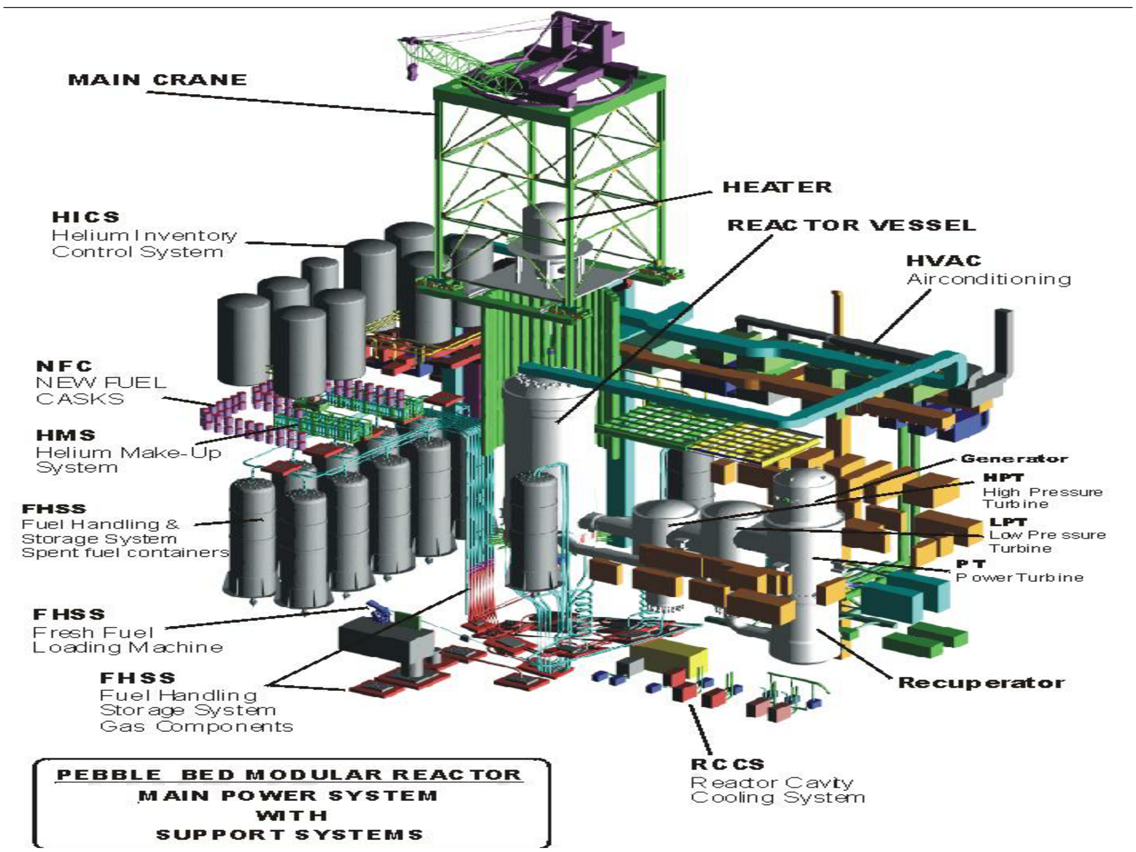
TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

A. 2. PEBBLE BED MODULAR REACTOR

The following information was extracted from a 2001 presentation, "PBMR Overview", by Frikkie van Niekerk, Potchefstroom University for Christian Higher Education, at the MHTGR Technology Course for the NRC and DOE and from the PBMR Ltd. Web page http://www.pbmr.com. This Web site has a wealth of information, diagrams, and a simulator to explain how the PBMR works (http://www.pbmr.com/SIMULATOR/800.html).

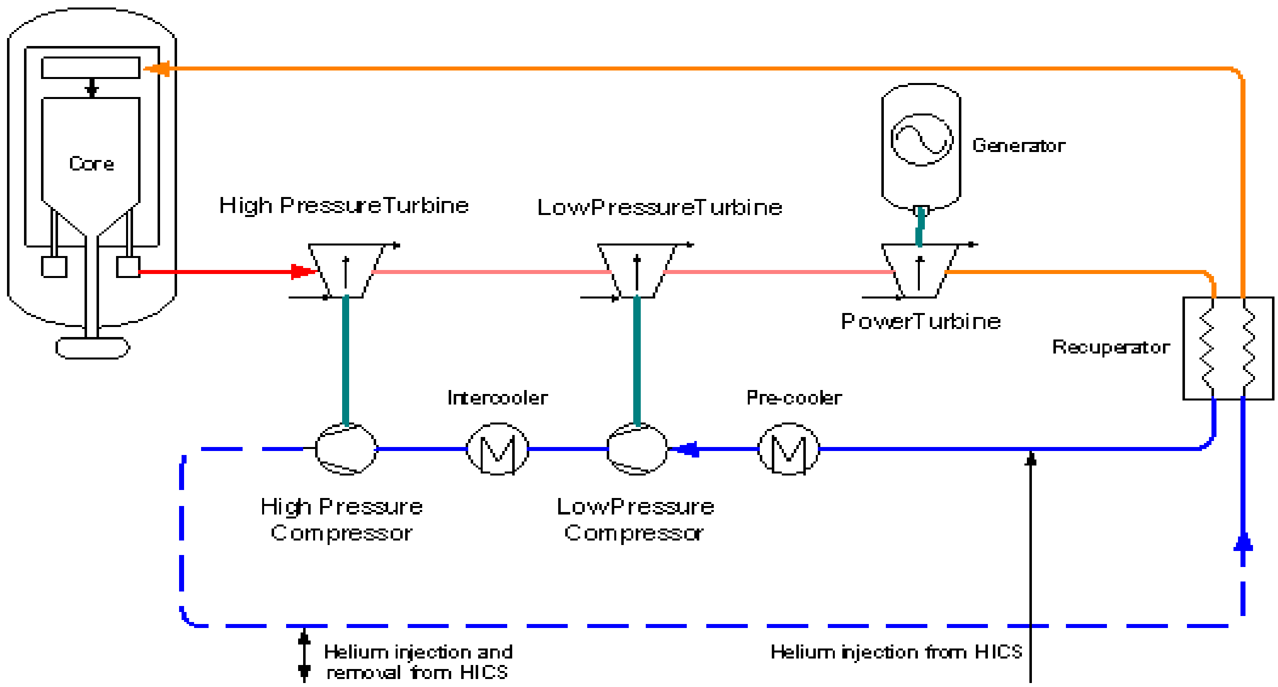
The South African-led consortium developing the Pebble Bed Modular Reactor, made up of BNFL (British Nuclear Fuel), Eskom, Excelon, and Industrial Development Corporation of South Africa, expects that preliminary construction activities could begin in 2002 if appropriate approvals are receive. Commercial operation is forecasted about four years later.

The main power system of the PBMR consists of two main parts. The reactor, where thermal energy is generated by a nuclear reaction, and the power conversion unit, where the thermal energy is converted to mechanical work and then to electrical energy by means of a thermodynamic cycle and a generator.



The PBMR is a helium-cooled, graphite-moderated high temperature reactor (HTR). The PBMR consists of a vertical steel pressure vessel, 6m in diameter and 20m high. The pressure vessel is lined with a layer of graphite bricks. This graphite layer serves as an outer reflector for the neutrons generated by the nuclear reaction and a passive heat transfer medium. The graphite brick lining is drilled with vertical holes to house the control elements. This graphite reflector encloses the core. The core is the region of the reactor in which the nuclear reaction takes place. The PBMR core is 3.7m in diameter and 9.0m in height. The core consists of two zones. The inner zone that contains approximately 185 000 graphite spheres and the outer zone (annulus) that contains approximately 370 000 fuel spheres. The nuclear reaction takes place in the fuel annulus. Helium flows through the pebble bed and removes the heat generated by the nuclear reaction from the core. This helium is the same gas that is used as the working fluid in the power conversion unit, hence the PBMR's direct gas cycle.

The PBMR power conversion unit is based on the thermodynamic Brayton (gas turbine) cycle and is shown in the following diagram.



A. 3. HIGH TEMPERATURE REACTOR FUEL CYCLE

A. 3. 1. Pebble Fuel Design

The basic concept consists of coated particle fuel. The center comprises the fuel, as a kernel, and is surrounded by multiple coatings that protect the fuel and retain the fission products.

The initial pebble fuel designs of HTR fuel in Germany for the THTR utilized BISO coated fuel particles based on the BISO fuel designed and manufactured in the US. This fuel involved pebbles with a central spherical fueled region consisting of coated particles randomly mixed in a graphite matrix surrounded by a fuel-free graphite outer shell. Highly sintered thorium and uranium oxide (10-to-1 thorium-to-uranium) at 93 % enrichment was initially utilized. All layers coating the fuel kernel in the BISO coated particle design involved pyrolytic carbon material.

The later reference fuel design for the HTR-Modul involves a TRISO particle that was used for reloads at the end of the AVR operating history. This fuel is also the reference design for the Pebble Bed Modular Reactor (PBMR). The HTR-Modul reference fuel has the same overall fuel element design as the THTR (i.e., a central 50 mm spherical fueled region consisting of coated particles randomly distributed in a matrix of graphite and binders surrounded by a 5 mm fuel-free graphite outer shell). However the coated fuel particles are of the TRISO particle design. The fuel kernel is highly sintered (near theoretical density) UO_2 with a uranium enrichment of 7-9 %.

For TRISO fuel particles the layers and the purpose of each layer was described as follows:

Inner Buffer Layer: Low density (i.e., ~50% porosity) pyrolytic carbon. The buffer layer provides void space for fission product gases, serves to accommodate the irradiation-induced swelling of the fuel kernel (including fission product recoil) and protects the other layers from damage due to these effects.

Inner Layer: High density pyrolytic carbon deposited from an argon/acetylene/propylene gas mixture. The inner layer retains most of the fission products; fixes the inner porous buffer layer; protects (seals) the next (SiC) layer from chemical attack from fuel kernel fission products; prevents hydrogen chloride, that is generated during the formation of the SiC layer, from entering fuel kernel.

Silicon Carbide (SiC) Layer: The layer is generated from the decomposition of trichloromethyl silane (CH_3SiCl_3) upon the fuel particle, in the presence of hydrogen gas. The SiC layer serves as the impervious barrier to the escape of gaseous or solid fission products (except ^{110m}Ag) from escaping the coated particles; provides the largest contribution to the mechanical strength of the particle; and functions as a pressure vessel. The silicon carbide layer temperature of formation is important to the effectiveness of the coating (1550°C was mentioned as an optimum).

Outer Layer: High density pyrolytic carbon deposited from an argon/acetylene/propylene gas mixture. The outer layer serves to protect the SiC layer from chemical attack from outside the particle and adds strength to the SiC layer.

Overall the purpose of the coatings is to prevent fission products from escaping the fuel kernel during fuel manufacture, in-reactor irradiation, and potential accidents.

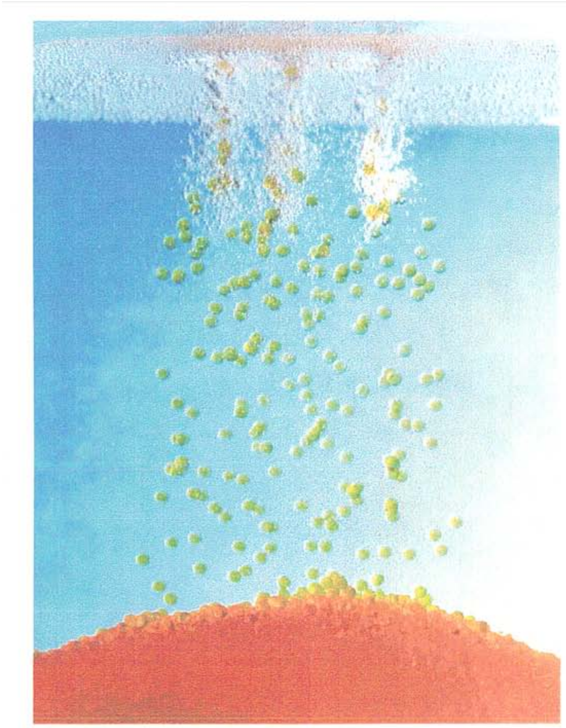
A. 3. 2. Pebble Fuel Element Manufacture

The fuel element manufacturing process consists of: UO_2 fuel kernel manufacture, coating of the fuel kernels, and manufacture of fuel elements.

The UO_2 fuel kernels, are prepared by a modification of the ammonium diuranate (ADU) process that uses vibrating nozzles to generate the initial spherical droplets. The manufacture of the fuel kernels begins with a uranyl nitrate solution. The solution is pre-neutralized and mixed with polyvinyl alcohol (PVA) and tetrahydrofurfyl alcohol. This forms the feed solution. A pump forces the feed solution through small diameter vibrating nozzles. This is termed vibrodropping. See figures below.

REAL EQUIPMENT:

* Conducted in vertical columns
* Uranium solution chilled
* Column temperature "warm"
* Sufficient drop height for ADU/particle stability



* Nozzles above surface

* Must have sufficient drop height for spheres to harden

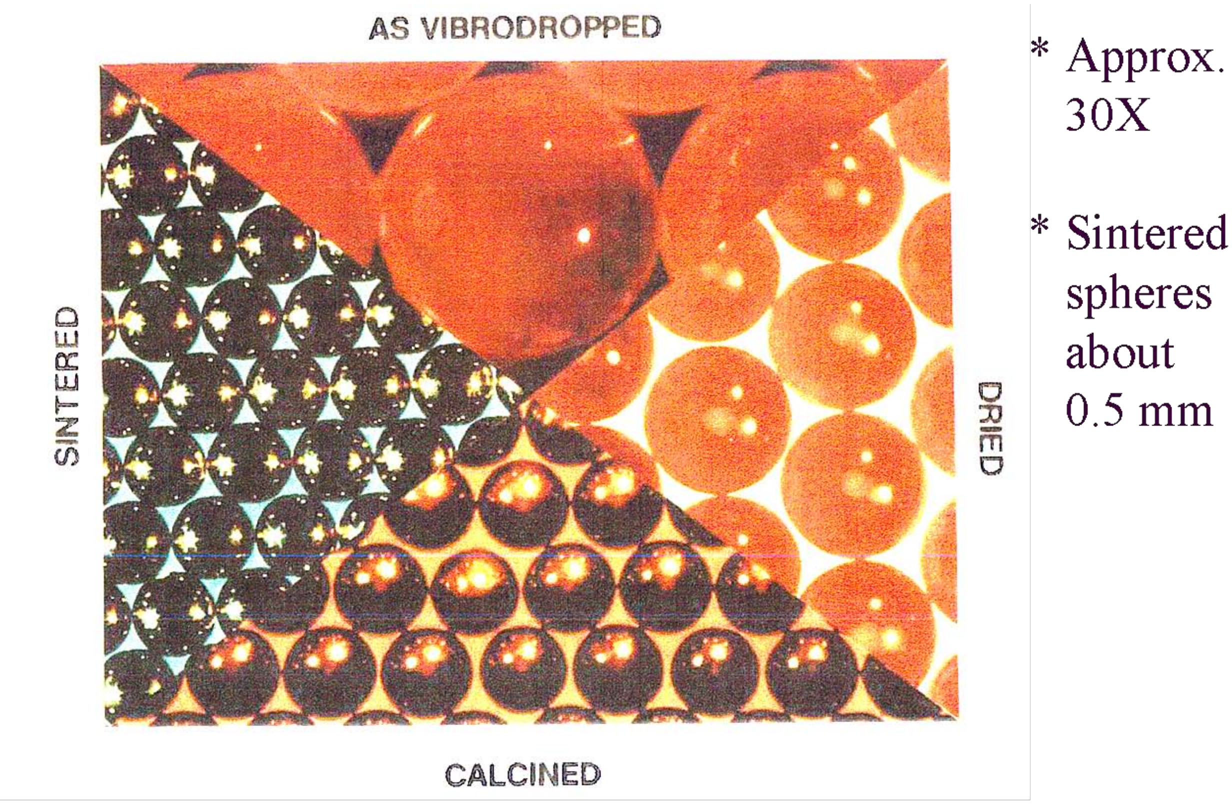
* Particles must age - ADU reactions - before drying

* Dimensions continually decrease

Aging mass of kernels at bottom of reservoir

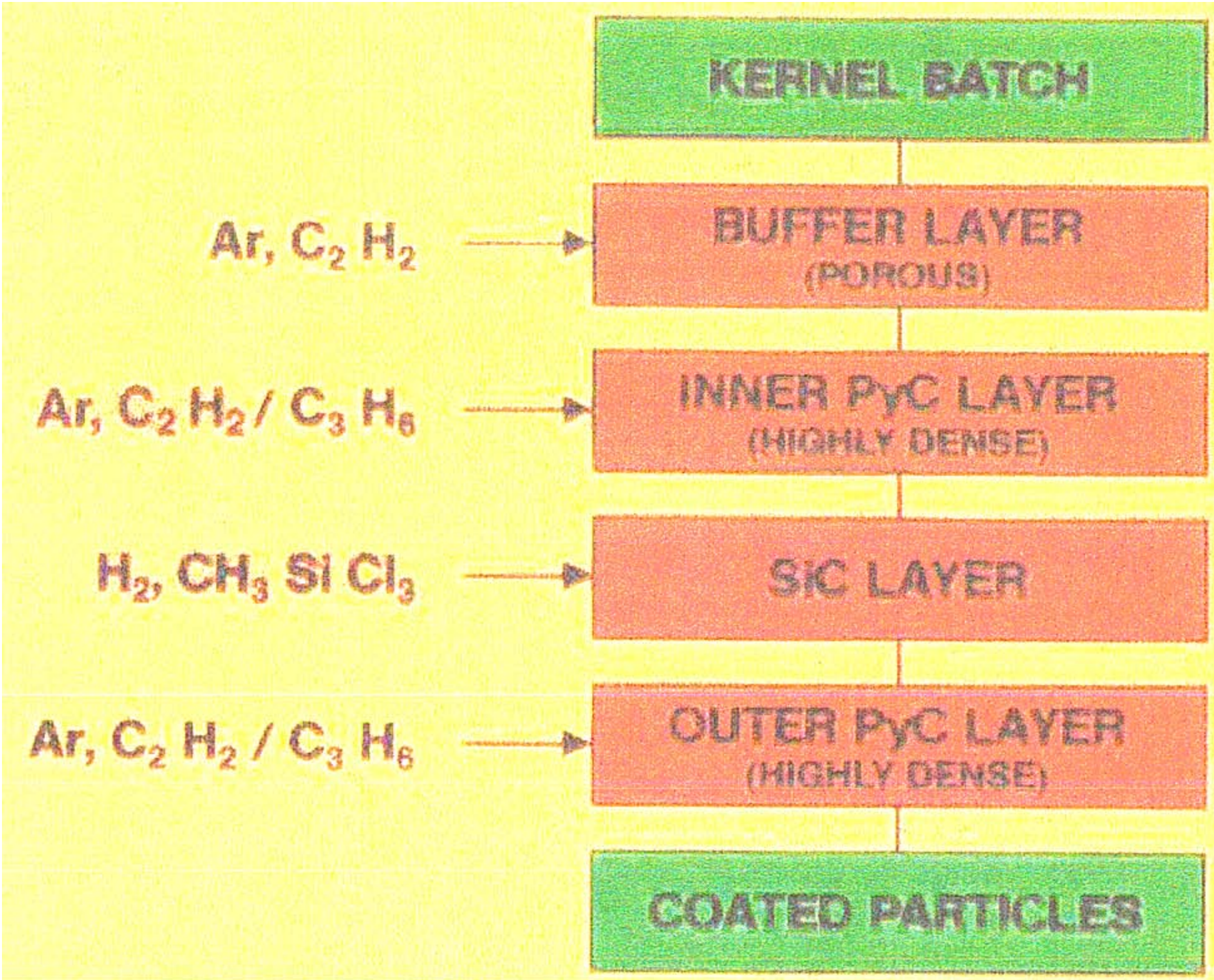
The diameter of each droplet (which determines the size of the fuel kernels) is very precisely controlled and is determined by the nozzle orifice diameter, pressure, and vibrating frequency. The free droplets fall through a small gaseous space and then a more concentrated solution of ammonium hydroxide. This continues the ADU precipitation reactions and the uranium/ADU particle assumes the shape of minimum energy – a sphere – as it falls through the ammonium hydroxide solution.

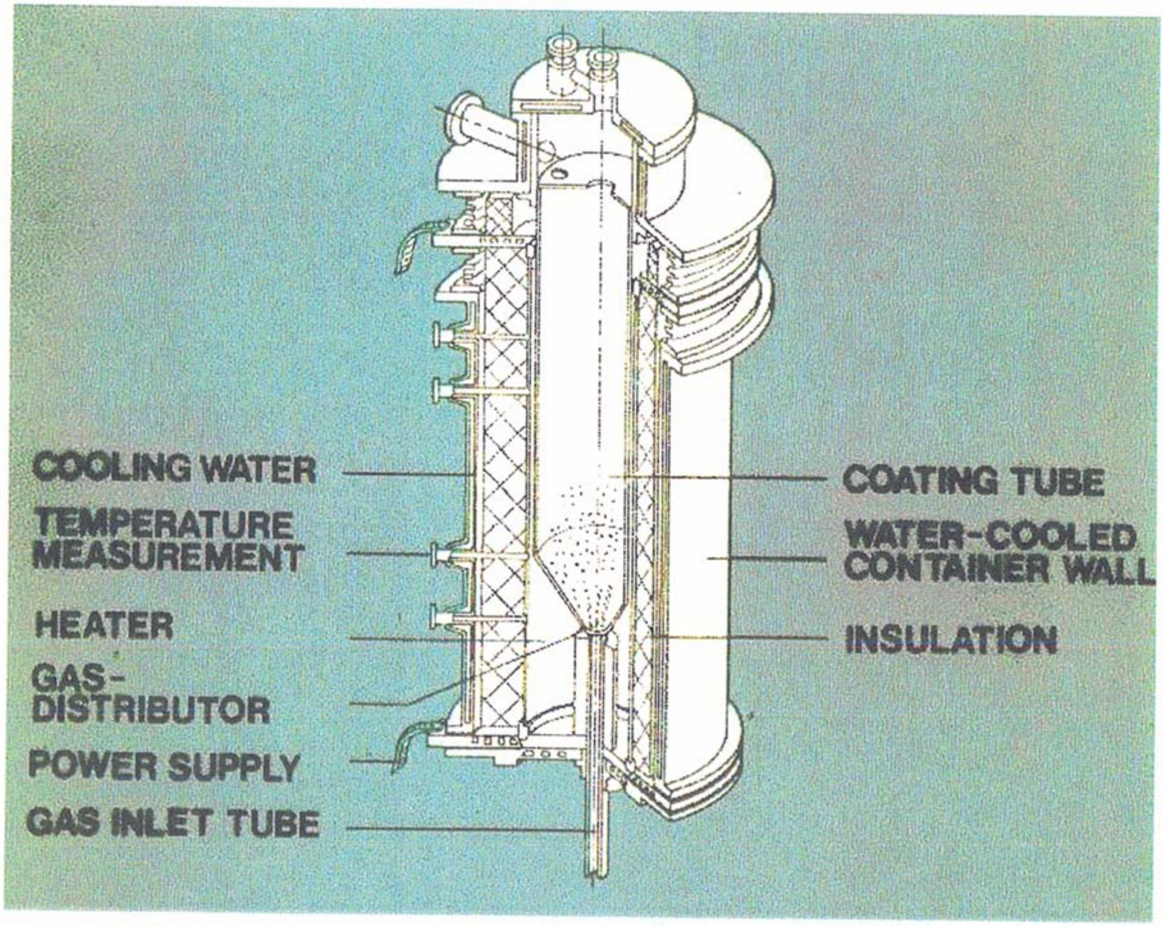
The ammonium hydroxide solution needs to have adequate height to allow sufficient conversion to ADU so that the sphere is mechanically stable when it reaches the bottom of the column or precipitation chamber. At the bottom of the column, the kernels (also called gel spheres because of their softness) are allowed to “age” and complete the ADU reactions. This forms an ADU kernel of adequate strength for handling. The ADU spheres are removed, washed to remove residual chemicals, and dried at moderate temperatures. A calciner converts the ADU to uranium oxide (UO_{2+x}), and reduction with hydrogen completes the conversion to uranium dioxide. A high temperature sintering step increases the density of the kernel to near theoretical density. The figure below displays the particle sizes from different operations.



The fuel kernels are sorted by sieving to ensure 100% meet the specified size and sphericity. The finished fuel kernels are measured and classified by size and roundness within the specified tolerance band. The reference German fuel for the AVR design had a sintered fuel kernel mean diameter of 500 μm. The PBMR fuel is based on this reference.

Each kernel is coated into a TRISO particle using a fluidized bed coater qualified for a 5 kg batch (lot) size as shown below.

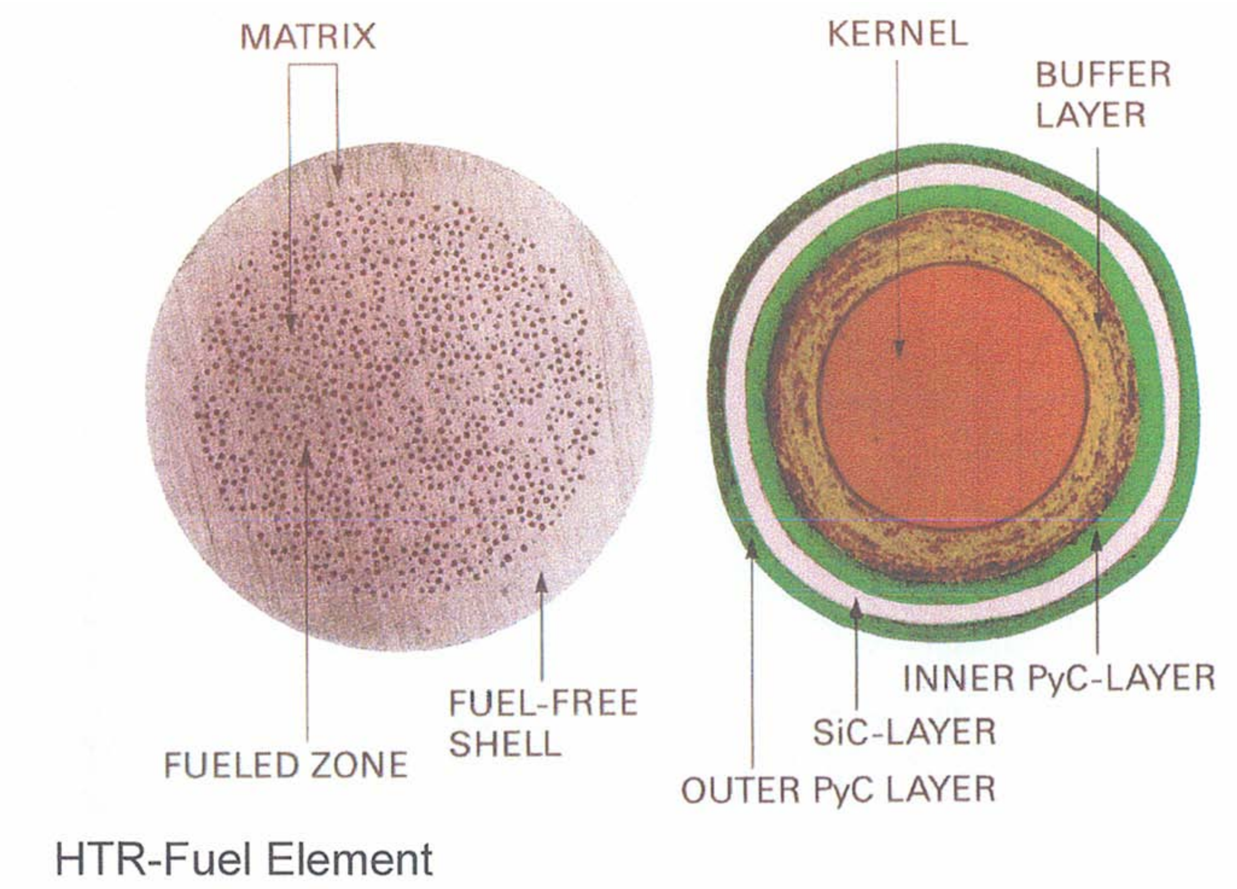

KERNEL BATCH
Ar, C_2H_2
BUFFER LAYER
(POROUS)
Ar, C_2H_2 / C_3H_6
INNER PyC LAYER
(HIGHLY DENSE)
H_2, CH_3SiCl_3
SiC LAYER
Ar, C_2H_2 / C_3H_6
OUTER PyC LAYER
(HIGHLY DENSE)
COATED PARTICLES


COOLING WATER
TEMPERATURE MEASUREMENT
HEATER
GAS-DISTRIBUTOR
POWER SUPPLY
GAS INLET TUBE
COATING TUBE
WATER-COOLED CONTAINER WALL
INSULATION

Small capacity

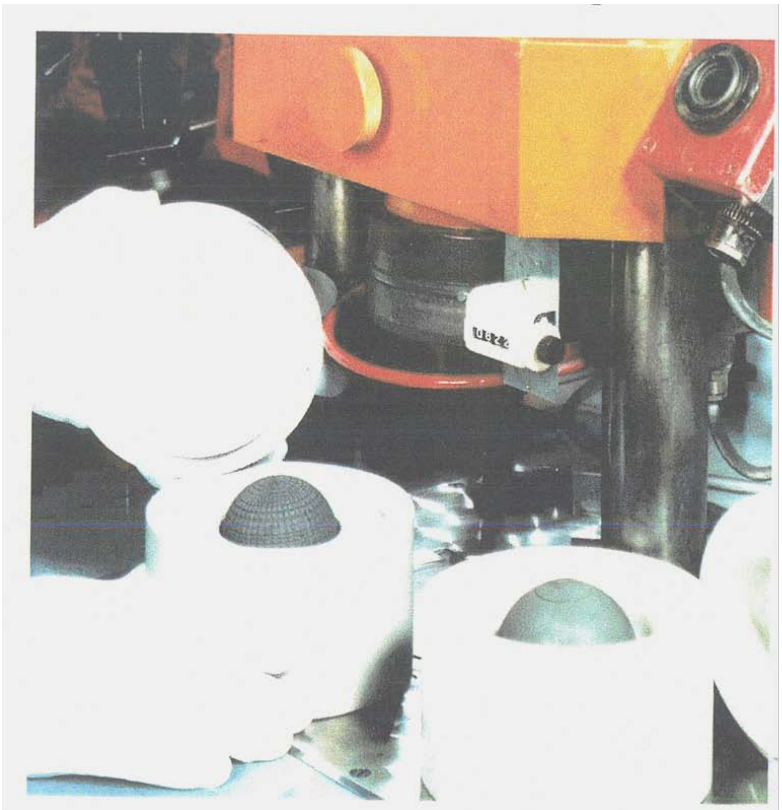
Each coating layer is added via a chemical vapor deposition (CVD) processes in a sequential layering process. The CVD process decomposes gaseous species at temperature in a high surface area medium (the kernels, as the fluidizing bed). The kernels act as nucleation sites for the decomposition which grows the various layers. Each coating is made from a mixture of a carrier gas (typically Argon) and a coating gas which depends on the layer involved. The silicon carbide layer is coated using H_2 as the carrier gas and CH_3SiCl_3 as the coating gas. As each layer in turn is added, the particle diameter increases from the 500 μm UO_2 kernel size to the 1000 μm diameter of the finished coated particle. The UO_2 fuel kernels result in limited heavy metal contamination inside the coater and represents the source for heavy metal contamination outside the SiC layer in the finished particles. The German fuel plant had a particle fuel capacity of approximately 2 MTHM/yr.

Finished particles are then characterized. The last step is to provide a 100 μm overcoat of pyrolytic carbon. The overcoat provides a protective layer for the finished particles to prevent damage and breakage during the high-pressure pressing in the graphite matrix in manufacture of the pebbles, as shown in the figure below.



With the standard design, one coater can process five kilograms (U) of fuel batch size and apply all four coatings in 8–10 hours. A larger coater has been tested for processing 10 kg (U) batches in the same 8–10 hour period but has not been licensed for LEU TRISO particle fuel manufacture based upon German State license (criticality) restrictions. This 5 kg coater is to be used for PBMR fuel manufacture. Safety analyses have shown that the 5 kg/batch coater can accept up to 10% assay material. The coaters use argon as the carrier gas for the pyrolytic carbon layers. Temperatures of 1200–1600°C are achieved by electrical heaters in the base and funnel area walls of the coater. Most of the surfaces in the coating system are graphite or graphite lined. The coater also has insulation, cooling water jackets, and thermocouples around the fluidized bed walls.

The finished TRISO particles are mixed with an approximately 50/50 mixture of graphite powder and binder material to form the fueled zone of the pebble fuel element. These are formed in spherical rubber molds, initially in a pre-molding at low pressure as shown in the figure below.



* LHS - fuel core Note striations for better adhesion

* RHS - fuel pebble; fuel core with fuel free graphite layer added (smooth)

* Isostatic (“even”) pressing in silicone rubber moulds

The pressure must be applied isostatically (uniform) to avoid particle failures from nonuniform external pressures. (The fuel particles are not strong when subjected to high non-isostatic external pressure.) The pre-molded fuel elements are then covered in a fuel free zone of graphite power and pressed a second time at high pressure (300 bar). The completed fuel elements are heat treated at up to 1950°C to remove all volatile material and convert the binder/graphite/fuel particle mass into a monolith. This temperature is sufficiently distant from the 2000°C plus at which the SiC layer would begin to decompose into its constituents. After the final molding and heat treatment, the pebbles are machined to the precise diameter and finish, as shown below.

Finished pebbles are then characterized.

German manufacturing experience of TRISO particle pebble fuel elements for the THTR involved about 1000 batches of kernels, about 4000 batches of coated particles and about 500 lots of finished pebble fuel elements (~1M pebble fuel elements). Overall yields (input uranium to uranium in the final fuel pebbles) were greater than 95% for these products.

Fuel quality is primarily verified by destructive analyses on selected samples from batches. Experience has developed a set of procedures and processes requiring verbatim compliance for generating the fuel with known quality; typical failure numbers of $1X10^{-4}$ to $1X10^{-5}$ were cited for defective pebbles, with one or two defective particles per pebble. This is generally better than the failure rates found during prior NRC efforts on HTR fuels.

The key to consistent manufacturing quality and consistency and fuel performance within expectations during irradiation and accident simulations is the proven manufacturing equipment and manufacturing process procedures, and a special and detailed quality assurance program for all aspects of fuel manufacture and fuel produced. The way to reproducing the consistent success that was eventually achieved by the German program in the 1980s must involve a deliberate and meticulous characterization of each aspect of manufacture in the fuel manufacturing development process and fuel products leading up to the proven performance and qualification of the final fuel facility production lines and fuel that will consistently meet all fuel product specifications. Exact compliance with the final fuel manufacturing procedures is essential. However, German researchers have indicated that improvements could be made with fuel manufacturing process.

German researchers have also stated that the irradiation fuel proof testing for the production fuel must be fully representative of the production fuel that will be made for the HTR plants. To achieve this consistency, both the production fuel elements and the fuel elements used for the proof tests must be manufactured using TRISO particles which are based on a split statistical sample taken from the same (number of) batches of TRISO particles made by the same fuel manufacturing lines (e.g., fluidized bed coaters).

The design drawings for the manufacturing equipment and the manufacturing process procedures and related documented still exist in Germany, although the manufacturing equipment itself has been sold to the Chinese for the manufacture of the HTR-10 fuel. German organizations also have retained personnel who have knowledge and experience in the manufacture of TRISO fuel particles and pebble fuel elements.

A. 3. 3. Spent Fuel Considerations

The irradiation time for fuel pebbles in the reactor averages approximately 3 years. Germany's plans for spent HTR pebbles (from AVR and THTR, and recommended for any future HTRs) consists of two phases:

Intermediate storage: this would be for 50–100 years after discharge from the reactor. During intermediate storage, the storage approach would be designed and operated to maintain pebble temperatures below 100°C.

Conditioning for final storage/disposal: This would be designed to keep the pebble temperature below 50°C in final storage/disposal.

Curves were presented showing the decay heat versus time curves for HTR-Modul and other HTR fuels. For HTR-M, the approximate values are: years after discharge (watts/pebble): 1 (0.4), 2 (0.2), 5 (0.08), 10 (0.05). The intermediate storage approach uses a can in cask method, with remote operations in cells.

The canister/cask system accommodates heat loads of up to 800 watts. For 1900 fuel pebbles at 1 year after discharge, the heat load was stated as about 760 watts. Most of the loaded casks contain fuel over 10 years old, and, thus, typical decay heats are around 60 watts per cask. Pebble fuel temperatures were stated to be under 200°C at the beginning of storage and would be below the 100°C target temperature sometime during intermediate storage; actual temperature decay curves were not presented. The accident analysis did not identify any events resulting in "non-allowable" releases of fission products. A paper on the cask approach was provided.

Germany has investigated using interstitial steel balls within the pebbles and silicon carbide filling as methods for increasing the conductivity and performance of waste disposal packages. Samples were passed around. Box, drum, and pressure-resistant disposal packages have been investigated and have been analytically shown to meet dose criteria. Analytical curves also compared the doses from disposal of the graphite fuel pebble with the same quantities of radionuclides in glass; the fuel pebble doses were lower. Some test data indicated a cesium leach rate of 100 Bq/day from a fuel pebble immersed in simulated groundwater. Curves were shown comparing fuel pebble toxicity to the uranium ore. These implied a time period of around 100,000 years before the HTR fuel toxicity equaled that of the natural ore. No specifics were given. Additional toxicity/time curves were presented for partition and transmutation. These displayed a reduction of the time period to around 1000 years for comparable toxicity to the uranium ore. FZJ researchers acknowledged that additional water immersion, leaching testing, and disposal analyses need to be performed.

From the information presented, the decommissioning program is placing approximately 1900 spent AVR fuel pebbles into two cans, with a total (unshielded) volume of about 0.51 cubic meters [31]. For the THTR, approximately 2100 spent fuel pebbles are placed into one can with an unshielded volume of about 0.61 cubic meters. From this experience, it is estimated that the unshielded packaged volume of spent nuclear fuel elements from reactors similar to the German HTR designs could potentially correspond to roughly an order of magnitude increase over that from light water reactors for the same electrical output.

Germany (FZJ) has initiated decommissioning of the AVR. Based upon one of the papers, the following are the non-fuel inventories of radionuclides in the AVR system, as of 1992:

Cobalt-60	3.2E15 Bq (8.6E4 Ci)
Strontium-90	4.9E13 (1.3E3)
Cesium-137	2.6E13 (7.0E2)
Carbon-14	1.2E13 (3.2E2)
Tritium	1.5E15 (4.1E4)

Note that carbon-14 is the principal long-lived isotope. The AVR non-fuel graphite amounts to approximately 500 tonnes. No estimates for the quantities of graphite involved or anticipated in other HTR designs, such as the HTR-M or the PBMR, were presented. However, due to their higher power levels and larger cores, the quantity of graphite is likely to be more than 500 tonnes. It was also indicated that the German program will most likely dispose of the graphite material in a subsurface disposal unit. AVR decommissioning operations will have to address the small number of pebble fuel elements that fell into and lodged flow slots in the graphite lower core support structure. Decommissioning will also have to address potential contamination from the graphite dust via adequate confinement during dismantling.

A. 3. 4. Key Issues for the Fuel Cycle

Key fuel cycle issues for NRC reviewers of future applications related to PBMR fuel cycles include:

- Fuel manufacture
- Fuel QA/QC
- Spent Nuclear Fuel (SNF - treatment, storage, and disposal)
- Operational wastes
- Decommissioning
- Safeguards and MC&A
- NEPA