4. PROTEUS CRITICAL EXPERIMENT FACILITY

The zero-power reactor facility PROTEUS is a part of the Paul Scherrer Institute (formerly EIR) and is situated near Würenlingen in the canton of Aargau in northern Switzerland

4.1. HISTORY OF THE FACILITY AND RECONFIGURATION FOR THE HTR EXPERIMENTS

PROTEUS has, in the past, been configured as a multi-zone (driven) system for the purpose of reactor physics investigations of both gas-cooled fast breeder and also high conversion reactors. For these experiments, the various test configurations were built into a central, sub-critical test-zone which was driven critical by means of annular, thermal driver-zones. For the LEU-HTR experiments described in this report however, PROTEUS was for the first time, configured as a single zone, pebble bed system surrounded radially and axially by a thick graphite reflector.

The rest of this chapter gives a brief history of the facility, including a description of the rebuild work undertaken for the HTR experiments, followed by a brief description of the present HTR-PROTEUS system.

- **Jan. 1968 - Sep. 1970**

  Operation as a “zero-reactivity experiment” with a thermal, D_2O moderated test-lattice and a graphite driver [4.1]

- **Sep. 1970 - Apr. 1972**

  Mixed fast-thermal system with a “buffer-zone” and reduced size test-zone.

- **Apr. 1972 - Apr. 1979**

  Sixteen different configurations of the gas-cooled fast reactor type [4.2].

- **Jan. 1980 - Aug. 1980**

  Preliminary HTR experiments [4.3].

- **Aug. 1980 - May 1981**

  Rebuild of the test-zone to accommodate light-water high conversion reactor experiments.

- **May 1981 - Oct. 1982**

  Phase I of the advanced light-water reactor experiments. Six configurations were investigated [4.4].

- **Feb. 1983 - May 1985**

  Re-configuration of the test-zone for Phase II of the light-water high conversion reactor experiments.

- **Jun. 1985 - Dec. 1990**

  Phase II of the advanced light-water experiments - fourteen different test-zones, containing more representative fuel than in phase I, were investigated [4.5].

- **Jan. 1991 - Jul. 1991**

  Rebuild for the LEU-HTR experiments. A brief summary of the work undertaken for this rebuild is now given:

- All driver and buffer fuel discharged and stored.
- Fuel in test-zone discharged and stored.
- All installations inside graphite-reflector removed.
- Construction of upper reflector assembly for HTR, an aluminum tank containing an annular region of old graphite and a central cylinder of new graphite.
- Filling of ~50% of the ~300 C-driver holes with new graphite rods. The other ~50% were filled with existing graphite rods.
- Renewal of the safety/shutdown rods - increased length to allow for greater core-height and better characterization of material properties - for improved benchmark quality of the experiments.
- Increased height of radial reflector by 12cms.
- Reconstruction of lower axial reflector, including central part of new graphite.
- Mounting of graphite panels in core cavity to modify the cavity shape to accommodate deterministic loadings.
- Fuel and moderator pebbles loaded.
- After the rest worths of the original ZEBRA control rods were found to be unacceptably high, these rods were replaced with conventional withdrawable control rods

The next section contains a brief description of the HTR-PROTEUS facility.

4.2. HTR-PROTEUS FACILITY DESCRIPTION

The description contained in this section serves only to give the reader a qualitative picture of the facility. Full details, for use in the benchmarking of codes and data, including atom densities, can be found elsewhere [4.6, 4.7] and are not included here for reasons of space. Schematic representations of the system presented in Figures 1 and 2.

The HTR-PROTEUS system can be described as a cylinder of graphite, 3304mm in height and 3262mm in diameter. A central cavity, with base 780mm above the bottom of the lower axial reflector and having a horizontal cross-section in the form of a 22 sided polygon with a flat-to-flat separation of 1250mm, contains fuel (16.7% enriched) and moderator (pure graphite) pebbles, either randomly arranged or in one of several different geometrical arrangements. Additional graphite filler pieces are used at the core-reflector boundary to support the irregular outer surface of the deterministic pebble arrangements. A removable structure in the form of a graphite cylinder of height 780mm contained within an aluminum tank forms the upper axial reflector, normally with an air gap between it and the top of the pebble bed. An aluminum "safety ring", which is designed to prevent the upper axial reflector from falling onto the pebble-bed, in the case of an accident, is located some 1764mm above the floor of the cavity.

Shutdown of the reactor is achieved by means of 4 boron-steel rods situated at a radius of 680mm and reactor control by four fine control rods at a radius of 900mm. In Core 1 of the program, these fine control rods comprised Cd Shutter or ZEBRA type rods, but in all subsequent cores, conventional, withdrawable stainless-steel rods were employed. A further, single servo-driven control rod, known as the autorod is also situated in the radial reflector. This rod is used to maintain the reactor in a critical state by responding to changes in the power level measured by a fixed ionization chamber.

For the simulation of water ingress, polyethylene rods are introduced to the vacant axial channels of the deterministic cores.

The system can be conveniently separated into the following groups of components:

- Fuel and moderator pebbles
- Graphite - radial, upper and lower axial reflectors and filler pieces
- Aluminum structures
- Shutdown rods
- Fine control rods
- Automatic control rod
- Static "Measurement Rods"
- Polyethylene rods used to simulate water ingress
- Miscellaneous components

Each of these component groups will now be described

4.2.1. Fuel, Moderator and Absorber Pebbles

Since the arrangement of fuel and moderator pebbles, by definition, changes from configuration to configuration, only the properties of the individual pebbles will be described in this section. Detailed descriptions of the pebble arrangements in each of the different core configurations are to be found in [4.7].

The main properties of the fuel pebbles are summarized in Table 1 and Figure 3. As a result of concerns that the manipulation of the pebbles during loading and unloading operations could have led to some erosion of the pebbles, the diameter and mass of the fuel pebbles was measured at PSI on 17.08.92 and again, after more than 3 years of experimentation, on 30.10.95. The masses of the fuel pebbles were not seen to have changed significantly over this period, although some slight reduction was observed in the average pebble diameter. This is presumed not to be due to a general loss of material from the fuel pebbles, but rather as a consequence of the diameter measurement technique in which the length of rows of 10 fuel pebbles were measured. The apparent diameter reduction was attributed to the presence of slight indentations in the surfaces caused during the loading process and is not thought to be significant. The measurements made on 17.08.92 appear in Table 1 and are those recommended in the system description [4.6]. As a by-product of these measurements it could be shown that fuel and moderator pebbles have nearly identical diameters, which was important for the geometric characterization of the regular pebble arrangements, containing different numbers of fuel and moderator pebbles.

The main properties of the moderator pebbles (obtained from measurements made at PSI on 17.8.92, 3.5.95 and 30.10.95) are given in Table 2. The values correspond well with those from the relevant QC records. No significant changes were noted in the properties of the moderator pebbles during the course of the experiments. The total boron equivalent of 1.39

millibarns given in the table results in an effective moderator pebble graphite 2200 m/s absorption cross section of 4.79 millibarns. Not included in the table are values for absorbed moisture in the pebbles. The amount of moisture contained in the pebbles was measured at PSI by choosing, at random, two moderator pebbles and heating them to 500°C in a vacuum for 5 hours. Each pebble showed a weight loss of 0.02g (0.01wt%).

4.2.2. Reflector Graphite Specifications

The HTR-PROTEUS reflector consists of graphite of various ages and from several different sources. The location of the various types of graphite is summarized in Table 3 along with the densities and nominal, "as delivered", impurity contents. It is seen in the table that the old graphite comprises the majority of the system, and therefore a global value of 1.763 g/cm^3 is recommended for the graphite density.

No attempt is made to describe the impurity content of individual components. Instead, it is recommended that the global value, measured and reported in [4.8] be used as a universal impurity content, expressed in terms of equivalent boron content. This recommended value is 4.09±0.05 mbarn and it should be noted that this approach has the advantage that absorbed moisture and intergranular nitrogen (air) is automatically taken into account.

4.2.3. Upper Reflector Tank

This is a complex structure which supports the graphite of the upper reflector in place above the cavity. It comprises two main parts, an inner and an outer aluminum tank. The inner tank, which contains a cylinder of graphite 780mm high and 394mm in diameter, is removable and indeed **must** be removed before the main outer structure can be removed. This main outer structure contains an annulus of graphite having again a height of 780mm, an inner diameter of 418.6mm and an outer diameter of 1234mm.

4.2.4. Safety/Shutdown Rods

There are eight, identical, borated-steel safety/shutdown rods located adjacent to the core in the radial reflector. These eight rods are separated into two groups with four rods in each group (rods 1-4 and rods 5-8). One of these groups is selected as the "safety rod" group and the other as the "shutdown rod' group. It should be remembered that the term "control rods" is reserved for the four, much lower reactivity worth, Zebra type Cd/Al reactivity control devices used in LEU-HTR PROTEUS Core 1 or the withdrawable stainless steel control rods used in Cores 1A onwards. The safety/shutdown rods consist of 35 mm diameter, borated steel rod-sections (nominally 5 wt% boron) enclosed in 18/8 stainless steel tubes of outside diameter 40mm and inside diameter 36mm. The rods are located in 45mm inner diameter graphite guide tubes in the radial reflector. The centers of the 45mm inner diameter guide tubes are 684 mm from the center of the core or about 59mm from the inner surface of the radial reflector (without filler pieces). The azimuthal positions of the 8 rods are shown in Figure 2 in which the slight azimuthal asymmetry of the rod positions should be noted.

4.2.5. Zebra Type Cd/Al Control Rods

Four Cd/Al control rods of the "Zebra" type were used in LEU-HTR PROTEUS Core 1. This type of control rod has the advantage that it causes minimal perturbations to the axial flux distribution at the price of a significant minimum (rest) reactivity worth. Because the minimum reactivity worth of this type of control rod varies with the core configuration and is somewhat time consuming to determine experimentally, the Zebra type control rods were used only in Core 1 and were then replaced by standard withdrawable type stainless-steel control rods.

4.2.6. Withdrawable Stainless Steel Control Rods

The control rods which replaced the ZEBRA rods described in the last section and which were used in all cores from 1A onwards are of the conventional withdrawable type. The rods are not situated in the same channels as the ZEBRA rods but rather in 4 C-Driver channels. With the intent of increasing operational flexibility, the new rods were designed to be operable at two radii, namely 789mm (ring 3) or 906mm (ring 5). Due to the thermal flux gradient in the radial reflector at these positions, significantly different rod worths are thus achievable. Figure 2 indicates the control-rod positions.

4.2.7. Automatic Control Rod

This is a single fine control rod, situated in the radial reflector at a radius of ~ 900mm and used to automatically maintain the critical reactor at a nominal demanded power. It responds to the signal from a single ionization chamber also situated in the radial reflector. The rod itself comprises a wedge shaped copper plate supported within an aluminum tube.

4.2.8. Static Measurement Rods

In order to investigate the spatial dependence of control-rod worths in a particular configuration and because the operational control rods are restricted in their locational possibilities, simulated control rods were specially manufactured for the experiments. These rods are so designed that they may be inserted either into the C-Driver channels in the radial reflector or into a specially designed graphite sleeve which replaces a column of pebbles in a columnar hexagonal core. Because the core and radial reflectors are of significantly different heights, it was necessary to produce two pairs of rods, which apart from their axial dimensions are nominally identical.

4.2.9. Polyethylene Rods

One of the main aims of the HTR PROTEUS project was the measurement of the effect of accidental water ingress to the core. Because the use of water in the experiments was 1) forbidden and 2) impractical, the presence of moisture was simulated by means of polyethylene rods. In order to simulate a range of water densities in the void space between the pebbles of the different geometrical configurations, a number of different shapes and sizes of polyethylene rods were used. The dimensions and specific densities, of the available rods are detailed in Figure 4. Most of the rods were produced in two variations, machined and unmachined. It was envisaged that the, cheaper, unmachined rods, which were expected to be less homogeneous along their length, would be used for approaches to critical, with the much more expensive, machined rods being used for the final critical balance, since these were (in theory) better characterized. However, measurements at PSI have subsequently shown that the 6 and 9mm unmachined rods show, surprisingly, a somewhat higher homogeneity than the machined versions, with the added advantage that the unmachined rods have not been exposed to an extra ‘impurity hazardous’ machine environment.

4.2.10. Miscellaneous

In at least one configuration (Core 6), an attempt was made to compensate the positive reactivity effect of adding polyethylene to the core by simultaneously adding high purity copper wire to the core region. The copper wire used was 99.9% pure and had a nominal diameter of 1.784mm and a specific density of 0.2232g/cm.

REFERENCES

[4.1] H.R. LUTZ et al., “Slightly Enriched Uranium Single -Rod Heavy - Water Lattice Studies“, EIR Bericht No. 99, September 1966.

[4.2] R. RICHMOND, “Measurement of the Physics Properties of Gas-Cooled Fast Reactors in the Zero Energy Reactor PROTEUS and Analysis of the Results“, EIR Report No. 478, December 1982

[4.3] R. RICHMOND and J. STEPANEK, “Application of a Coupled Zero Energy Reactor for Physics Studies of HTR Systems“, EIR Internal Report TM-22-81-25, August 1981

[4.4] R. CHAWLA et al., “Reactivity and Reaction-rate Ratio Changes with Moderator Voidage in a Light Water High Converter Reactor Lattice“, *Nucl. Technol*, **67**,360 (1984).

[4.5] H.-D. BERGER et al., “Dokumentation der PROTEUS-FDWR Phase II-Experimente“, PSI Internal Report TM-41-93-05, May 1993

[4.6] D. MATHEWS and T. WILLIAMS, "LEU-HTR PROTEUS System Component Description", PSI Internal Report TM-41-93-43, November 1995.

[4.7] T. WILLIAMS, "Configuration Descriptions and Critical Balances for Cores 1-7 of the HTR-PROTEUS Experimental Programme", PSI Internal Report TM-41-95-18, November 1995.

[4.8] T. WILLIAMS, "Measurement of the Absorption Properties of the HTR-PROTEUS Reflector Graphite by Means of a Pulsed-Neutron Technique", PSI Internal Report TM-41-93-34, October 1995.

Tables

^{235}U mass per fuel pebble	1.000±0.01g
^{238}U mass per fuel pebble	4.953±0.05g
Total U mass per fuel pebble	5.966±0.06g
Carbon mass per fuel pebble	193.1±0.2g
Total mass per fuel pebble	202.22±0.18g
Fuel pebble inner (fueled) zone radius	2.35±0.025cm
Fuel pebble outer radius	3.0006±0.002cm
Radius of fuel particles (UO_2)	0.0251±0.001cm
Density of fuel particles	10.88±0.04g/cm^3

Table 1. LEU-HTR Fuel Pebble Physical Specifications

Moderator pebble mass	190.54±1.44g
Moderator pebble outer radius	2.9979±0.0015cm

Table 2 Moderator Pebble Specifications

GRAPHITE TYPE	OCCURENCE	DENSITY ($g.cm^{-3}$)	NOMINAL σ_a ($mbarn.atom^{-1}$)
Old graphite	Majority of system	1.76±0.01	3.785±0.3
New graphite for HTR PROTEUS - Batch 1	1.Central part bottom axial reflector 2. Central part top axial reflector 3. Filler rods for ≈ 50% "C-Driver" channels (inner channels) 4. Top 12cm of radial reflector 5. Filler pieces to adjust cavity shape	1.75±0.007	3.77±0.09
New graphite for HTR PROTEUS - Batch 2	1.Filler rods for ≈ 50% "C-Driver" channels (outer channels) 2. Filler pieces for old ZEBRA rod channels 3. Alternative central part of bottom reflector with longitudinal channel to allow axial traverses.	1.78	4.08
Moderator pebbles	Core	1.68±0.03	4.79
Fuel pebbles	Core	1.73	0.3829ppm B

Table 3 Summary of Reactor Graphite Properties in HTR-PROTEUS

Figures

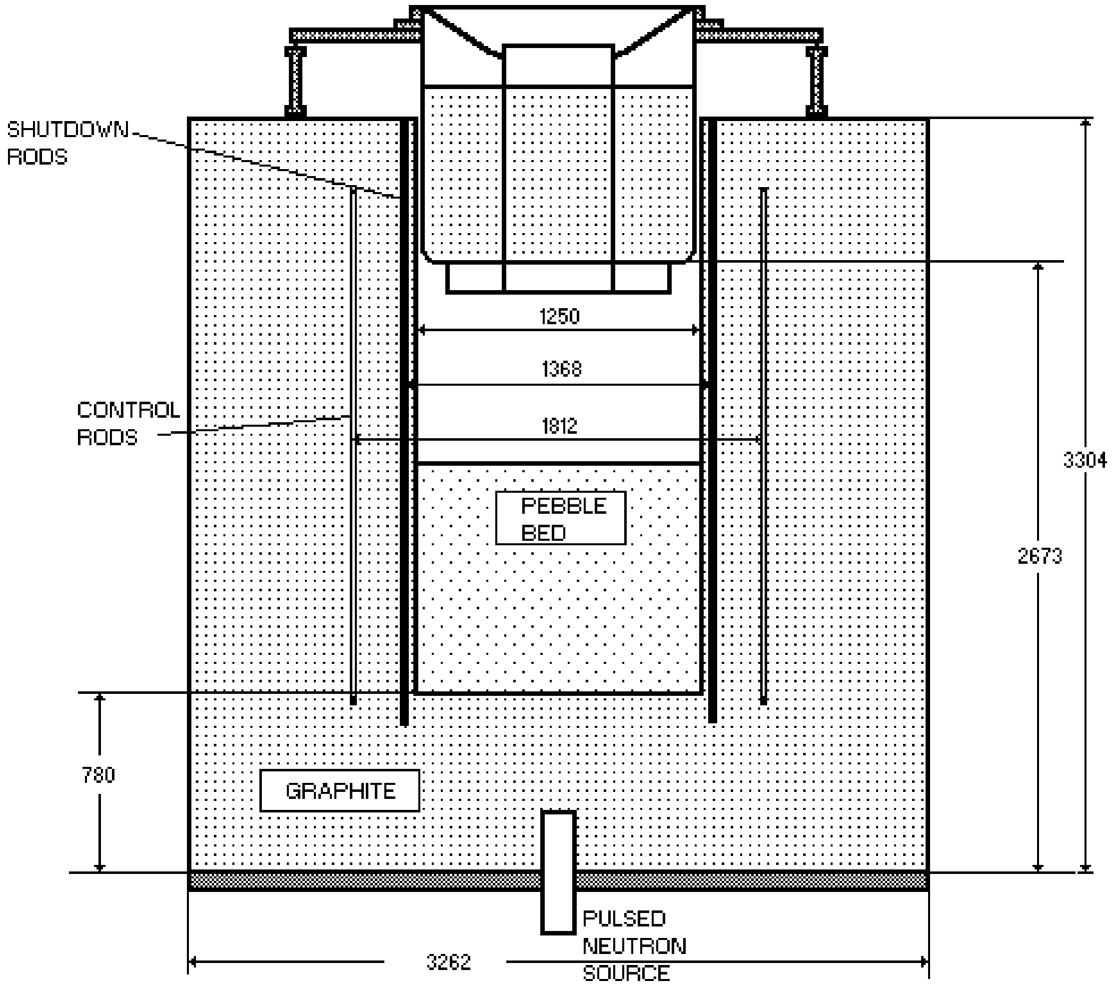
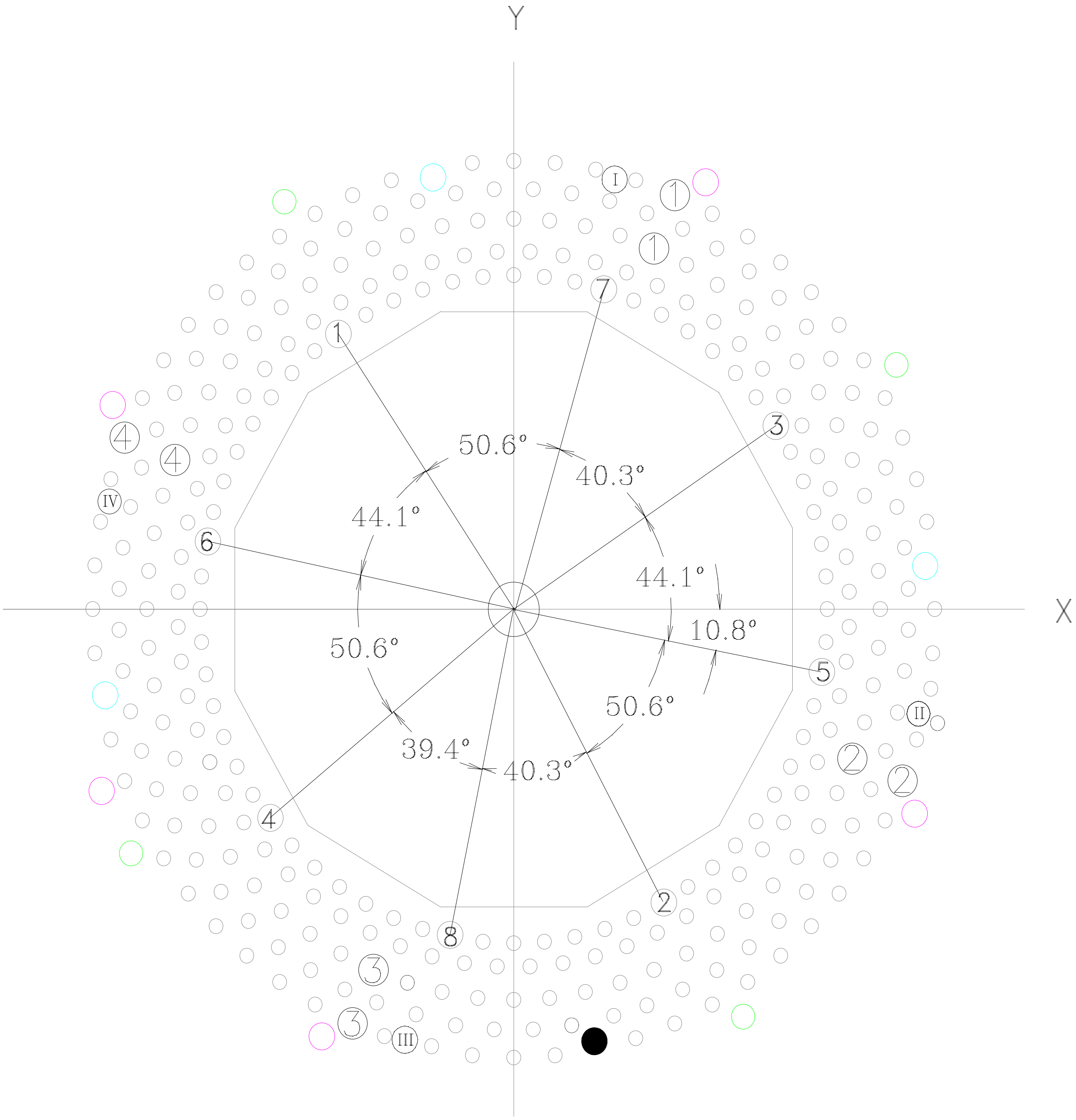


Figure 1. A Schematic Side View of the HTR-PROTEUS Facility (dimensions in mm)



①-④ - control rods (2 possible radial positions)

①-⑧ - safety and shutdown rods

● - automatic control rod

I - IV - Zebra control rods

Figure 2. **Horizontal Cross-Section Through the Core Region of HTR-PROTEUS**

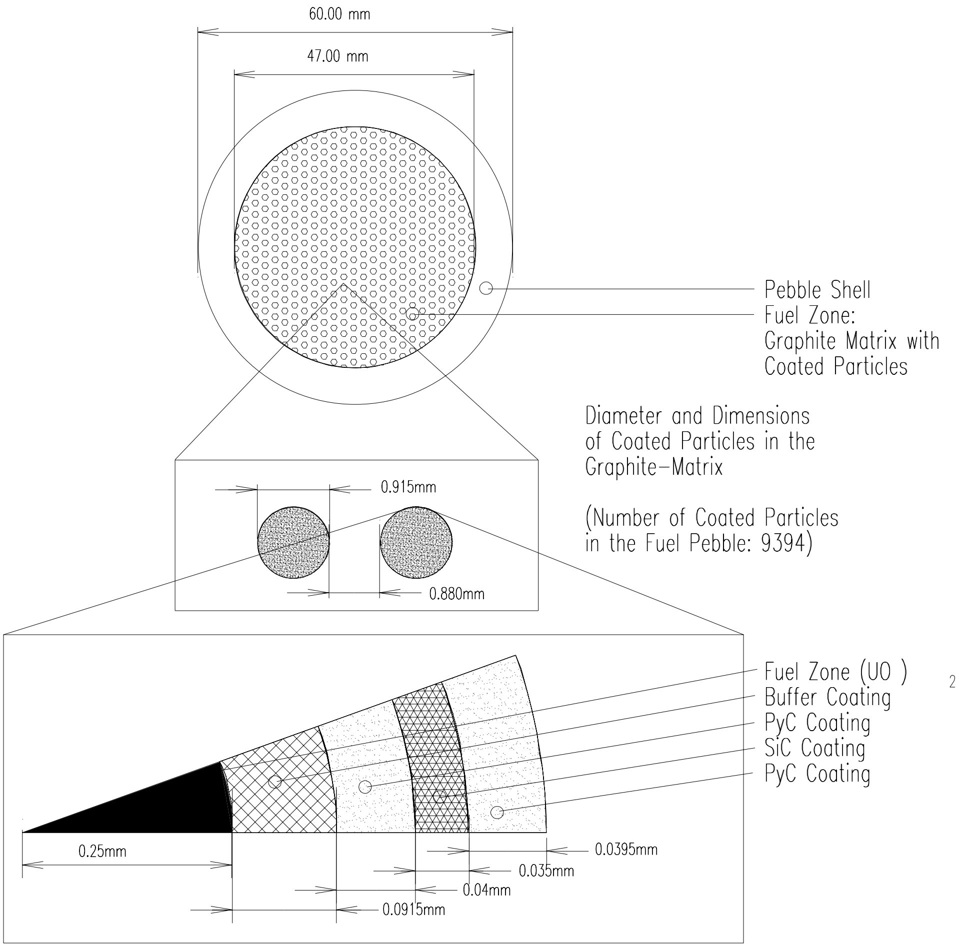
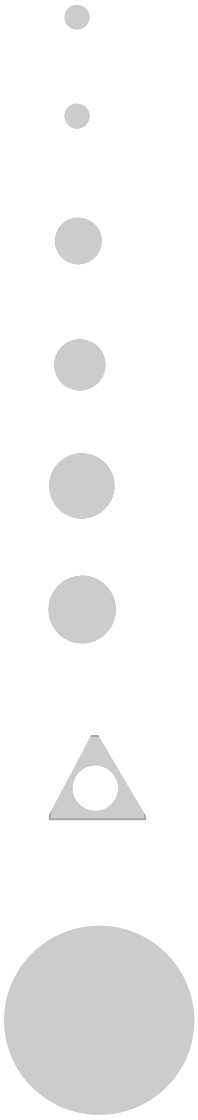


Figure 3 Fuel Pebble Construction and Dimensions



2.96mm diameter (machined)	0.0667±0.00006g/cm
3mm diameter (unmachined)	0.06616±0.00006g/cm
5.9mm diameter (machined)	0.2575±0.0001g/cm
6.5mm diameter (un-machined)	0.3161±0.0001g/cm
8.3mm diameter (un-machined)	0.5087±0.0007g/cm
8.9mm diameter (machined)	0.5867±0.0019g/cm
13.5mm sides 6mm hole	0.646±0.05g/cm
25mm diameter	4.808±0.001g/cm

Figure 4 Physical Properties of the Available Polyethylene Rods