WORKING DRAFT

PEBBLE BED MODULAR REACTOR

PBMR

FUEL QUALIFICATION

TEST PROGRAM

March 18, 2002

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1. Introduction

The purpose of this document is to describe the fuel qualification test program for TRISO-coated particle fuel in support of planned efforts directed toward the licensing of the Pebble Bed Modular Reactor (PBMR). An integrated international program is planned involving testing in South Africa, the Russian Federation and the United States. A quality assurance program that meets the applicable objectives of NRC quality assurance requirements will be implemented for the testing conducted in South Africa and the Russian Federation as well as the US.

Section 2 discusses the relationship of the fuel qualification testing to PBMR US licensing. The fuel performance requirements will establish the licensing basis contained in the PBMR combined construction permit and operating license (i.e. COL) application and will be based on meeting the applicable dose requirements over the range of events considered. The fuel response characteristics used in the COL application will be primarily based on existing test data. The PBMR fuel qualification test program will be confirmatory in nature and will demonstrate that the fuel manufactured by PBMR Pty will meet the design basis acceptance criteria as necessary to support plant licensing and subsequent operation.

Section 3 provides background information on PBMR fuel manufacture including; design, specifications and quality control. Data generated by the quality control program will be an important part of the overall qualification of the fuel for loading into PBMR.

Section 4 summarizes the existing body of knowledge and experience relevant to uranium dioxide (UO_2) coated particle fuel. A broad range of data has been produced and documented regarding UO_2 coated particle fuel performance under normal and accident conditions. The majority of the data are for coated particle designs that are very similar to the PBMR design, with additional data based on variations in design parameters broadening the overall applicability.

Lastly, section 5 introduces the international PBMR fuel qualification test program element. This integrated program will involve fuel characterization, irradiation testing, safety tests, and post irradiation examinations.

2. PBMR Fuel Testing Licensing Strategy

The PBMR licensing strategy will be to obtain a US COL for a PBMR plant. The licensing basis will include fuel material and performance specifications to be met by PBMR fuel, as well as reactor operational performance specifications (e.g., allowed circulating activity in the primary system). As discussed in Section 3, the design and fabrication process for PBMR fuel will be based directly on recent German experience fabricating Low Enriched Uranium (LEU) UO_2 coated particle fuel. As discussed in Section 4, a large body of international fuel test data and plant operating experience exists in support of the establishment of performance criteria for PBMR fuel under normal and accident conditions. The data and experience developed within the German program constitute the largest and most directly relevant body of information. Additional data and experience from China, Japan, and Russia complement the German information and expand its applicability. These data constitute a solid proof of principle for the UO_2 coated particle fuel form and, in conjunction with PBMR plant safety analyses and information developed regarding the PBMR fuel production process, will form the basis for the fuel specification contained in the PBMR COL application.

2.1 Relationship of Fuel Qualification Test Data to the PBMR Licensing Process in the US

The details of the PBMR fuel performance requirements will be established in the course of obtaining the COL, and will be driven by plant response characteristics and requirements for the protection of plant personnel and the general public. However, based on safety analyses performed to date on the PBMR, supplemented by licensing reviews of the HTR-MODUL in Germany and reviews of test and power high temperature gas cooled reactor designs in other countries, the requirements can be sufficiently well defined at present to proceed with planning the test program. For example:

- Normal Operation – Experience to date with plants operating with coated particle fuel has demonstrated that circulating activity can be expected to remain very low relative to normal operational considerations such as personnel exposure. Thus the fuel performance requirements under normal operation will likely be driven by considerations of the plant and fuel response under accident conditions. In other words, the release of fission product gases from the coated fuel particles under normal operation can be used as an indicator of the state of the fuel and its ability to withstand accident conditions (e.g., elevated temperatures).

- Accident Conditions – Based on the large body of existing data discussed in Section 4, fission product release due to increased temperature can be expected to be small if the fuel does not exceed temperatures in the range of 1600-1700ºC. The PBMR plant is being designed such that its inherent characteristics will limit temperatures below this range for all design basis events.

The major objective of the PBMR fuel qualification test program will be to demonstrate compliance with the PBMR fuel performance requirements specified in the PBMR licensing basis. Irradiation under conditions that conservatively approximate the environment that would be encountered by fuel in the PBMR during normal operation, with on-line monitoring for gaseous fission product release, will address performance requirements for normal operation. These data will be complemented by metallic fission product release data developed during post irradiation examination of fuel specimens. The response of fuel during accidents will be addressed by the testing of irradiated fuel specimens under conditions that conservatively approximate those that would be encountered by PBMR fuel under accident conditions. Based on the international experience in plant design and licensing, and in testing of UO_2 coated particle fuel, the greatest challenge to the fuel is the elevated temperatures reached following a depressurized loss of forced cooling. Thus the focus of accident condition testing will be on ability of the irradiated fuel specimens to retain radionuclides during heatup to elevated temperatures for a sufficiently long period of time. Data will be obtained regarding the release of gaseous and metallic fission products during and after the heatup tests, as well as the physical condition and internal fission product distribution in selected fuel specimens after the heatup tests.

The fuel performance requirements are expected to require a very low particle failure rate and fission product release, consistent with experience with modern UO_2 coated fuel particle data. Demonstrating compliance with sufficient statistical confidence will establish the quantity of fuel required to be tested. It is expected that the combined data from the US, Russian and South African test programs will be used to satisfy the fuel performance requirements.

2.2 Relationship of PBMR Licensing and Fuel Qualification Testing Schedules

As noted earlier, the PBMR fuel material specifications and performance requirements will be developed from existing data reflecting the performance of UO_2 coated particle fuel under normal operation and accident conditions in conjunction with PBMR plant safety analyses and data from the PBMR fuel production process. Since the data produced by the PBMR fuel qualification testing will be confirmatory in nature, test results are not required for the approval of the PBMR COL, although some early results may be of value and relevance in that process. The PBMR fuel qualification test program will confirm the fuel performance requirements as specified in the PBMR licensing basis.

The purpose of the qualification test program is to conduct testing of fuel that is representative of large-scale fuel production. Production fuel test specimens will not be available until a large-scale production facility has been established and is approaching equilibrium in terms of product quality and production levels. It is expected that the first PBMR core loading will be manufactured before completion of the entire fuel qualification test program. Therefore, the early in-pile fuel qualification program results may be used to qualify the fuel for initial core loading and power ascension, with continued operation contingent upon continuing successful performance of test fuel at burnups that exceed the maximum burnup that is being reached in the PBMR plant. The plan to continue to manufacture production fuel in parallel with fuel qualification testing considers the potential negative impacts of stopping large-scale production for a prolonged period that can affect production quality, fuel plant personnel skills and production plant efficiency.

2.3 PBMR Fuel

The PBMR fuel manufacturing and quality control processes and methods have been specified to be comparable to those that were used in the German fuel fabrication (i.e. NUKEM) plant. Where important from a process equivalence aspect, the PBMR fuel fabrication facility designs include the same type and basic design of manufacturing equipment, as well as the same process and equipment parameters as those that were used in the NUKEM plant.

The German fuel qualification program proved that fission product release from LEU-TRISO fuel of German reference design could be kept within acceptable levels under all normal operating and accident conditions. Thus PBMR fuel that is fabricated based on the German reference fuel design can be expected to perform to the same specifications, provided the expected irradiation conditions for PBMR fuel fall within the envelope of German fuel qualification tests, and that it can be proved that PBMR fuel is comparable to German fuel.

Comparability with the German fuel will be proved by:

- Showing that manufacturing specifications for PBMR fuel and German reference fuel are comparable.
- Showing that input raw materials are comparable to materials used to manufacture German reference fuel.
- Showing that important fuel manufacturing processes and equipment parameters are the same as those used for German fuel.
- Showing that the working parts used for critical processes are of comparable design as for German fuel.
- Showing that comparable QA procedures and tests are used for PBMR fuel.

The nature of coated particle fuel permits representative testing to be performed that envelopes the most limiting plant parameters that can be expected from abnormal plant conditions. This testing provides demonstration of the required fuel performance.

Fuel manufactured on the PBMR manufacturing line will be subjected to an irradiation-testing program similar to the HTR-Modul Phase 2 tests. These tests will demonstrate that the PBMR fuel will perform well under normal operating and accident conditions specific to PBMR, and that fission product release will remain at an acceptably low level under these anticipated conditions.

3. Production of PBMR Fuel

A fundamental aspect of the PBMR is the robustness of the PBMR TRISO-coated particle fuel. The production of high quality fuel is essential for ensuring the retention of fission products during both normal operating and accident conditions. A set of well defined manufacturing process and quality controls is critical to the consistent production of high quality fuel.

3.1 Overview of TRISO Fuel Manufacturing Process

PBMR fuel elements consist of TRISO-coated particles embedded in cold pressed graphite matrix material. The coated particles consist of spherical UO_2 kernels surrounded by four concentric layers. The first layer surrounding the kernel is a porous pyrocarbon layer, known as the buffer layer. This is followed by an inner high-density pyrocarbon layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon layer. The layers are deposited sequentially by dissociation of gaseous chemical compounds in a continuous process in a fluidized bed.

The spherical fuel kernel consists of stoichiometric uranium dioxide (UO_2). The basic manufacturing steps for the kernel are as follows. U_3O_8 powder is dissolved in nitric acid to form uranyl nitrate. The solution is neutralized with ammonia and allowed to flow through an oscillating nozzle to produce droplets. As the droplets fall through a gaseous ammonia atmosphere, the spherical outer surface of the droplet gels. The particles fall into an aqueous ammonia solution where they solidify into ammonium diuranate. They are then aged and washed to remove ammonium nitrate and organic additives, dried, and calcined. This is followed by reduction to UO_2 in hydrogen and sintering to produce the final kernels. The kernels are then sieved to remove over- and under-sized particles, and are then sorted on vibrating plates to remove odd-shaped particles.

The first layer in contact with the kernel is known as the buffer layer, and it is deposited at a temperature of 1200 ºC from acetylene (C_2H_2). The other conditions in the fluidized bed are arranged to keep the density of this layer below the maximum allowed value of 1.05 g/cm^3, which is about 46% of the theoretical density of pyrocarbon (2.26 g/cm^3).

The inner high-density, isotropic layer of pyrolitic carbon is also referred to as the Inner Pyrocarbon (IPyC) layer. It is deposited from a mixture of C_2H_2 and propylene (C_3H_6) at a temperature of 1300 ºC in a fluidized bed, and has an average density of 1.90 g/cm^3. This layer forms the first barrier against the pressure exerted by fission products within the fuel kernel, thereby reducing the pressure on the next layer (SiC). During irradiation, this layer shrinks at first, and then expands again as higher fast neutron dose levels are reached. The interaction between the inner and outer high density pyrocarbon layers and the SiC layer during irradiation plays an important part in keeping the SiC layer under compressive stress for a considerable portion of its service life.

The SiC layer is deposited from methyltrichlorsilane (CH_3SiCl_3) at 1500 ºC, achieving a minimum density of 3.18 g/cm^3 (nearly theoretical density). At high temperatures, the IPyC layer partially loses its ability to contain cesium and strontium. The purpose of the SiC layer is to prevent the release of these fission products into the graphite matrix and eventually into the reactor coolant stream. The SiC acts as the principal pressure barrier in the coated particle. The coated particle structure results in the SiC layer being kept under compression as long as possible by its interaction with the inner and outer pyrocarbon layers.

The Outer Pyrocarbon (OPyC) layer is deposited in the same way as the IPyC layer. The function of this layer is to protect the SiC layer against damage during the fuel sphere pressing stage of the fuel manufacturing process. It also provides a pre- stress on the SiC layer, due its shrinkage under fast neutron irradiation during the early phase of its lifetime in the reactor core, thereby reducing the tensile stress in the SiC layer.

The coated particles are over-coated and embedded in graphite matrix material consisting of a mixture of natural graphite and electrographite, together with a phenolic resin which acts as a binder material. The function of the graphite matrix is to contain and protect the coated particles from mechanical damage and to provide a heat conduction path between the coated particles and the reactor coolant. PBMR fuel elements are pressed in two steps. Before the coated particles are mixed into the matrix material for pressing, a coating of matrix material is applied to the outer surface of each coated particle in a rotating drum. This coating is known as the 'overcoat' and its purpose is to prevent coated particles from coming into contact with each other, and thereby damaging their coatings during pressing of the fuel elements. In the first step, coated particles and matrix material are mixed and pressed to form a fuel containing inner sphere. Fuel particles are distributed as evenly as possible in the inner fuel-containing zone (diameter of 50 mm) to prevent the development of hot spots in a fuel element. In the second step, matrix material is added to the mold and pressed to form a 5 mm thick fuel free zone around the fuel-containing zone. The purpose of this zone is to protect the inner zone from mechanical and chemical damage during fuel handling and operation. The spheres are machined, carbonized at 800 ºC, and then receive a final heat treatment at a temperature of 1950 ºC.

3.2 Fuel Specifications

The specification for the manufacture of fuel for the PBMR will be based on the NUKEM specification used to manufacture the AVR 21-2 reload for the AVR reactor in Germany. The process used for this batch was the state of the art at the time that the German program ended; fuel produced using this process demonstrated the lowest free uranium release fraction when subjected to a burn leach test. The PBMR fuel specifications are identical to the AVR 21-2 reference batch process with the exception of the anisotropy specification for the IPyC and OPyC layers for which the PBMR fuel will use a more restrictive value. It should be noted that the fuel design for AVR 21-2 differs from the PBMR design in that its enrichment was ~ 17% versus ~ 8% for PBMR, and the number of particles per sphere was ~ 9,600 versus ~ 15,000 for PBMR.

The direct materials used to manufacture the spheres include both natural and electrographite powders, as well as phenolic resin. These direct materials will be compliant with the same specification used for the reference batch process. In the case of the natural graphite powder, the original supplier is still in business. The original graphite source is still available to them, and they can supply the material in accordance with the NUKEM specification. The original supplier of the phenolic resin is also still in business and can supply the resin in accordance with the NUKEM specification.

The original supplier of the electrographite powder has been incorporated into a new supplier, and the original petroleum coke source is no longer available. The new supplier is working to identify an alternative coke source which will provide an equivalent product to the archive samples of the original material.

Material specifications for the indirect materials used in manufacturing the fuel, such as the process gases used to produce the coatings, have been established to ensure sufficient purity.

3.3 Quality Control Process

There are several quality control (QC) check points in the manufacturing process. The first check is performed as needed on the incoming feed materials. The checks that may be performed on the feed material are primarily chemical tests for impurities and chemical makeup. As an example, the specific characteristics that may be measured as part of this quality check are shown in Table 3-1.

Table 3-1: QC Measured Characteristics - U_3O_8

Characteristic
Uranium enrichment
Isotopic content
Impurities
Stoichiometry
Uranium content
Equivalent boron content
Moisture content
Particle size

The next quality check is performed on the uncoated UO_2 kernels following completion of sintering, sieving and sorting. Table 3-2 lists the specific quality attributes which are measured as part of this quality step. A check performed at this stage is the measurement of the sphericity of the kernels. Highly spherical kernels are required to ensure that stress peaks do not occur in the coatings during operation. This check is performed, and the kernel diameters are measured, by the use of an optical particle size analyser. Kernel batches which fail to meet any of the quality specifications are recycled; the uranium is recovered and fed back as feed material. Kernel batches which pass all the criteria are released for coating.

Table 3-2: QC Measured Characteristics - UO_2 Kernels

Characteristic
Diameter
Density
Sphericity
Equivalent boron content
Stoichiometry

Quality checks are performed at several points during the coating process. Samples are removed from the batch at each stage of the coating process, and specific attributes are measured. Table 3-3 lists the quality attributes measured for the coated particles. Typical measurement methods to determine the thickness and density of each coating layer include the following:

- The buffer layer thickness is determined by use of metallography and an image analyser. A particle size analyser and weigh scale is used to measure the buffer layer density.
- The thickness of the IPyC layer is also measured using metallography and an image analyser; the density of this layer is measured by use of a gradient column.
- The thickness of both the SiC and OPyC layers is determined by radiography.
- The densities of each of these layers is measured by use of a gradient column.

Coated particle batches which fail to meet one or more of the quality characteristics in Table 3-3 are recycled. The coatings are removed by chemical and mechanical processes and the recovered uranium is fed back as feed material.

The final quality check is performed on the final pressed fuel spheres after the completion of heat treatment.

Table 3-4 lists the quality characteristics measured as part of this final quality check. These checks primarily involve chemical tests for impurity content, and mechanical tests for physical integrity. Spheres which fail any of the criteria are recycled and the uranium is recovered.

Table 3-3: QC Measured Characteristics - Coated Particles

Characteristic
Buffer layer thickness
Buffer layer density
IPyC layer thickness
IPyC layer density
SiC layer thickness

Characteristic
SiC layer density
OPyC layer thickness
OPyC layer density
Anisotropy of IPyC and OPyC layers
Unconfined uranium (burn leach)
Isotopic content
Uranium content
Uranium enrichment

Table 3-4: QC Measured Characteristics – Fuel Spheres

Characteristic
Uranium enrichment (calculated from coated particle results)
Uranium content (calculated from coated particle results)
Equivalent boron content of matrix material (plus kernels)
Ash content of matrix material
Lithium content of matrix material
Unconfined uranium (burn leach)
Carbon content
Sphere diameter
Fuel free zone shell thickness
Surface defects
Drop strength
Crushing strength
Thermal conductivity of matrix material
Anisotropy of matrix material
Abrasion of matrix material
Corrosion of matrix material
Density of matrix material

4. Supporting International Fuel Data

The PBMR fuel design is the beneficiary of a broad array of international coated particle fuel development and testing, information exchange and collaborative activities. Initially addressing a wide range of fuel kernel compounds and coating combinations, the last 25 years saw a convergence of effort in many countries on a LEU UO_2 kernel and a TRISO coating design, with a buffer, inner pyrocarbon (IPyC), silicon carbide (SiC), and outer pyrocarbon (OPyC) layers.

The PBMR design ties directly to the German fuel development program, which was the most sustained and extensive. The German program benefited considerably from early efforts in the United Kingdom and the United States. Data and experience developed in Russia, Japan and China on LEU UO_2 TRISO fuel provide additional complementary support for the understanding of fuel performance under normal operation and accident conditions, and proof that high quality fuel can be fabricated at other facilities based on the German design and process. The most comprehensive compilation of international data and experience is provided in a document[i] produced by an IAEA Coordinated Research Project (CRP) on Validation of Predictive Methods for Fuel and Fission Product Behaviour. This CRP, conducted between 1991 and 1996, included participants from China, France, Germany, Japan, Russia, the United Kingdom and the United States and included fuel testing conducted in the Netherlands. The combined body of international data provides a clear and convincing demonstration of proof of principle for UO_2 coated particle fuel and a basis for confidence that PBMR fuel performance at a level comparable to the modern German fuel, from which the design was derived, can be achieved.

4.1 <u>Background</u>

Coated particle fuel for High Temperature Gas-Cooled Reactors (HTGRs) has been under development for over forty years in many countries. The particle kernels studied have included high and low enriched uranium, thorium, uranium/thorium mixtures and plutonium in oxide, carbide and oxycarbide forms. Early coatings included a single high density pyrocarbon layer, a buffer (low density pyrocarbon) layer with high density isotropic pyrocarbon outer layer (BISO) and other combinations. Most of the later development focused on the TRISO design, as noted earlier. Most of the countries with active HTGR programs in the 1980's and 1990's became focused on low enriched UO_2 fuel very similar to the PBMR fuel in the major parameters, as illustrated in Table 1.

Table 4-1. Comparison of Primary UO_2 Reference Coated Particle Design Parameters[ii]

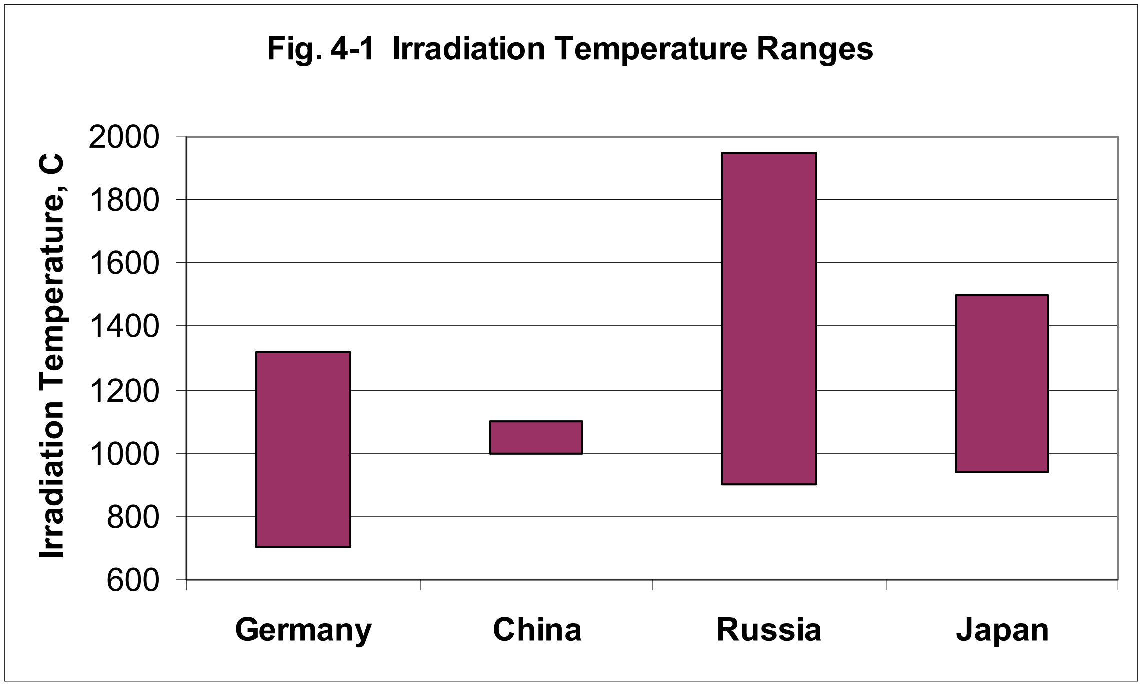
PBMR/ Country	Kernel Diameter (Microns)	Buffer Thickness (Microns)	IPyC Thickness (Microns)	SiC Thickness (Microns)	OPyC Thickness (Microns)	Fuel Form
PBMR	**500**	**95**	**40**	**35**	**40**	**Sphere**
Germany	500	95	40	35	40	Sphere
China	500	90	40	35	40	Sphere
Russia	500	95	75	60	60	Sphere
Japan	600	60	30	30	45	Block

As seen in Table 4-1, the designs being pursued in these countries are very similar to the PBMR design and thus fuel fabrication and testing data and experience are highly relevant to the PBMR fuel. It should be noted that while the Russian reference design coating thicknesses differ considerably from the PBMR design, a range of coating thicknesses that included the PBMR values were used in the test program. The test data includes a broad range of normal operation and accident conditions as summarized in the following sections. Additional large quantity performance data have been generated through operation of reactors using UO_2 coated particle fuel, including the AVR and THTR in Germany, the HTTR in Japan, and the HTR-10 in China.

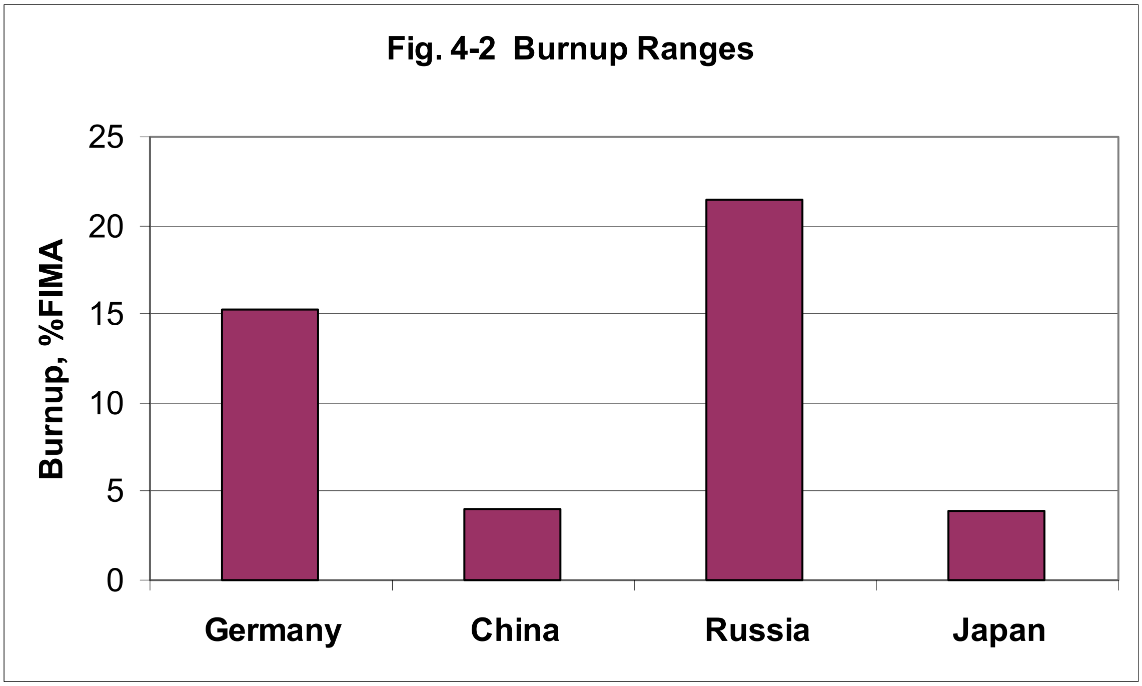
4.2 Fuel Performance in Normal Operation

Extensive irradiation programs of UO_2 coated fuel particles and fuel elements were conducted in Germany, Japan and Russia. Fuel produced in China is currently under irradiation in the Russian test reactor IVV-2M. The results of the irradiations in Germany, Japan and Russia are reported in considerable detail in IAEA-TECDOC-978, with references to more detailed data. The early results of the irradiation of fuel from China are reported in the proceedings of a seminar held in China in March 2001[iii].

Figures 4-1, 4-2 and 4-3 provide a simplified overview of the available data. The German testing followed broader developmental testing in the 1960's and 1970's, and was primarily focused on supporting the design and licensing of the HTR-MODUL concept. Testing in China is in progress and is directed toward supporting the operation of the HTR-10 reactor. Testing in Russia was more exploratory, covering a wider range of conditions including investigating the limits of the capability of the fuel. Testing in Japan was directed primarily toward supporting the operation of the HTTR reactor.



As indicated in Figure 4-1, the irradiation temperatures span a broad range, and taken together bound the expected PBMR fuel temperature design limit. The German data[iv] were intended to cover the range anticipated for the HTR-MODUL design and the Chinese data[v] are planned to support the HTR-10. As noted earlier, the Russian program[vi] was directed toward exploring the capability of the fuel, and thus included higher temperatures and burnups. The program in Japan[vii] has been directed toward the use of HTGRs for high temperature process heat, and thus for higher coolant outlet temperatures. This, in conjunction with the block fuel design and its associated higher fuel temperature for a given coolant outlet temperature, resulted in testing at higher fuel temperatures.

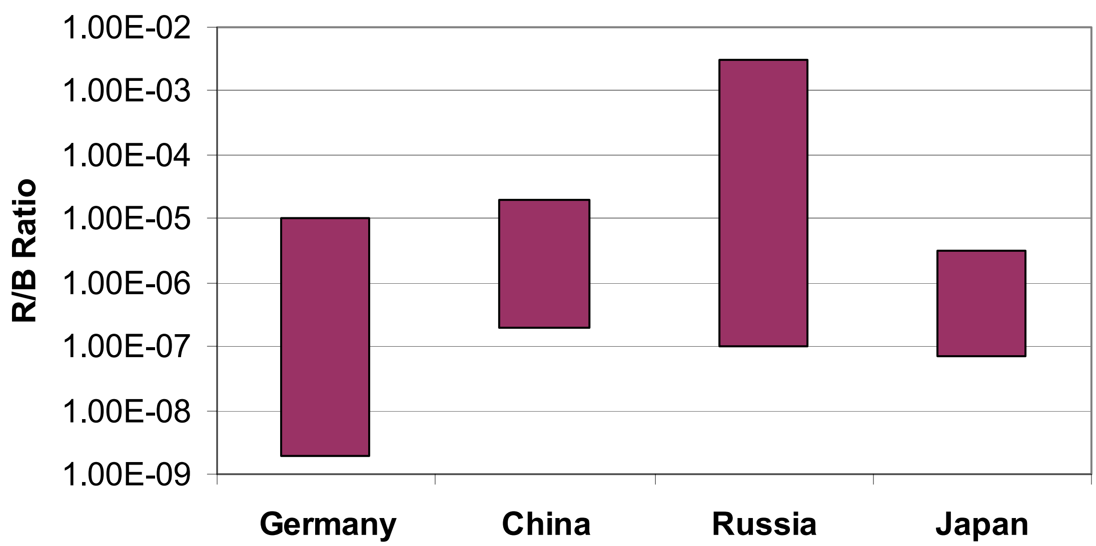


As indicated in Figure 4-2, fuel specimens in Germany and Russia were taken to burnups considerably above the expected PBMR average discharge burnup of 9% Fissions per Initial Metal Atoms (FIMA). The burnups for the fuel irradiations in Japan are considerably lower, consistent with the design conditions for the HTTR first core loading. The value given for China is the burnup achieved as of early 2001, with planned maximum burnup of approximately 11% FIMA at the completion of the test.

The range of in-pile gaseous fission product release-to-birth (R/B) ratio for the irradiation testing is shown in Figure 4-3. The data for Germany and China is reported as R/B of the isotope Kr-85m, which typically runs slightly higher (< 2x) than the Kr-88 R/B reported for the data from Russia and

Japan. This difference is sufficiently small that the comparison is not significantly affected. The German data shows the lowest in-pile release, consistent with the more mature status of the German fuel program in the time period of the testing. The much higher release of the Russian testing reflects the exploratory nature of the testing, which subjected the fuel to burnups and temperatures well beyond expected design conditions. The data from Japan reflects the higher operating temperatures experienced by the fuel during irradiation (in-pile R/B was determined for whole capsules that included multiple compacts at a range of temperatures). The data from China were for the early products from the fuel fabrication program for the HTR-10 initial fuel loading, and reflect a lesser degree of maturity. Burn leach testing of the HTR-10 fuel batches showed approximately an order of magnitude improvement in fuel quality during the production of the first 25 lots.

Fig. 4-3 In-Pile R/B



Taken as a whole, the body of international fuel irradiation data on UO_2 coated particle fuel of similar design, as summarized above and discussed in greater detail in IAEA-TECDOC-978, constitutes a solid proof of principle for the PBMR fuel. These data are in turn supported by a larger body of data on a variety of coated particle fuel designs. The international information exchanges and collaborations supported the successful transfer of important aspects of the German fuel process to other countries. In comparison with programs in these countries, the German fuel product specification, process specification and procedures have been obtained in much greater detail for the establishment of the PBMR fuel design and production process. Thus, the irradiation program for PBMR fuel is directed toward qualification for service under PBMR design conditions, with the understanding that results of this limited test program are supported by a large body of data from similar fuels tested under PBMR relevant conditions.

4.3 Fuel Performance Under Accident Conditions

The conditions experienced by the fuel during accidents are determined by analysis of plant response to design basis events and consideration of other events of lower probability that are considered relevant to emergency planning, typically designated emergency planning basis events. Events can be categorized as heatup events, associated with a loss of coolant with no active residual heat removal; oxidation events, associated with air or water ingress at high temperature; and reactivity transients, associated with control rod motion or changes in core geometry. Existing international data for these categories are summarized in the following sections.

4.3.1 Heatup Testing

The irradiation history of the fuel prior to a heatup event has been shown to be an important factor affecting how the fuel will perform. In an actual pebble bed reactor, the core will contain a mixture of fuel ranging from fresh fuel to fuel approaching the allowed burnup limit. Fuel samples used in heatup testing have spanned a range of burnups, but most of the data are associated with burnups approaching or exceeding the discharge burnup. Fuel performance during a heatup event will be a function of time at temperature, with peak temperatures (typically approximately 1600ºC) reached and a slow decline beginning over a period of several days. Much of the testing has been conducted by heating irradiation fuel specimens to a specific temperature and holding it constant for periods ranging from 30 to 500 hours. Testing has also been conducted simulating the expected time dependent temperature behavior, as well as slowly increasing temperatures reaching as high as 2500ºC.

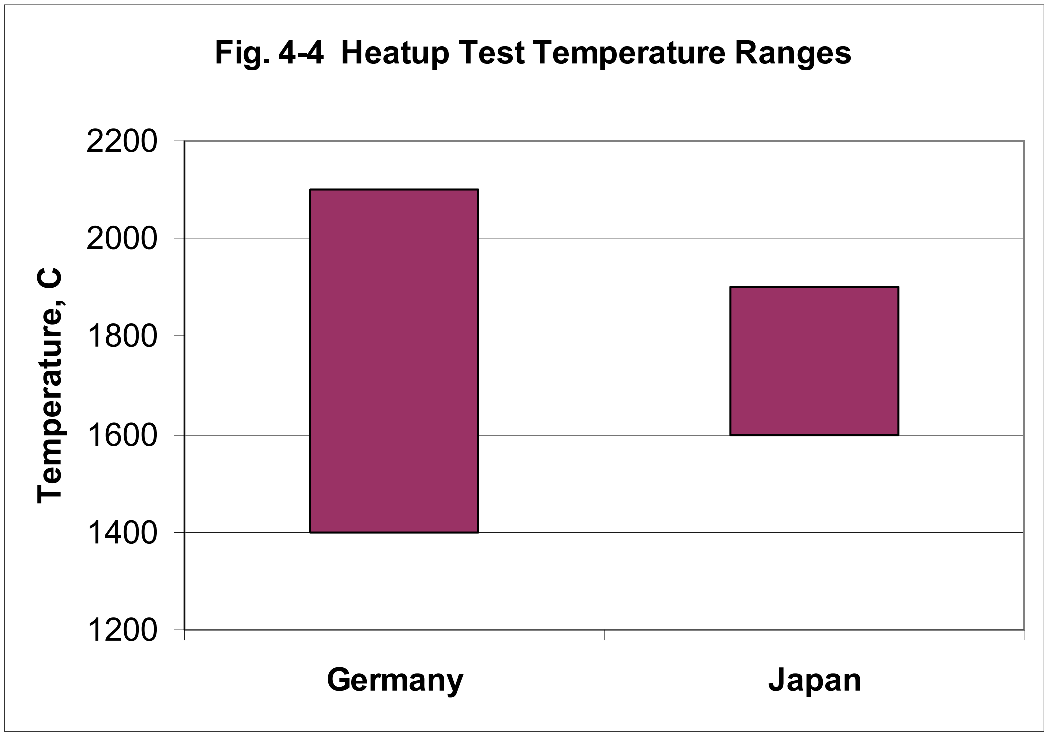


Figure 4-4 shows the range of temperatures used in constant temperature post irradiation heatup tests in Germany[viii] and Japan[ix]. In addition to the heatup tests, a limited amount of irradiation testing at high temperatures (1500-2000ºC) was conducted in Japan. The behavior of radionuclides during the tests are determined by on-line gaseous release measurements, periodic metallic fission product release measurements using a cold finger in the furnace, and post test fission product profiling of the test specimens and holders. The Russian program included high temperature irradiations as reported earlier, and linear ramps to temperatures in excess of 3000ºC. China will be conducting heatup tests of fuel samples currently under irradiation in the IVV-2M reactor in Russia.

4.3.2 **Oxidation Testing**

Oxidation of graphite and coated particle fuel has been reviewed and addressed since the beginning of HTGR technology development over 40 years ago. For the steam cycle designs, oxidation from steam or water entering the primary system due to steam generator tube leaks has been the most likely issue. In the case of the PBMR gas turbine design, there is no steam generator, and the water heat exchangers operate with much smaller inventories at pressures far below the helium pressure, so significant water in-leakage is highly unlikely.

Air ingress following a system depressurization has also been studied in considerable detail. Significant oxidation due to air ingress is conceivable in the case of a very large break opening that remains for several days without mitigating action. However, this event is sufficiently unlikely that it is not considered to be within the PBMR licensing basis and consequently no fuel testing is planned to address air ingress. Nonetheless, considerable data exists with regard to oxidation of UO_2 coated particle fuel, as summarized below.

Extensive international testing with regard to oxidation resulting from moisture ingress has been conducted[x]. These tests addressed conditions that could occur with large amounts of water entering the primary system under hot pressurized conditions, diffusing into the fuel elements and attacking the particles. Earlier testing had shown that intact coated particles are not affected by the water, so the tests focused on failed particles. Some tests involved designed-to-fail particles (e.g., thin coatings with missing buffers), while others involved locating failed particles in irradiated fuel elements or crushing particles deconsolidated from the elements. The release characteristics for failed particles as a function of burnup and temperature are reasonably well understood. Since only the failed particles are affected, releases are low and of no significance given the low probability of water ingress in the PBMR design.

Testing for oxidation resulting from air ingress has also been conducted[xi]. In Japan, unirradiated particles and compacts were subjected to an air atmosphere for temperatures ranging from 900 to 1400ºC[xii]. The results showed a low level ($5.4x10^{-4}$ failure fraction) of particle failure in loose particles exposed to air for 600 hours at 1300ºC. Fuel compact behavior was quite different, with the difference attributed to the possibility of elevated temperatures occurring in the compact interior.

In Germany, irradiated particles and spheres were subjected to an air environment for temperatures ranging from 1300 to 1620ºC[xiii]. Loose particle tests showed failures increasing to 100% at 1500ºC. Sphere testing showed low failures (~10^{-4} failure fraction after 400 hours) at 1300ºC, increasing (~10^{-3} failure fraction after 140 hours) at 1400ºC. These data indicate a high degree of retention of fission products even under oxidizing conditions where all of the graphite outside the silicon carbide coatings has been consumed.

4.3.3 Reactivity Transient Testing

The online refueling of a pebble bed reactor allows for operation with a limited amount of excess reactivity, thus limiting the potential for reactivity transients. Within the PBMR design and licensing bases, reactivity transients are relatively benign and the resulting fuel temperature conditions are well within temperatures addressed for heatup events, thus no specific reactivity transient testing is envisioned for PBMR fuel. A limited amount of reactivity transient testing of UO_2 coated particle fuel has been conducted in Japan and Russia as summarized here.

Short term pulse tests were conducted in both Japan and Russia. In Japan, loose particles and compacts were subjected to pulses of 10-30 millisecond duration, with energy deposition ranging from 200-2300 J/gUO_2. In Russia, loose particles and spheres were subjected to pulses of 1-2 millisecond duration, with energy deposition ranging from 100-1700 J/gUO_2. The results of these tests are in good agreement and widely available in summary form[xiv].

In addition to the pulse tests, longer duration high power tests were conducted on spherical fuel elements in Russia. In the first series of tests the fuel elements were subjected to three sequential power pulses: 1.6 seconds at 150 kW/element, 1.0 seconds at 300 kW/element, and 0.7 seconds at 620 kW/element, values exceeding 100 times design maximum power per sphere. In the second series of tests the fuel elements were subjected to three pulses ranging in duration from 7 to 30 seconds at a power level of 46 kW/element, approximately 10 times design power levels. The most extreme of these tests reached maximum temperatures of approximately 3000ºC and resulted in the destruction of the spheres, while the spheres remained intact in less extreme tests. These data are not directly relevant to the PBMR, because it has no large reactivity transients within the licensing basis events, but illustrate the capacity of the fuel to withstand very large overpower events.

5. PBMR Fuel Qualification Testing

The large irradiation database on the TRISO-coated UO_2 fuel developed by Germany, supplemented by other international data as discussed in section 4, provides proof of concept for the PBMR fuel. The objective of the fuel qualification test program is to provide the data necessary to demonstrate that the PBMR production fuel meets the in-reactor performance requirements as specified in the PBMR licensing basis. An integrated international program is planned involving testing in South Africa, the Russian Federation and the United States. A quality assurance program that meets the applicable objectives of the NRC quality assurance requirements will be implemented for the testing conducted in South Africa and the Russian Federation as well as the US.

The fuel qualification test program contains irradiation, safety testing and post irradiation activities to be conducted at the SAFARI reactor in the Republic of South Africa (RSA), the IVV-2M reactor in Russia and in the Advanced Test Reactor (ATR) in the US. Archived German fuel manufactured for the AVR, pre-production (or lab scale) and production fuel produced by the South African PBMR fuel production facility will be used in the program. The exact details of the irradiations, accident testing and post irradiation examinations will be a function of the operating envelopes and accident conditions established by the PBMR licensing basis.

Table 5-1 summarizes the PBMR fuel qualification test program in terms of objectives and testing to be conducted. A review of the fuel failure mechanisms, the key variables that control the phenomena, and their impact on the testing program are presented in Section 5.1. Details of the irradiation testing are discussed in Section 5.2, including background and rationale, and the proposed test matrices. In Section 5.3, the testing to be performed under accident conditions is presented. Section 5.4 delineates the post irradiation examination activities that are currently envisioned.

Table 5-1. Summary of PBMR Fuel Qualification Program

Type of Testing	Type of Fuel or Nature of Test	Objectives/Comments
Pre-demonstration	Pre-production fuel in RSA and Russia Archived German fuel in US	Use these tests to shakedown all systems. Irradiate German fuel to test influence of PBMR operating temperature
Demonstration Irradiations	Production fuel. Statistically significant quantities under irradiation in Russia and RSA	Demonstrate acceptable fuel performance under normal operating conditions (temperature, fast fluence and burnup).
Irradiation Margin Testing	Temperature, burnup and fluence margin testing in US	Explore behavior outside of normal operating envelope. Supplement statistical database
Safety Testing	Traditional isothermal heatup testing. Russia and RSA testing of safety envelope.	Demonstrate acceptable fuel performance under accident conditions. Statistical quantity of fuel at 1600°C. Burnup and temperature are key variables
Safety Margin Testing	US testing will explore beyond the safety envelope (margin)	Explore behavior at and outside of the safety envelope (test at and beyond 1600°C). Supplement statistical database
Post irradiation Examination	After irradiation and safety tests	Characterize the state of the fuel after irradiation and safety testing.

5.1 Fuel Failure Mechanisms, Key Variables and Their Impact on the Test Program

Development of the fuel qualification test program requires an understanding of the behavior of the fuel and the potential fuel failure mechanisms under normal and accident conditions. A review of the literature of coated particle fuel reveals a number of potential failure mechanisms. These failure mechanisms are functions of temperature, burnup, fluence, and temperature gradient across the particle. In this section, these mechanisms are briefly reviewed and the variables that control them are described. The impact that such mechanisms have on the test program is also presented.

5.1.1 Overpressure

Under irradiation coated particle fuel is subjected to a number of forces that put stress on the TRISO coating. One of the earliest recognized mechanisms is overpressure due to gas generation under irradiation and/or accident conditions. During irradiation, fission product gases are released from the kernel to the porous buffer layer. The pressure that is generated exerts tensile forces on the inner PyC and SiC layer of the particle. In addition to fission product gas, in coated particle fuel with UO_2

kernels, there is excess oxygen released during fission. The rare earth and other fission products tie up about 1.6 atoms of oxygen per fission, leaving an excess of 0.4. This excess oxygen will react with the buffer to form CO gas. Both the fission product gas and CO production are functions primarily of burnup and temperature. As with all TRISO-coated fuel, PBMR fuel particles are designed with a large enough buffer void volume to ensure that nominal particles do not fail by overpressure during irradiation or under accident heatup conditions. Particle failure is only postulated to occur in the event that during the coating process, particles are coated with an insufficient or missing buffer layer (i.e., void volume to accommodate the gases). Thus, PBMR fabrication process limit the number of particles produced with thin or missing buffer layers.

5.1.2 Irradiation-Induced IPyC Cracking

Under irradiation, PyC initially shrinks in both the radial and tangential direction. At modest fluences (~ 1 to 2 x 10^{25} n/m^2) depending on the density, temperature and anisotropy of the material, it begins to swell in the radial direction but continues to shrink in the tangential direction. This behavior puts the PyC layers into tension in the tangential direction. At longer irradiation times, irradiation induced creep works to relieve the tensile stress in the PyC layer. If the IPyC anisotropy is excessive, the stresses lead to shrinkage cracks in the layer. However, if the PyC is more isotropic and remains strongly attached to the SiC layer, as is the case for fuel produced using the German coating process, the PyC shrinkage is tolerable and in concert with the OPyC layer provides a strong compressive stress in the SiC layer that offsets the tensile stresses generated by gas production in the kernel. In fact, the particles are fabricated to limit the level of anisotropy such that in intact particles, shrinkage cracks do not occur and the SiC layer remains in compression throughout their lifetime in the reactor. Thus, this failure mechanism is not expected in PBMR fuel.

5.1.3 Creep Failure of PyC

Under stress, thermal creep of the PyC will occur. In some post irradiation heating tests, photomicrographs reveal a thinning and failure of the PyC. This is primarily for tests at very high temperatures (> 2000°C) and very long times when thermal creep can operate. Such failure has not led to failure of the SiC layer. Because this failure mechanism operates well beyond the PBMR safety envelope, it is not expected to be important in PBMR fuel.

5.1.4 Kernel Migration

Kernel migration is defined simply as movement of the kernel in the coated particle toward the TRISO-coating. If the migration is excessive, the kernel will eventually come into contact with the SiC layer with increased chemical attack leading to thinning and failure of the SiC layer. Kernel migration, also known as the amoeba effect, is associated with carbon transport in the particle in the presence of a temperature gradient. This phenomenon is strongly dependent on the temperature gradient in the fuel with secondary dependence on temperature and burnup. Kernel migration has not been observed in German irradiation experiments or in AVR and THTR operation because of the low thermal gradient. Similarly, it is not expected to be a significant failure mechanism in the PBMR. In the design of irradiation experiments, however, it is important to limit the thermal gradient or power per particle to values that are not substantially higher than of that in the reactor application to ensure that no false positives are observed. As a result, the level of acceleration of any coated particle fuel irradiation is recommended to be no greater than 3 times real time. For the PBMR fuel testing, a power per pebble limit of < 2500 W has been established.

5.1.5 Fission Product Attack

Past irradiation experiments indicate that fission products can be transported from the kernel to the inner surface of the SiC where they interact and can damage and potentially fail the SiC layer. In UO_2 kernels, palladium is very important, as are some of the rare earth and noble metal fission products. Pd attack of the SiC is more accelerated under the higher temperatures associated with accidents than under normal operation, although the thermal gradients in the fuel under accident conditions are expected to be less than in normal operation. Studies have been conducted to understand the mechanism for Pd attack of the SiC. The migration of the fission products is thought to be functions of temperature and burnup as well as temperature gradient. As a result, the level of acceleration of any coated particle fuel irradiation is recommended to be no greater than three times real time. Unacceptable Pd attack has not been observed in German fuel and thus is not expected to be significant for PBMR fuel.

5.1.6 SiC Thermal Decomposition

At very high temperatures (> 2000°C), thermodynamics and data from German furnace-heating tests show that the SiC layer undergoes thermal decomposition. The phenomenon is primarily a function of temperature and time and has not played a major role in fuel failure at the lower accident temperatures (1600-1800°C) which bound PBMR conditions. Thus, it is not expected to be important in the PBMR testing presented here.

5.1.7 Enhanced SiC Permeability

Although not formally a failure mechanism, there is some limited evidence that fast neutron fluence and/or burnup plays a role in the permeability of the SiC layer to fission products under irradiation and high temperature heating. Pebbles exposed to higher fluence ($4\text{-}6 \times 10^{25}$ n/m^2) and higher burnup (14% FIMA) than the PBMR operating envelope have exhibited a greater release of fission products (e.g., cesium) in heating tests than similar pebbles exposed to conditions inside the PBMR operating envelope.

5.1.8 As-Manufactured Defects

In the absence of any of the above failure mechanisms, any fission gas and metal release during irradiation is attributed to heavy metal contamination outside of the SiC layer and initially defective particles. Initially defective particles can be the result of undetected defective particles that have not been removed during fabrication, attack of the particles by impurity metals (e.g. Fe), or particles that have failed as a result of the formation of the particles into a pebble. Numerous process improvements were made to the German fuel fabrication process over the years to minimize these defects. For example, particles are tabled at numerous points during fabrication to remove out of round particles. Metal screens are no longer used in some fabrication lines to limit metal pickup during fabrication. Graphite furnaces are used exclusively in all critical heating steps. A soft overcoating is put on the particle after the OPyC layer to reduce out of roundness and to limit stresses induced by particle-to-particle contact during pebble manufacture.

5.1.9 Impact on the Test Program

These failure mechanisms have been observed to some extent in TRISO-coated fuel testing activities conducted around the world, especially under service conditions more severe than the PBMR. They are in general functions of temperature, burnup, fluence and temperature gradient in the particle. Based on the previous German experience, the PBMR and its fuel are designed such that none of the fuel failure mechanisms are expected to be significant. Fission product releases during irradiation and heatup testing will be dominated by as-manufactured defects in the production fuel. Nevertheless, the fuel qualification test program will be designed to bound the burnup, fluence, temperatures and temperature gradients expected in the PBMR and to limit the test conditions/parameters to values that will not result in inadvertent failure of the fuel.

5.1.10 Relevant Statistical Issues

As discussed in section 3, strict process control and proper statistical quality control is needed to limit as-manufactured defects in coated particle fuel. A qualification test of fuel from the production line must consider the statistical nature of this fuel. A statistically significant amount of fuel must be tested to ensure at 95% confidence that the fuel can meet the failure fraction specification. As shown in Figure 5-1, to demonstrate that a core average failure fraction specification of 2×10^{-5} has been met based on no failures observed during the irradiation(s), simple binomial statistics indicates that a sample size of ~ 200,000 particles is needed. For the PBMR, this corresponds to ~ 13 pebbles.

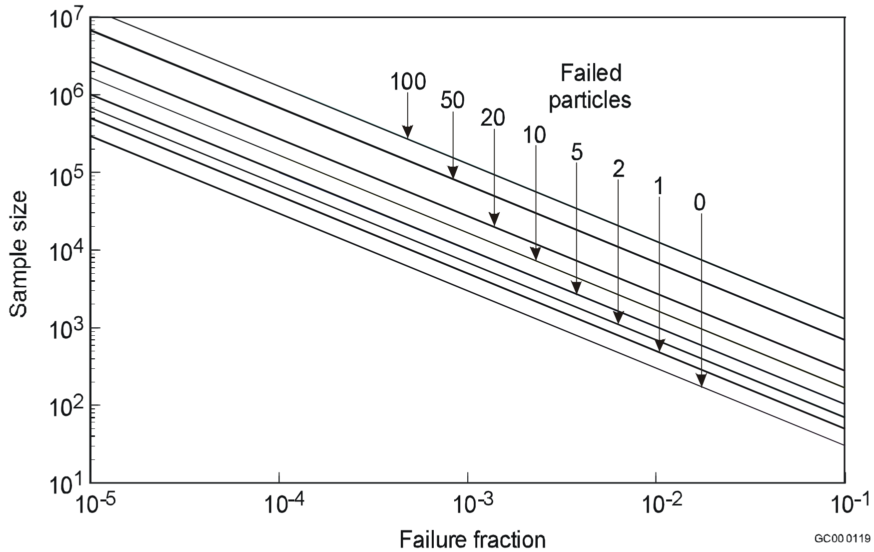


Figure 5-1 Particle Failure Statistics

5.2 Fuel Performance Testing Under Normal Conditions

The purpose of this section is to define an irradiation test matrix for PBMR coated particle fuel. The test matrix will relate the testing conditions to the design service conditions of the reactor to confirm a normal design envelope for this fuel and also contribute to the understanding of margins around this envelope. The technical basis and rationale for the irradiations will also be established.

5.2.1 Irradiation Test Matrix and Technical Rationale

A test matrix for all of the irradiations is shown in Table 5-2. Listed is the facility, the number of pebbles to be irradiated, the temperature, burnup and fluence expected in each irradiation and comments about the goal of the irradiation and/or the disposition of fuel after irradiation. All irradiations are slightly accelerated between 1.5 and 3 times real time (i.e., one to two year irradiations). The exact value depends on the test reactor and irradiation location therein. Four types of irradiation testing are proposed for coated particle fuel: testing of pre-production lab-scale fuel, irradiation of archived German fuel, demonstration irradiations and margin testing.

Table 5-2. PBMR Irradiation Test Matrix

Facility Location	# Pebbles	Temperature	Burnup (% FIMA)	Fast Fluence ($*10^{25}$ n/m^2)	Comments
Pre-production Fuel					
South Africa	4	HOT[i]	9%	2	Constant temperature irradiation
Russia	4	Temperature cycles – LOT[ii] to HOT	11%	2	Multiple temperature cycles – 1/3 cycle @ LOT, 2/3 cycle @ HOT
Archived German Fuel					
US	6	HOT	9% to 11%	2.1 to 4	Constant temperature irradiation
Production Fuel - Demonstration Portion of Qualification Program					
South Africa	4	HOT	4%	1	Constant temperature irradiation
	4	HOT	6%	1.6	Constant temperature irradiation
Russia	12	Temperature cycles – LOT to HOT	11%	2.8	Multiple temperature cycles – 1/3 cycle @ LOT, 2/3 cycle @ HOT. PLOFC[iii] simulation for several pebbles at end of irradiation. Statistically significant quantity of fuel.
Production Fuel - Margin Portion of Qualification Program					
US	2	HOT + 100°C	11%	~ 6 - 8	Constant temperature irradiation. High temperature margin test
	2	HOT	11%	~ 6 - 8	Constant temperature irradiation. Fluence margin test
	6 - 8	HOT	11%	~ 6 - 8	Constant temperature irradiation. Feedstock for safety margin testing. Supplement Russian statistics.
	2 - 4	HOT	~ 5%	~ 6	Constant temperature irradiation. Feedstock for margin safety testing.

Notes: i - High Operating Temperature (HOT) - high temperature expected during normal operation
ii - Low Operating Temperature (LOT) - low temperature expected during normal operation
iii - Pressurized Loss of Forced Cooling (PLOFC)

Irradiations, safety tests, and post irradiation examination of the PBMR pre-production (lab scale) fuel are planned in the SAFARI and IVV-2M reactors to gain experience prior to production fuel testing (i.e. shakedown all experimental facilities) and to provide early confidence about the performance of this fuel. The irradiations are planned to go to 11% FIMA and a goal fluence of 2 x 10^{25} n/m^2. An irradiation of six archived German fuel pebbles is proposed in the ATR at the high operating temperature to the goal burnup (9% FIMA) and slightly beyond the goal fast fluence (2.1 x 10^{25} n/m^2). An option exists to extend the irradiation to a target burnup of 11% FIMA if program constraints permit.

Demonstration (i.e. confirmatory) testing is designed to qualify the fuel produced from the production line and confirm that it is in compliance with the requirements of the PBMR licensing basis. The testing should demonstrate that the fuel performance specifications under normal operation and accident conditions are met using a statistically sufficient quantity of fuel particles. The demonstration testing should adequately encompass the burnup/temperature/fluence envelope of pebbles discharged from the reactor. Because of the range of flux and temperature expected in the reactor, definition of this envelope is very important. In the PBMR, the pebbles may see almost all of the conditions in the reactor during their life. A pebble cycles through the core multiple times and can take different trajectories ranging from the highly thermal flux region near the inner reflector, to the mixed fuel/graphite pebble region, to the fueled region. On each of these trajectories the pebbles accumulate different burnup, fluence and temperature histories on a statistical basis.

Irradiations of four pebbles at low burnup (4% FIMA) and four pebbles at moderate burnup (6% FIMA) are planned in SAFARI. An additional twelve pebbles at high burnup (11% FIMA) are planned in the IVV-2M in Russia. These 12 pebbles constitute the statistical demonstration test for the fuel. Some of the pebbles from the margin tests in the US can be used to enhance the statistical database of this fuel under normal operation. The testing in SAFARI will be isothermal at the high operating temperature. Irradiation in IVV-2M will simulate the temperature cycling expected under normal operation in the PBMR, with one third of the irradiation performed at the low operating temperature and two thirds of the irradiation performed at the high operating temperature. This temperature cycling will be performed in a periodic manner during the irradiation to envelope the multiple passes through the core that an average pebble sees during its lifetime. Finally, a few of the pebbles from each capsule will be subject to a high temperature (high operating temperature +

100°C) for a few hours to simulate a pressurized loss of forced cooling (PLOFC). The Germans have historically tested using this sort of protocol to bound variations in the temperature, burnup, and fluence expected in a pebble bed reactor.

The purpose of margin testing is to explore the limits of the fuel in terms of the key operating parameters and the failure mechanisms that have been identified earlier. These tests are intended to demonstrate that there is additional margin in the fuel design relative to uncertainties in actual pebble temperature histories, burnup and fluence relative to the reactor operational limits. An important aspect of margin testing is the extent to which these variables are explored in the irradiation testing. These decisions have been based on an understanding of the fuel failure mechanisms and any physical constraints imposed by the irradiation facility. Temperatures ~ 100°C greater than the peak temperature, burnups 2% FIMA above goal burnup and fluences 2 to 4 times greater than goal fluence are proposed for the margin tests and still achievable in existing irradiation facilities. The margin testing will be performed in the ATR in the US. Only a few pebbles are needed to explore the margins beyond the operating envelope. Because of the configuration of the flux trap in the ATR, the 10 to 12 pebbles positioned around the axial centerline of the reactor will achieve approximately the same burnup of 11% FIMA. An additional four pebbles, two at the top and two at the bottom will achieve burnups of about half this value (5% FIMA). Of the 10 to 12 pebbles at 11% FIMA, two pebbles are proposed to serve as a fluence margin test, two pebbles are proposed as a high temperature margin test (High operating temperature + 100°C). The remaining six pebbles will be irradiated at the high operating temperature to serve as irradiated feedstock for safety testing. The four pebbles at moderate burnup will be used for safety testing.

A schematic representation of the test matrix for the irradiation testing of production fuel is shown in Table 5-3. The purpose of the table is to provide a graphical representation of how the testing in South Africa and Russia encompasses the PBMR operating envelope and the margin testing in the US explore the region outside the planned operating envelope.

Table 5-3 Schematic Representation of Combined Irradiation Test Matrix for PBMR Production Fuel

<table>
<tr><th rowspan="2">Temperature</th><th colspan="4">End of Life Burnup
(% FIMA)</th></tr>
<tr><th>Low
(4)</th><th>Medium
(6)</th><th colspan="2">High/Margin
(11)</th></tr>
<tr><td>Low Operating</td><td colspan="2"></td><td rowspan="2">12 pebbles
Russia</td><td></td></tr>
<tr><td>High Operating</td><td>4 pebbles
South Africa</td><td>4 pebbles
South Africa

2 to 4 pebbles
US</td><td>8 to 10 pebbles
US</td></tr>
<tr><td>Margin
(High Oper. + 100°C)</td><td colspan="2"></td><td colspan="2">2 pebbles US</td></tr>
</table>

5.3 Fuel Performance Testing under Accident Conditions

The purpose of this section is to outline the planned testing for coated particle fuel related to accident conditions. The goal of such testing is to demonstrate that the PBMR production fuel meets the performance requirements for accident conditions as specified in the PBMR licensing basis. The environmental conditions and fuel performance requirements for limiting accident conditions will be established in the course of the PBMR plant licensing review. Prior operating experience with pebble bed reactors, the licensing review of the HTR-MODUL design, and ongoing PBMR safety analysis and licensing interactions in South Africa form a basis for preliminary test program planning. In this section, a safety test matrix is presented, including the technical basis and rationale for testing and a discussion of how these tests will address key licensing issues. A conceptual outline of the tests will be presented including the expected temperature, burnup and fluence conditions.

5.3.1 Technical Rationale

As discussed in section 2.1, the elevated temperatures reached following a loss of coolant event without mitigative measures other than the inherent response characteristics of the PBMR plant (a depressurized conduction cooldown) represent the greatest challenge to the fuel. From the outset of the PBMR design, limiting the maximum fuel temperature reached during a depressurized conduction cooldown has been a primary design constraint. The limit for a conservatively analyzed plant response was chosen as 1600ºC based on the results of extensive prior heatup testing of UO_2 coated particle fuel, as discussed in Section 4. For a given reactor vessel size and core geometry, this constraint determines the maximum design power level

As discussed in section 4.3.2, the design of the PBMR significantly reduces the risk associated with events that could lead to oxidation of the fuel. Since a considerable body of data exists regarding UO_2 coated particle fuel performance under oxidizing conditions, sufficient data are already available for a qualitative assessment of residual risk associated with this event category. Thus no further fuel oxidation testing is proposed for PBMR fuel qualification.

As discussed in section 4.3.3, the online refueling of a pebble bed reactor allows for operation with a limited amount of excess reactivity, thus limiting the potential for reactivity transients. Within the PBMR design and licensing bases, reactivity transients are relatively benign and the resulting fuel temperature conditions are well within temperatures addressed for heatup events. Data are available with general applicability to the PBMR demonstrating very large margins for transient overpower events. Thus no further reactivity transient testing is proposed for PBMR fuel qualification.

5.3.2 Test Matrix

For reasons discussed above, the focus of accident condition testing will be on the ability of the irradiated fuel specimens to retain radionuclides during heatup to elevated temperatures for a sufficiently long period of time. During a depressurized conduction cooldown, the fuel slowly heats up until the declining decay heat falls below the increasing heat loss from the vessel, typically several days after event initiation, and then slowly declines. As indicated in section 4.3.1, constant temperature tests have been conducted for temperatures from 1400 to 2100ºC for durations from 30 to 500 hours (typically shorter times at the higher temperatures).

Table 5-4 summarizes the safety test matrix that is proposed for qualification of PBMR fuel. Pre-production, archived German, and PBMR production fuel will all undergo safety testing. The test matrix lists the number of pebbles to be tested, the location of the testing, the temperature and comments relative to the irradiation origin of the pebble and the disposition of the pebble after safety testing.

Heating tests for the archived German and pre-production fuel will be used to shakedown experiment facilities and provide early data on behavior under accident conditions to compare to the German database. The focus on 1600°C is based on the results of PBMR safety analysis that this temperature defines the safety envelope for the fuel. Similarly, testing of the irradiated archived German fuel will be performed in the US with one pebble each at 1600, 1700 and 1800°C to verify adequate fuel performance and to augment existing data regarding the margins to failure above 1600°C. Production fuel will be tested in South Africa and Russia at 1600°C. The focus on 1600°C is to obtain a statistically significant sample size at this critical temperature. The larger quantity of fuel tested satisfactorily (i.e., no failures) at 1600°C will allow a reduction in the statistically limited failure fraction under accidents that would be needed to show compliance with the fuel performance requirements in the licensing basis. This testing will also provide additional data regarding the influence of burnup on the behavior of the fuel under accident conditions.

Table 5-4. PBMR Safety Test Matrix

Facility Location	# Pebbles	Test Temperature (°C)	Comments
Pre-production Fuel			
South Africa	3	1600	
Russia	3	1600	
Archived German Fuel			
US	1	1600	
	1	1700	Safety margin test
	1	1800	Safety margin test
Production Fuel - Demonstration Portion of Qualification Program			
South Africa	3	1600	4 % FIMA
	3	1600	6 % FIMA
Russia	11	1600	Statistically significant quantity of fuel.
Production Fuel - Margin Portion of Qualification Program			
US	2	1600	Supplement Russian statistics. Includes fluence irradiation margin.
	1	1600	High temperature irradiation margin
	2	1700	Safety margin test
	1-2	1700	Safety margin test. Medium irradiation burnup
	2	1800	Safety margin test
	1-2	1800	Safety margin test. Medium irradiation burnup

Notes: Duration will be tied to thermal response of peak fuel pebble under depressurized conduction cooldown conditions in the PBMR. Times on the order of 100 hrs are envisioned. Constant temperature heating will be used to allow for easier interpretation of data. Under consideration are safety tests that would simulate the time-temperature profile of a fuel pebble under accident conditions.

The US testing of production fuel will use fuel irradiated from the margin irradiation in the ATR and will focus primarily on adding to the data reflecting the safety margin for the fuel under these conditions. Both moderate and high burnups will be considered explicitly. Implicitly, because the fast fluence will be higher in these pebbles than in those irradiated in Russia and South Africa, the influence of fast fluence can be studied. Two pebbles at each of 1600, 1700 and 1800°C are planned. Beyond these tests, one pebble from the high temperature margin irradiation and one pebble from the high fluence irradiation will be tested to investigate the influence of higher irradiation temperature and higher fluence on the accident heating response behavior of the pebble.

A schematic representation of the safety testing currently planned is shown in Table 5-5. The test matrix is a cross tab of burnup and temperature. The results illustrate the integrated nature of the program and demonstrate that the South African and Russian testing is centered on confirming the behavior at 1600°C and the US testing is centered on adding data covering the safety envelope/safety margin for the pebbles.

Table 5-5. Safety Test Matrix Burnup vs. Temperature

Temperature °C	Moderate Burnup (~ 4 - 6% FIMA)	High Burnup (~ 11 % FIMA)
1600	3 South Africa @ 4% 3 South Africa @ 6%	3 Pre-Prod South Africa 3 Pre-Prod Russia 11 Russia 1 German pebble 1 US high temperature margin 2 US (includes fluence margin)
1700	1-2 US	2 US 1 German pebble
1800	1-2 US	2 US 1 German pebble

5.4 Post Irradiation Examination

Post Irradiation Examination (PIE) is a collection of non-destructive and destructive techniques that can be used to characterize the state of the fuel either after irradiation or after safety testing. Similar techniques will be used on unirradiated fresh fuel to provide a baseline pre-test characterization for the fuel that is to be tested. In this section, the different types of analyses or measurements that can be performed are described, the purposes of the measurements are outlined and their value to the overall fuel qualification plan will be discussed.

There will be considerable flexibility in the scope of PIE as the program goes forward. Specific needs identified during license application preparation and review or experience with fuel irradiation or safety testing could significantly alter the value of various PIE procedures. Thus the discussion provided here should be considered as tentative and subject to change.

5.4.1 Post Irradiation Examination Techniques

Following capsule disassembly and removal of the fuel compacts or pebbles, the general condition of the fuel is noted, the specimens can be weighed, and dimensional measurements of the specimens can be performed to characterize the shrinkage or swelling that has occurred during irradiation.

To examine the physical characteristics of irradiated fuel particle coatings high magnification optical metallography can be performed on cross sections of the fuel pebble. These examinations provide excellent visual evidence of the condition of the fuel following testing. This technique can be used to investigate layer integrity, possible layer debonding, densification of layers (e.g., buffer) the degree of void formation due to fission gas, the extent of kernel migration and swelling, the nature and extent of fission product attack on SiC. With proper etching techniques, SiC grain orientation and sizes can be determined.

To identify fission product concentration profiles, that is, where the fission products are located within irradiated fuel particles, the spherical fuel element is deconsolidated to obtain individual particles for examination by electron microscopy to reduce the radiation background. The reduced background radiation from a single fuel particle is usually required for good measurements by electron microprobe, where one is looking for x-rays characteristic of specific fission products (measured by energy dispersive or wave length diffraction techniques). This technique will be performed on a limited number of particles.

Another destructive technique that has been performed with coated particle fuel is the leach burn leach test. In this technique the fuel compact or pebble is leached with acid to remove any fission metals (e.g., cesium) that have been released from defective fuel particles as well as heavy metal contamination. (On-line measurements during irradiation will only provide measurements of gaseous fission product release.) The pebble is then burned in air to remove all carbon matrix material and the outer pyrocarbon layer from the fuel particle. The particles are then leached with an acid solution to remove any exposed uranium (from contamination and failed SiC). The measurement of free uranium is converted to a SiC defect fraction.

5.4.2 Post Irradiation Examination Test Matrix

Post irradiation examination is planned for pebbles of all types both after irradiation and after safety testing. The PIE matrix is shown in Table 5-6. It contains the location of the examination, the number of pebbles involved, the irradiation and/or safety test conditions that the fuel was exposed to. Most of the PIE is focused on metallography to characterize the physical state of the fuel and the microstructure of SiC, and other analysis where appropriate to understand the location of fission products in the fuel.

Table 5-6. Post Irradiation Examination Matrix

Facility Location	# Pebbles	PIE Comments
Pre-production Fuel		
South Africa	2	One pre and one post safety test
Russia	2	One pre and one post safety test
Archived German Fuel		
US	1	One pre safety test
Production Fuel - Demonstration Portion of Qualification Program		
South Africa	2	4% FIMA - one pre and one post safety test
	2	6% FIMA - one pre and one post safety test
Russia	3	One pre and two post safety test
Production Fuel - Margin Portion of Qualification Program		
US	2	High Temp Margin - one pre and one post safety test
	1	Fluence Margin - one pre safety test (contingent on Hi Temp Margin)
	3	Post 1600, 1700 & 1800 safety tests (includes fluence margin)

Much of the PIE of pre-production fuel in Russia and South Africa is aimed at shaking down procedures and processes. For the archived German fuel, one pebble will undergo PIE following irradiation. After safety testing of the archived fuel, no PIE is currently planned.

For production fuel undergoing demonstration irradiation, PIE will be performed on one pebble at 4% FIMA, one at 6% FIMA in South Africa, and one pebble at 11% FIMA in Russia. PIE will also be performed on four pebbles that have undergone safety testing at 1600°C. In terms of the margin testing in the US, PIE will be performed on one pebble from the high temperature margin test and from the fluence margin test (contingent based on high temperature margin PIE results).

PIE of pebbles safety tested at 1600, 1700 and 1800°C and high temperature margin (post safety test) will be conducted.

[i.] IAEA-TECDOC-978 "Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors", available electronically at http://www.iaea.org/inis/aws/htgr/index.html.
[ii.] IAEA-TECDOC-978", Table 2-1.
[iii.] Proceedings of the Seminar on HTGR Applications and Development, Beijing, China, paper 21, available electronically at http://www.inet.tsinghua.edu.cn/english/HTR_meetings_S/CONTENTS.htm.
[iv.] IAEA-TECDOC-978, Table 3-3 pg. 66
[v.] Proceedings of the Seminar on HTGR Applications and Development, Beijing, China, paper 21
[vi.] IAEA-TECDOC-978, Table 3-9 pg. 89 and Table 3-13 pg. 93
[vii.] IAEA-TECDOC-978, Table 3-5 pg. 73
[viii.] IAEA-TECDOC-978, Table 4-1 pg. 128 and Table 4-6 pg. 143
[ix.] IAEA-TECDOC-978, Table 4-9 pg. 164 and Table 4-11 pg. 177
[x.] IAEA-TECDOC-978, pg. 218-243
[xi.] IAEA-TECDOC-978, pg. 243-252
[xii.] IAEA-TECDOC-978, Table 5-6, pg. 245
[xiii.] IAEA-TECDOC-978, Table 5-7, pg. 247
[xiv.] IAEA-TECDOC-978, pg. 198-201