Design Optimization and Analysis of Coated Particle Fuel Using Advanced Fuel Performance Modeling Techniques

By

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Abstract

Modifying material properties provides another approach to optimize coated particle fuel used in pebble bed reactors. In this study, the MIT fuel performance model (TIMCOAT) was applied after benchmarking against the experiment results. The optimization study focuses on the fracture toughness of silicon carbide and Bacon anisotropy factor (BAF) of pyrocarbon. The variations on the silicon carbide toughness show that higher fracture toughness leads to a lower fuel failure probability, as expected. However, the results from the BAF variations reveal that a higher BAF lowers a fuel failure probability. This quite contradicts the generally believed notion that a higher BAF would increase fuel failures. In addition to the fuel design optimization, the failure characteristics of coated particle fuel are explained and the key factors influencing such characteristics are identified.

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Chapter 1

Introduction and Review

High temperature gas-cooled reactor (HTGR) technology has recently received much attention worldwide. The technology provides an alternative source for future energy needs. A renewed interest in the HTGR technology largely grows out of its uniquely passive and inherent safety to retain radioactive fission products even at very high temperatures. With this high degree of safety, the modern HTGRs are designed to reside in more compact units that drive down the construction time and cost. Consequently the HTGRs become more affordable to many developing countries where economic growths drive up energy demand.

1.1 Overview of High Temperature Gas-Cooled Reactors

The HTGR technology has dated back to the time when the first man-made sustained fission chain reaction took place in a pile of graphite. This event was an inspiration for the first experimental and production reactors. Since then the HTGR research program has undergone development processes in several countries including the United Kingdom, Germany, and the United States. As a result, variations in HTGR research and development have taken place in these countries.

The developments in the HTGR technology have focused on two different core designs: prismatic and pebble bed. Both reactor designs utilize the multi-coated fuel concept. This fuel scheme consists of fuel in micro-spheres coated with multiple ceramic layers. In the prismatic fuel design, coated fuel micro-spheres mixed with graphite are bonded together and shaped into small cylindrical fuel compacts. These fuel rods reside inside the channels of hexagonal graphite blocks. The channels are not only for fuel insertions. Some channels serve as cooling passages while the others function as the locations for absorber and control material. An assembly of the hexagonal blocks forms a reactor core for a conventional stationary system such as the modular gas-turbine helium-cooled modular reactor (GT-MHR) [8]. This stationary system needs to be refueled periodically by replacing depleted compacts with the fresh fuel.

Unlike its counterpart, a pebble bed reactor has a continuous refueling system. The pebble bed reactor design uses fuel pebbles to generate power. Each pebble is in a spherical shape with a size of a tennis ball and contains approximately 15,000 coated fuel particles within graphite matrix inside the pebble. It takes about 380,000 pebbles to run a typical 120 MWe reactor core. Fresh fuel pebbles are loaded on the top of the core. During an operation they move continuously down the core and exit at the bottom of the core. Then each pebble is checked for its integrity and burnup. Based on this inspection, an irradiated pebble is either re-circulated in the core again or replaced by a fresh fuel pebble.

The advanced design of the pebble bed system increases the level of safety and efficiency. Typically a pebble bed reactor utilizes helium as a coolant. Its conversion from thermal to electric powers goes up to 45% compared to about 33% for light water reactors. As a reactor coolant circulates through the spaces between fuel pebbles, it carries heat along with it. The coolant then transfers the heat at a heat exchanger which heats up a steam or gas to run a turbine system. In some cases the hot gas is supplied directly to a power conversion system in a direct cycle. When in operation a pebble bed reactor core runs at a much higher temperature than a conventional light water reactor. It can extract higher mechanical power from the same amount of thermal energy.

When temperatures in pebble bed reactors rise, the more rapid motions of the atoms in the fuel increase the probability of neutron capture by U-238 atoms through an effect known as Doppler broadening. This reduces the number of neutrons available to cause U-235 fission, reducing the power output by the reactor. This natural negative feedback places an inherent upper limit on the temperature of the fuel without any operator intervention.

1.2 Coated Fuel Particles

Each fuel pebble is a 6cm sphere made of pyrolytic graphite with approximately 15,000 fuel spheres inside the containment layer of a pebble. These spheres are coated particles with nuclear fuels as their kernels. The kernels contain oxides of uranium, thorium, or plutonium and are enclosed by four containment layers. A low density porous pyrolytic carbon (PyC) buffer layer first surrounds the kernel. Then a triple-layered coating follows. This structural coating consists of a silicon carbide layer (SiC) sandwiched between two dense PyC layers designated as the inner PyC (IPyC) and outer PyC (OPyC) layers. This design of fuel particles is termed TRISO fuel particles (tri-isotropic PyC/SiC/PyC structural layers). Figure 1-1 shows actual coated fuel particles.

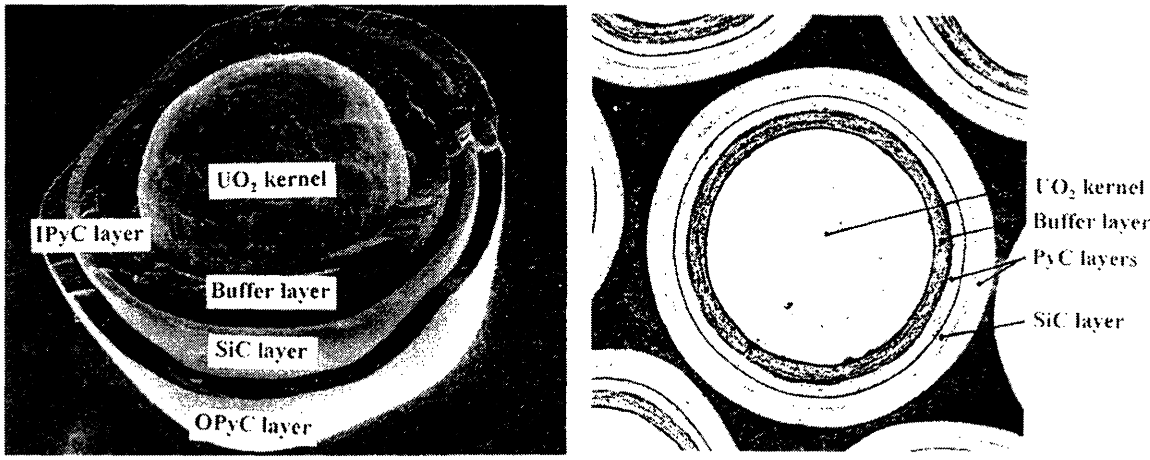


Figure 1-1 Coated fuel particles

Coating of each layer is accomplished in a fluidized bed coater. The coating chamber is made of a graphite tube that can be maintained at a desired temperature level by electrical heating. Fluidizing gases enter the bottom of the coating chamber via a feeding nozzle. The flow rate of the fluidizing gas is appropriately adjusted to float and randomly shuffle the bed of particles in the chamber. A too high flow rate can throw particles out through the opening at the top of the chamber. This will result in coating defects.

Besides the fluidizing gases, coating gases also enter at the bottom of the chamber through a set of gas distribution nozzles. The coating gases are hydrocarbons such as methane (CH_2), acetylene (C_2H_2) and propylene (C_3H_6) for the PyC layers and methyltrichorosilane (CH_3SiCl_3) for the SiC layer. During the coating process, the particles floating in the chamber are continuously agitated as the fluidizing gases such as hydrogen and argon in a mixture of the coating gases flushing in. The chamber wall heats up the gas mixture so that coating agents in the gas mixture decompose themselves and form coalescence before attaching to the fuel particle surfaces. As all particles freely levitate inside the chamber, each particle will receive coating over time with about the same amount of material.

The coating for each layer can be done either continuously or interruptedly. Continuous operating means when one layer is finished, another layer will be coated right after that. By doing so, the particles stay in the same chamber and wait for a new set of parametric adjustments (feed gases, flow rates, and temperature as a function of time). The continuous coating method greatly reduces introduction of foreign objects into the coatings. It also improves adhesion between two coatings. One drawback is that during the continuous operation defective particles cannot be removed until the operation is completed. However, the defective particles can be screened out at the end of the complete coating process. In contrast, the interrupted process allows layer-by-layer inspection before a start of a new layer coating. Such inspection may damage newly finished layers or permit impurities into the coatings. Therefore greater care is required for the interrupted coating.

As mentioned earlier, each fuel particle contains a kernel enclosed by four layers. From the inside out the four layers are

- Buffer layer
- Inner pyrocarbon layer
- Silicon carbide layer
- Outer pyrocarbon layer

Each layer is described in more details below [7].

Buffer Layer

The buffer layer serves three main purposes:

1. Fission Product Recoil Attenuation. The buffer layer prevents the impacts of the fission products generated from the fuel kernel to the inner pyrocarbon layer. During fission reactions, the fuel kernel ejects the fission products at high velocities. While having high kinetic energies, the fission products repeatedly bounce around whenever they hit the nearby material and give up some kinetic energies after each impact within the buffer layer. Eventually the buffer layer will be able to capture those recoils or slow them down significantly before they reach out the inner pyrocarbon layer. As a result the inner pyrocarbon layer can avoid heavy damage from the recoils.
2. Void Volume. The porous buffer layer absorbs various fission gases emitted from the irradiated fuel kernel. It also stabilizes the pressure arising from the fission gas buildup.
3. Sacrificial Layer. When the fuel kernel swells due to irradiation, the buffer layer gives the expanded fuel kernel extra volume.

Generally, for the buffer layer, the layer thickness turns out to be the most important property. If the buffer layer is too thin or missing, it can cause dramatic internal pressure increase and leads to premature failures of fuel particles. However, since the buffer layer has a low thermal conductivity compared to the thermal conductivities of other layers, a very thick buffer layer can cause an undesired temperature rise in the fuel kernel. An increase in temperature will accelerate the diffusion of fission gas releases through the coatings. Since the core temperature limits are imposed to control these release rates.

The strength of the buffer layer is not considered to be an important design factor. In fact it is acceptable that the buffer layer exhibits deformation and shrinkage or even cracking to some degree as long as it isolates the fuel kernel from the inner pyrocarbon layer. However, crack paths through the buffer layer will expose the inner pyrocarbon layer to the fission recoils and introduce serious recoil damage.

Inner Pyrocarbon Layer

The inner pyrocarbon layer performs the following functions:

1. It protects the fuel kernel from chlorine compounds (HCl) used during the coating process of the silicon carbide layer. If chlorine can infiltrate to the fuel kernel, it will react with uranium. The resulting chlorides ingress through the fuel kernel contaminate the coating layers they come in contact with. When fissioning, these uranium compounds will emit fission products that damage the layers.

2. It helps smooth out the surface area of the silicon carbide layer during the silicon carbide coating. The buffer layer alone is too porous and hence will create roughness on the silicon carbide surface. The rugged surface on silicon carbide would become the potential sources of sharp crack openings for easy crack paths.

3. It can retard transport of the fission products to silicon carbide layer. The layer also confines most of the gas, fission product and, especially carbon monoxide (CO) that heavily attacks the silicon carbide layer at high temperatures.

4. It induces compression in the silicon carbide layer, and hence lengthens the life of fuel particles.

Silicon Carbide Layer

The silicon carbide layer has two important functions:

1. It acts as a pressure vessel to accommodate internal fission gas releases.
2. It serves as the main barrier to fission products.

The silicon carbide layer exhibits an excellent tensile strength given that its layer surfaces are sufficiently smooth. In addition most metallic fission products find the silicon carbide to be impermeable. In fact the strength and its distribution of silicon carbide remain as the only serious concerns for fuel particle design purposes. Other physical properties such as density, grain size, and grain orientation do not factor much in the design purposes. Chemical vapor deposition (CVD) of silicon carbide from methyltrichorosilane (CH_3SiCl_3) at about 1500 °C at appropriate conditions results in a density of about 3.20 g/cm^3 which approaches its theoretical density of 3.21 g/cm^3. However, there is no conclusive evidence that the fuel particle irradiation performance depends on these properties.

Although silicon carbide performs well at a low operating temperature (~1000 °C), high operating temperatures make silicon carbide susceptible to the environment. When the temperature rises above 1250 °C, fission products begin to heavily attack the silicon carbide layer. Palladium and lanthanides (cesium and strontium, for examples) are known as the key attackers at accident temperatures (~1600 - 1800 °C). In fact lanthanides are found active even at low temperatures, but the fuel kernel can retain lanthanides in oxide forms. Being a noble metal, palladium cannot be confined within the kernel in the oxide form, so palladium can reach the silicon layer and start degrading the layer. Additionally silver (Ag-110m) has been found to migrate out of the silicon carbide layer. It is used to be believed that diffusion drives the silver migration, but the new evidence points toward silver transport through micro cracks in the silicon carbide layer [4]. At temperatures beyond 2000 °C, silicon carbide decomposes and loses its integrity. Therefore, due to the issues at high temperatures, the normal irradiation temperatures are capped below 1300 °C with a maximum of 1600 °C in transient and accident conditions.

During irradiation the interactions between the silicon carbide layer and the pyrocarbon layers can activate failure of the silicon carbide layer. Irradiation causes shrinkage in the pyrocarbon layers and both inner and outer pyrocarbon layers are then in tension. This puts the silicon carbide layer in compression. As long as the silicon carbide is in compression, the likelihood of silicon carbide failure will be small. The compression in the silicon carbide layer increases the chance that a fuel particle will not fail because the silicon carbide layer is the strongest layer among all layers. Thus, for design purposes, two important points are needed to be considered:

1. The pyrocarbon layer must keep the silicon carbide layer in compression as long as possible.
2. As a result from the previous point, the pyrocarbon layers must be intact as long as possible. When cracks occur in the pyrocarbon layers, the pyrocarbon layers can no longer keep the silicon layer in compression. The stresses in the silicon carbide layer reverse themselves from compression to tensile. Once the silicon carbide layer cracks, the fuel particle is at risk for failure.

Outer Pyrocarbon Layer

The outer pyrocarbon layer is the final layer on the coated fuel particle. It has the following duties:

1. It serves as the final barrier to fission products generated by the fuel kernel.

2. It protects the silicon carbide layer from mishandlings during processes and handlings before irradiation.

3. It compresses the silicon carbide layer during irradiation

4. It isolates the silicon carbide layer from external chemical reactions.

5. It provides a bonding surface for matrix material during fuel fabrication.

The basic properties of the outer pyrocarbon layer are similar to those of the inner pyrocarbon layer. The only difference exists in the permeability of the two layers. The inner pyrocarbon layer takes a role to protect the fuel kernel from chlorine generated during the coating of the silicon carbide layer. The outer pyrocarbon layer takes part in bonding a fuel particle to the matrix material. So the surface of the outer pyrocarbon must be porous enough for the intrusion of the matrix material. However, if the outer pyrocarbon layer contains too many pores, too strong interlocking will take place due to favorable intrusion of the matrix material into those asperities. The heavy bonding between the outer pyrocarbon and matrix material will crack the outer pyrocarbon layer due to the shrinkage of pyrocarbon during irradiation.

To summarize, the layers surrounding the fuel kernel serve two distinct purposes. When a fuel kernel releases radioactive gases, mostly xenon, the porous PyC layer absorbs them. This function also helps retaining fission gases within a reactor core and can provide heat as the energy. The TRISO layers function as containment layers, especially the SiC layer. The SiC layer does not burn and has very high fracture toughness. The high-density nonporous PyC layers bounding the SiC layer form the barriers to fission products released during fission reactions while the SiC layer acts as the main pressure vessel.

1.3 Failure Mechanism of Coated Fuel Particles

The failures of the coated fuel particles have been observed and studied [7]. The list below shows the important phenomena that cause coated fuel particles to fail.

1. Pressure vessel failure caused by internal gas pressure
2. Pyrocarbon layer cracking and/or debonding due to irradiation induced shrinkage that ultimately leads to the failure of the SiC layer
3. Fuel kernel migration (amoeba effect), which leads to interactions with the coating layers
4. Fission product/coating layer chemical interactions
5. Matrix/OPyC interaction
6. As-manufactured defects produced during fabrication of fuel particles or during pressing of fuel compacts/spheres
7. Thermal decomposition of the SiC layer at very high temperatures
8. Enhanced SiC permeability and/or SiC degradation (high burnup considerations)
9. Chemical attack
10. Reactivity insertion (accident)

Each failure case is described in more details below.

1.3.1 Pressure vessel failure

Under irradiation fuel kernels continuously generate fission gases. As a result the pressure slowly builds up inside the fuel particle. In addition if the kernels are made of UO_2, oxygen released from the kernels will react with pyrocarbon to form carbon monoxide, another source of internal pressure. Usually buffer layers inside the fuel particles are designed to be thick enough to absorb these gases. However, it is possible that a very small number of fuel particles have buffer layers that are too thin or do not have buffer layer at all. Therefore quality control during the production can prevent pressure vessel failure.

1.3.2 Pyrocarbon layer cracking and/or debonding

At low fluence the pyrocarbon layers shrink in both radial and tangential directions. As fluence reaches approximately 2×10^{25} n/m^2, the pyrocarbon layers begin to swell in the radial direction but continue to shrink in the tangential direction. The shrinkage behavior of pyrocarbon helps suppress tensile stresses in the silicon carbide layers. However, too much shrinkage can exceed the tensile stresses of the pyrocarbon layers. As a result, cracks occur in pyrocarbon layers, and they can lead to very high local stress concentrations in the silicon carbide layers, causing the silicon carbide layers to fail. Pyrocarbon shrinkage can also result in the pyrocarbon layers debonding from the silicon carbide layers. At higher burnups, highly localized tensile stresses may occur in the silicon carbide layers within the area of debonding because the pyrocarbon layers are no longer there to suppress the tensile stresses.

1.3.3 Fuel kernel migration (amoeba effect)

In the presence of thermal gradients and at temperatures above 1000 °C, the fuel kernels can move up the gradients toward the inner pyrocarbon layers in UO_2 fuel. This is solely due to the mass transport of carbon down the gradients. If very large thermal gradients persist, the fuel kernels will eventually penetrate the coating layers, causing the fuel particles to fail. Usually the equilibrium among carbon, uranium dioxide, and carbon monoxide keep the fuel kernels in place. However, when thermal gradients arise, carbon is prompted to migrate. Pebble bed reactors do not encounter this fuel kernel migration as frequent as prismatic reactors due to the lower power densities (hence less thermal gradients) in the pebble bed reactor cores.

1.3.4 Fission product/coating layer chemical interactions

The fission product attacks on the fuel coatings depend on temperature and temperature gradient as well as the degree of initial enrichment which determines the fission product inventory. Generally prismatic reactors encounter the fission attack problem more frequent than pebble bed reactors due to the higher power densities in prismatic fuel. The elements such as silver and palladium can migrate to the outer pyrocarbon layers and sometimes get released into the environment. Recent study suggests that silver transports through micro cracks in the pyrocarbon layers [4].

1.3.5 Matrix/OPyC interaction

The interaction between the matrix material and the outer pyrocarbon layer caused the failures in the early irradiation in the United States [7]. Intrusions from the low viscosity graphite matrix into the pyrocarbon layers induced cracking and debonding of the outer pyrocarbon layer from the silicon carbide layer. Sharp cracks initiated at the intrusion points resulted in easy cracking. Since pyrocarbon shrinks at low neutron fluence, the strong bonding between the matrix and the outer pyrocarbon layer due to the embedded intrusions in the layer induced debonding of the outer pyrocarbon layer from the silicon carbide layer.

1.3.6 As-manufactured defects

Reportedly as-manufactured defects are the most common cause of particle abnormalities [7]. Fuel particles may be missing the entire coatings, leaving only fuel kernels. Fuel particles may also be found with heavy metal contamination (such as iron) on the outside of the silicon carbide layers. Contamination and defects contribute to an increase in fission product releases during irradiation.

1.3.7 Thermal decomposition of the SiC layer at very high temperatures

Experimental data indicates that at accident temperatures above 1600 – 1800 C, silicon carbide suffers from thermal decomposition [7]. As a result the release rate of the fission products dramatically increases at the very high temperature range. The study also shows that thermal decomposition depends on both time and temperature. As fuel is irradiated at a very high temperature for a long period of time, fission product release rate becomes much greater. However, decomposition alone may not dictate how silicon carbide behaves at very high temperatures as corrosion may also be a factor.

1.3.8 Enhanced SiC permeability and/or SiC degradation (high burnup considerations)

The degradation or enhanced permeability of silicon carbide hinders attempts to push a burnup as high as possible. When exposed at high fluence (> 4.6×10^{25} n/m^2) and high burnup (> 14%) during the irradiation tests, pebbles emitted the extraordinary amount of fission products compared to similar pebbles underwent the less severe irradiation conditions [7]. Among the other released fission products, cesium significantly weakens the silicon carbide layers, causing the fuel particles to fail.

1.3.9 Water and air ingress (accident)

During an accident, water and air (especially oxygen) may come in contact with the fuel. A break in one of the water coolant loops would allow water to enter the primary system. Water can expose the fuel kernels to the environment as it leaks into the fuel particles and brings out the retained fission products to the environment. Water does not dissolve much of the pyrocarbon layers at high temperatures when the accident occurs. Thus the release of the fission product is relatively modest. Oxygen, however, actively reacts with the pyrocarbon layers and exposed fuel kernels. A break in one of cooling ducts can result in an air ingress event. The resulting oxides corrode the coating layers and fission product releases take place.

1.3.10 Reactivity insertion (accident)

A coated fuel particle can withstand energy below 1000 – 2000 J/gram range. During an accident, a sudden increase in energy deposition will cause a series of events such as overheat and overpressure that lead to a failure. Energies much higher than 1000 – 2000 J/gram range can damage the fuel kernel.

1.4 Thesis Objective

This thesis aims to study the effect of the material properties of fuel particles, particularly the Bacon anisotropy factor (BAF) and fracture toughness of silicon carbide on the failure probability of coated fuel particle fuel. Although Wang has proposed a step-by-step optimization, his results focused on optimization of particle dimensions [1]. This study keeps particles dimensionally unchanged, but focuses more on the variations of the BAF and silicon carbide's fracture toughness. The quality control during the fuel production very much affects these fuel material properties.

Chapter 2

MIT Fuel Performance Model

TIMCOAT is an advanced fuel performance model for coated particle fuel used in HTGRs [1]. It was developed by Jing Wang at the Massachusetts Institute of Technology. The model development process involved two major modeling tasks: (1) modeling the mechanical and chemical behaviors of the fuel, and (2) modeling the environment during fuel irradiation. The current version of the model deals only with the modeling of the mechanical behavior of the coated particle fuel. Future versions of the model will integrate the modeling of the chemical interactions to the current mechanical code.

2.1 General Description of the MIT Fuel Performance Model

TIMCOAT can model fuel performance for both types of fuel systems: prismatic blocks and moving pebbles. For a prismatic reactor core, TIMCOAT only needs time dependent histories of fuel particles as inputs. As fuel particles stay bonded together in fuel rods contained in hexagonal graphite blocks, every fuel particle in a core essentially runs through the same irradiation history. For a pebble bed reactor, the multipass fueling system adds another dimension of complexity in modeling. As fuel is recycled through the core several times before the final discharge, each subsequent pass of one pebble does not depend on the previous passes it has made through the core. A recycled pebble will be extracted from the bottom of the core and fed back in at the top of the core. Therefore the location of the fuel pebble within a single pass is determined in a random manner based on the location of initial entry into the top of the bed.

Besides its unique feature regarding refueling scheme in pebble bed reactors, TIMCOAT departs from a traditional simple pressure vessel model to predict particle failures. Since the silicon carbide layer remains in compression at least for the early stage of irradiation, the simple pressure vessel model will neglect the localized stresses in the silicon carbide during this period. According to the simple pressure vessel model, failure occurs only when the tensile stress in a layer exceeds the layer's facture stress. Yet, in experiments, fuel particles fail at an early irradiation period. Alternatively TIMCOAT considers the introduction of a sharp crack at the interface between the pyrocarbon and silicon carbide layers. The crack can initiate a local stress concentration factor that may lead to a locally concentrated high tensile stress even though the net section circumferential stress in the layer stays compressive.

The model in TIMCOAT first considers all of the factors resulting in deformation of a fuel particle. Such factors include irradiation-induced dimensional change, irradiation-induced creep, thermal expansion, and internal pressure buildup from fission gases. The code then translates all of these factors into stress and strain distributions in a fuel particle. Using the stress and strain distributions as inputs, the fuel failure model in the TIMCOAT model calculates the given inputs against strengths of fuel particle layers. It then determines whether there is a failure in the fuel particle.

A fuel particle fails whenever its SiC layer breaks. Since SiC is much stronger than PyC, it can be assumed that when the SiC layer breaks, the other two PyC layers must also break. During irradiation in a core, both PyC layers are in tension and the SiC layer is held in compression by the shrinkage of PyC layers. Eventually when pressure due to fission gas becomes high enough, it can force the SiC layer into tension. As a result the SiC layer breaks and the particle fails.

In several cases the failure occurs at a much earlier irradiation dose. Instead of an internal pressure buildup, the SiC layer breaks due to local tensile stresses at the PyC crack tip/SiC interface. As mentioned earlier, the PyC layers are put in tension during irradiation due to shrinkage. When tensile stresses overcome PyC strengths, the PyC layers break. This initiates local tensile stresses at the PyC/SiC interface. If these local stresses exceed the fracture toughness of SiC, they will be able to crack the SiC layer open without any aid from an internal pressure.

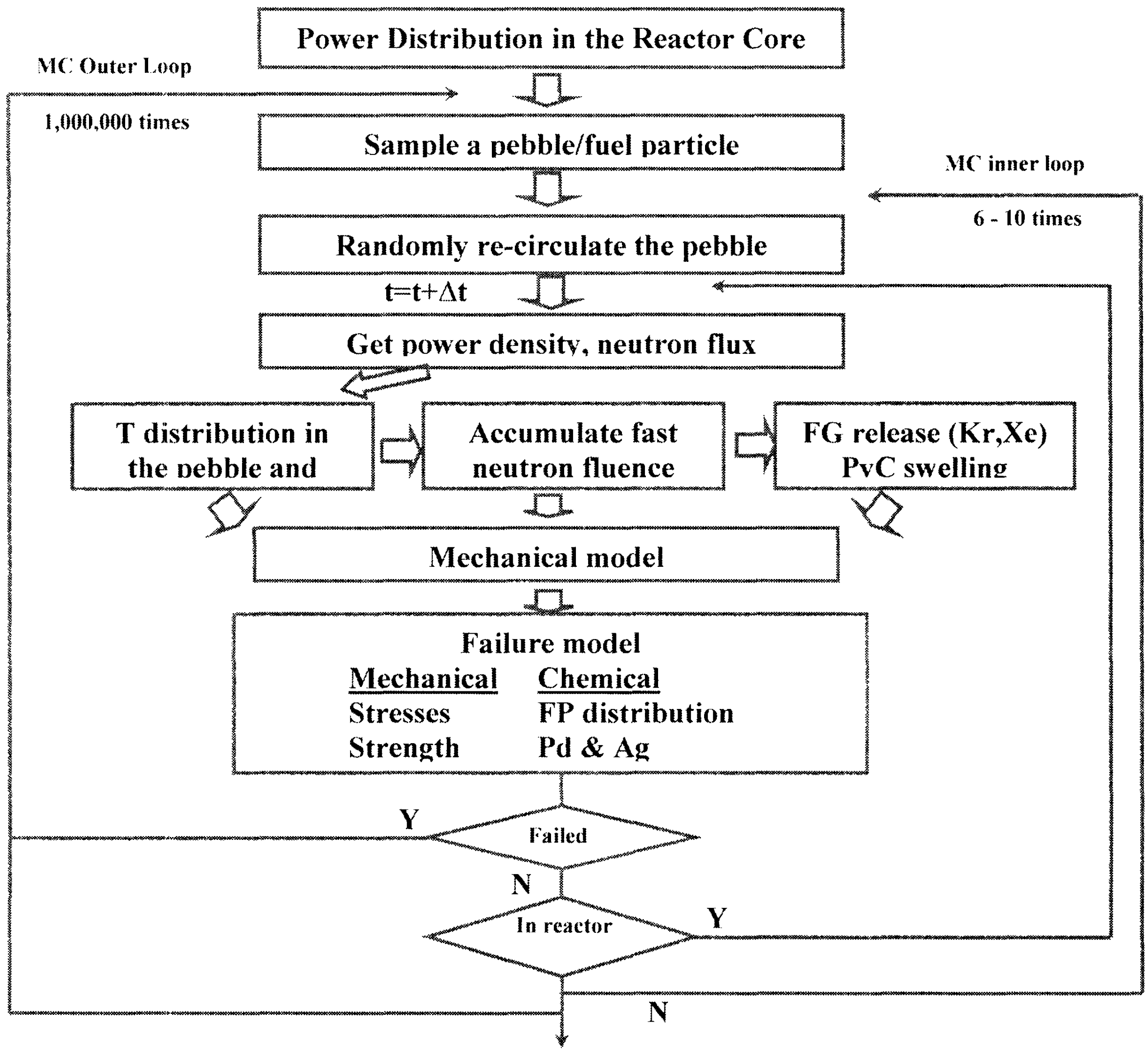
Apart from the failure model in the TIMCOAT model, another important module in the model is to sample fuel particles and place them in a core. In reality it is impossible to verify each individual fuel particle that all of the fabrication requirements are met. At best a manufacturer can inspect the outside dimensions of fuel particles. However, it cannot check the layer thicknesses, fuel kernel diameter, and other physical and mechanical properties of fuel particles. To do so, the manufacturer must perform a destructive inspection. Therefore, before the program does the sampling, the property distributions of fuel particles must be given as inputs. The upper and lower values of each material property must be specified in the distribution. So there exists a finite range of each material property and the triangular distribution is suitable for this.

In addition to sampling physical properties of fuel particles, the TIMCOAT model needs to sample where a pebble to be fed at the top of a core. Each pass through the core is independent of previous and subsequent passes. Therefore this process is totally random. The model then requires realistic power and neutron flux distributions in a core. This way the model can map out the paths that each pebble takes and its power history. Since each pebble enters the core at a random place, this generates a unique power history for each individual pebble.

2.2 Execution of Modeling Program

When executed, TIMCOAT first greets a user with a welcome message. When the user clicks the "START" button the welcome window, another window will pop up and ask for an initial input file. At this point all input files must be in the same directory as the TIMCOAT program. A future version of TIMCOAT may allow the user to browse for input files. After the user enters the initial input file, the user will have three simulation options to choose from (more details on the three types of the simulations below). After the simulation option window, the user interface returns to a more traditional MS-DOS window. Each simulation type shows a slightly different interface window. The TIMCOAT running window will close itself when calculations are completed. TIMCOAT will place all of the output files in the same directory of the main TIMCOAT program. Again a future version of TIMCOAT may allow users to specify output directories. Figure 2-1 shows the running process of TIMCOAT.

Figure 2-1 Flowchart of fuel performance model TIMCOAT [1]



2.2.1 Input Description

TIMCOAT requires a general input file before a specified simulation option reads in extra input files pertaining to its modeling requirements. More details on the extra input files specific to the simulation options are described in Section 2.2.2. The example of the general input file below represents the general input file for the NPR1-A8 case [1].

```
$INPUT

        CORE_HEIGHT = 10.0D0, ! core height (m)

        CORE_RADIUS = 1.75D0, ! core radius(m)

        P_CORE = 250.0D0, ! core power (MWth)

        QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)

        T_IRR = 845.0D0, ! irradiation temperature (degree C)

        IRRTIME = 170.0D0, ! irradiation time(Day)

        T_GASIN = 450.0D0, ! coolant inlet temperature (degree C)

        T_GASOUT = 850.0D0, ! coolant outlet temperature ( degree C)

        MF_HE = 118.0D0, ! helium mass flow rate (kg/s)

        PEBRADIUS = 3.0D-2, ! pebble radius (m)

        PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)

        NPEBBLE = 360000, ! number of pebbles in core

        NPARTICLE = 11000, ! number of particles per pebble

        DT = 1.728D5, ! time step size (s)

        OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)

        EOLBUP = 0.74D0, ! EOL burnup (FIMA)

        EOLFLU = 2.4D0, ! EOL fluence (10^21 n/cm2)

        SHUFFLE = 10, ! number of fueling cycles

        FUELTYPE = 'UCO', ! fuel kernel type

        CURAT = 0.36D0, ! Carbon to Uranium ratio

        OURAT = 1.51D0, ! Oxygen to Uranium ratio

        U235ENR = 93.15D0, ! U235 enrichment (%)
```

U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)

KERND = 10.52D0, ! kernel density (g/cm^3)

KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)

KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)

KERNDIA = 200.0D0, ! kernel diameter (micron)

KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)

BUFFD = 0.9577D0, ! buffer density (g/cm^3)

BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)

BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)

BUFFTHK = 102.0D0, ! buffer thickness (micron)

BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)

IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF

IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF

IPYCCRATE = 1.5D0, ! IPyC coating rate (micron /min)

IPYCLC = 29.98D0, ! IPyC crystallite length (micron)

IPYCD = 1.923D0, ! IPyC density (g/cm^3)

IPYCF = 24.0D0, ! IPyC characteristic strength (MPa. micron^3/modulus)

IPYCM = 9.5D0, ! IPyC Weibull modulus

IPYCTHK = 53.0D0, ! IPyC thickness (micron)

IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)

OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF

OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF

OPYCCRATE = 3.0D0, ! OPyC coating rate (micron /min)

OPYCLC = 29.98D0, ! OPyC crystallite length (micron)

OPYCD = 1.855D0, ! OPyC density (g/cm^3)

OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)

OPYCM = 9.5D0, ! OPyC Weibull modulus

OPYCTHK = 39.0D0, ! OPyC thickness (micron)

OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)

SICTHK = 35.0D0, ! SiC thickness (micron)

SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)

SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)

SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa. micron^1/2)

SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness

SICM = 6.0D0, ! SiC Weibull modulus

PAMB = 0.10D0, ! ambient pressure (MPa)

TITLE = 'Capsule NPR-1#A8 specifications_MC sampling', ! particle description

OSPEC = 'NPR1_8s', ! output file name

DEBUG = .TRUE., ! flag for debugging

ISEED = 30285171, ! initial seed for random number generator

NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles

NCASES = 1000000, ! number of particles to be sampled

NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling

DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release

HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs

RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation

USERSEED = .FALSE., ! flag determining whether ISEED from users is used

$END

2.2.2 Simulation Type

TIMCOAT provides three types of simulations for users:

1. Simulation in pebble bed reactor environments
2. Simulation of irradiation tests
3. Simulation under constant irradiation conditions

Each type of the simulations requires a different set of inputs (more details on the inputs are provided below). The users can also tell TIMCOAT whether or not they want some certain output files.

2.2.2.1 Simulation in pebble bed reactor environments

In this option TIMCOAT simulates a real environment in a reactor core. It models the refueling scheme for a typical pebble bed reactor. A user must provide the steady state power and fast neutron flux distributions specific to the reactor that the user wants to study. In addition TIMCOAT needs two input files to configure the reactor core: blocks.dat and channels.dat. The file "blocks.dat" specifies the axial position and fast neutron flux of each block in a reactor core. The file "channels.dat" sets the radial and axial positions of the channels in a reactor core. Table 2-2 lists the parameters in a general input file that are only specific to this simulation type. The other two simulation types do not use these parameters during modeling.

Table 2-1 The parameters specific to the pebble bed simulation option

Parameters	**Explanation**
CORE_HEIGHT	core height (m)
CORE_RADIUS	core radius(m)
P_CORE	core power (MWth)
QPPP_AVG	averaged power density (W/m^3)
IRRTIME	irradiation time(days)
T_GASIN	coolant inlet temperature (°C)
T_GASOUT	coolant outlet temperature (°C)
MF_HE	helium mass flow rate (kg/s)
PEBRADIUS	pebble radius (m)
PFZRADIUS	pebble fuel zone radius (m)
NPEBBLE	number of pebbles in core
NPARTICLE	number of particles per pebble
DT	time step size (s)
OUTTIME	time pebble is taken out of the core in each cycle (s)
SHUFFLE	number of fueling cycles

2.2.2.2 Simulation of irradiation tests

In this option TIMCOAT requires an irradiation history to run a simulation. TIMCOAT does not need to know a configuration nor a type of a reactor in order to run the simulation. All simulated particles will have the same irradiation history. The example of the irradiation history below represents the irradiation history file for the NPR1-A8 case (up to 45.02203 days).

Time (days)	EFFD (days)	Irr. Temp. (°C)	Fluence ($\times 10^{21}$ n/cm^2)	Burnup (%FIMA)
0.00000	0.00000	882.90155	0.00000	0.00000
1.85022	1.85022	893.26425	0.00387	1.31814
3.70044	3.70044	893.26425	0.00774	2.63627
5.85903	5.85903	893.26425	0.01225	4.17409
7.70925	7.70925	889.11917	0.01612	5.49223
9.86784	9.86784	889.11917	0.02064	7.03005
11.71806	11.71806	889.11917	0.02451	8.34819
13.87665	13.87665	891.19171	0.02902	9.88601
15.72687	15.72687	895.33679	0.03289	11.20415
17.88546	17.88546	901.55440	0.03741	12.74197
20.44800	20.44800	907.77202	0.04277	14.56913
33.56800	20.44800	810.36269	0.04277	14.56913
34.22907	21.10907	872.53886	0.04413	14.96325
35.46256	22.34256	887.04663	0.04668	15.70109
37.31278	24.19278	889.11917	0.05050	16.80784
39.16300	26.04300	884.97409	0.05433	17.91460
39.77974	26.65974	897.40933	0.05560	18.28351
41.32159	28.20159	901.55440	0.05879	19.20581
42.55507	29.43507	907.77202	0.06134	19.94365
45.02203	31.90203	907.77202	0.06644	21.41932

2.2.2.3 Simulation under constant irradiation conditions

This option does not require any extra input file other than a general input file. So it becomes the simplest simulation as the general input file lays out irradiation conditions. The parameter T_IRR sets an irradiation temperature. The parameter IRRTIME tells how long an irradiation takes. The parameters EOLFLU and EOLBUP specify end-of-life fluence and end-of-life burnup, respectively. A fast neutron flux is calculated by $\frac{EOLFLU}{IRRTIME}$ and a burnup rate is given by $\frac{EOLBUP}{IRRTIME}$.

2.2.3 Output Description

Users can set flag to a set of parameters in the general input file in order to control the output files TIMCOAT generates. Table 2-3 shows a list of the important output-controlling parameters in the general input file.

Table 2-2 The important output-controlling parameters in TIMCOAT

Parameter	Description	Flag
NOMINAL	Turning on/off Monte Carlo sampling	• .TRUE. • .FALSE.
RUNIRR	Turning on/off fuel failure evaluation	• 'FAILURE' • 'STRESS'
DEBUG	Turning on/off debugging	• .TRUE. • .FALSE.
HISTOGRAM	Turning on/off histogram outputs	• .TRUE. • .FALSE.

TIMCOAT creates the general output file in a ".out" file. There are three sections in the general output file. The first section contains the echo of the input parameters a user entered in. The second section shows the failure details documented every NBURP particles for each layer in the fuel particles. The final section presents detailed statistics on the stresses and failures of the particles.

TIMCOAT will perform failure evaluation only if the parameter RUNIRR is set to 'FAILURE'. If RUNIRR is set to 'STRESS', it will only calculate stresses within the coating layers without applying the fuel failure model. When choosing to study fuel particle failures, users can decide whether or not they want to look at designated fuel particles with the specified physical properties given by the general input file. They also have a choice of doing fuel particle sampling with the specified distributions of the particles' physical properties. When the parameter NOMINAL is set to .TRUE., TIMCOAT will not run Monte Carlo sampling. Instead it will provide users with several output files containing useful information. Table 2-4 lists the additional output files when NOMINAL = 'TRUE'.

Table 2-3 The additional output files when NOMINAL = 'TRUE'

Output file	**Information in the output file**
out_sigr.dat	Radial stresses
out_sigt.dat	Tangential stresses
out_epir.dat	Radial strains
out_epit.dat	Tangential strains

out_ur.dat	Radial displacements
out_swel.dat	Irradiation induced dimensional change rate

In addition if the parameter NOMINAL is set to .TRUE. while TIMCOAT runs a simulation in pebble bed reactor environments, more extra output files are added to the list. The list of these additional output files is shown in Table 2-5.

Table 2-4 The additional output files for pebble bed reactor simulations when NOMINAL = 'TRUE'

Output file	**Information in the output file**
out_core.dat	Actual irradiation history of a particle
out_temp.dat	Temperature distribution in a particle
test.dat	Detailed passes of a pebble through a core

If TIMCOAT runs a simulation of an irradiation test with NOMINAL set to .TRUE., TIMCOAT will produce a file called "irr_history.out" in addition to the six common output files. The file "irr_history.out", as its name suggests, contains the irradiation history of a simulated particle. However if TIMCOAT simulates constant irradiation conditions and NOMINAL is set to .TRUE., TIMCOAT will give out another output file called "cap_test.out" to add to the current list of the six common output files. The file "cap_test.out" reports the irradiation history of a simulated particle at constant irradiation.

The parameters DEBUG and HISTOGRAM also introduce the other supplemental output files. If DEBUG is set to .TRUE., an output file with a ".dbg" extension will be generated. This file reveals intermediate calculations which are normally skipped in the general output file. The debug file allows user to look for errors while programming or modifying the code. When HISTOGRAM is set to .TRUE., TIMCOAT creates an output file with a ".his" extension. The file provides four failure histograms for each of the three layers and a fuel particle as a whole. Each histogram has counting bins corresponding to time, stress, fluence, and burnup. The number of bins is specified by the parameter NHIS. The data range for time goes from 0 to TIMELIMIT. Stress values range from SIG_LOWER to SIG_UPPER. Fluence and burnup has a range of 0 to EOLFLU and a range of 0 to EOLBUP, respectively. Each particle failure will be placed into a corresponding bin for if it belongs to the data range of time, stress, fluence, and burnup.

Chapter 3

Benchmarking Against the NPR Experiment Results

Benchmarking against the actual experiment results ensures the validity of TIMCOAT. The experiments on the New Production Modular High Temperature Gas Cooled Reactor (NP-MHTGR) provide the excellent data which are suitable to be compared with the simulations from TIMCOAT. This chapter starts with the summary of the experiment program on NP-MHTGR in Section 3.1. Then Section 3.2 covers the details of the benchmarking TIMCOAT simulations against the NP-MHTGR fuel in this study. Finally Section 3.3 provides the discussions on the benchmarking results.

3.1 Review of the NPR Irradiation Program

In the 1980's the Oak Ridge National Laboratory (ORNL) began experiments in support of the development of the New Production Modular High Temperature Gas Cooled Reactor (NP-MHTGR). The fuel prototype used in this program was similar to typical TRISO fuel particles. It consists of spherical coated particles suspended in graphite cylinders with 12.5mm in diameter and 49.5mm in height. Nevertheless there exist the following differences between them:

- The fuel kernel of the NP-MHTGR consisting of highly enriched UCO is smaller in diameter, only about 200 micron.
- To reduce the damage during compaction of fuel particles, a low density protective PyC layer (PPyC) was added to the outer surface of OPyC layer.

- Seal coats, extra dense thin PyC layers, were added to both sides of PPyC and between the buffer and IPyC layers.

The main purpose of this experimental program was to provide fuel performance data. The fuel performance was monitored by measuring Krypton gas (Kr-85m) releases during the irradiation. The fuel performance measure was characterized by the Release-to-Birth ratio (R/B), a ratio between the measured fission gas release rate and the calculated fission gas birth rate. An increase in the readings of the R/B ratio of Kr-85m would indicate fuel failure.

The experimental program used a special test fuel called the Performance Test Fuel (PTF). By May 1991, General Atomics and its subcontractors had manufactured the PTF, and the resulting coated particle fuel achieved the best quality ever produced in the United States [5]. The PTF consisted of three fuel capsules with a number of compacts in each capsule. The three fuel capsules were labeled NPR1, NPR2, and NPR1A. The data from the NPR1 capsule was used in the study of maximum service life conditions of temperature, burnup, and fast neutron fluence. The NPR2 capsule provided the data for the study of core average fuel temperatures. The NPR1A capsule served as a backup test capsule for Capsule NPR1. The NPR1 and NPR2 capsules were irradiated in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The Capsule NPR1A was irradiated in the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL).

The NPR1 and NPR2 capsules shared an identical design but the NPR1A capsule had another different design. The NPR1 and NPR2 capsules each had 16 fuel compacts with H-451 graphite fuel enclosures. The fuel particle arrangement in each compact nicely compensated for the axial cosine-shaped flux distribution in HFIR. As a result, each individual compact generated a relatively uniform heat flux. The design for the NPR1 and NPR2 capsules is shown in Figure 3-1. The NPR1A capsule contained 20 compacts of 1.7 cm in diameter. Each compact in the NPR1A capsule sat on top of another to form a stack of 122 cm long. The fuel stack was put in a graphite sleeve before inserting into a stainless steel capsule. Figure 3-2 shows the design of the NPR1A capsule.

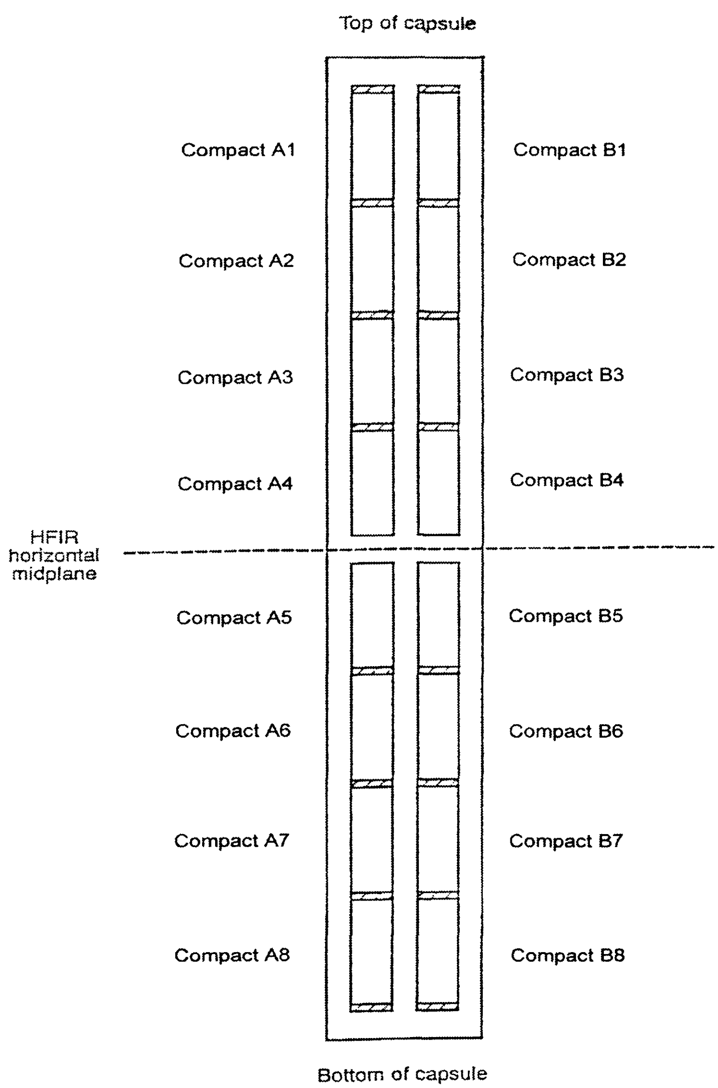


Figure 3-1 Schematic of NPR1 and NPR2 Capsules [6]

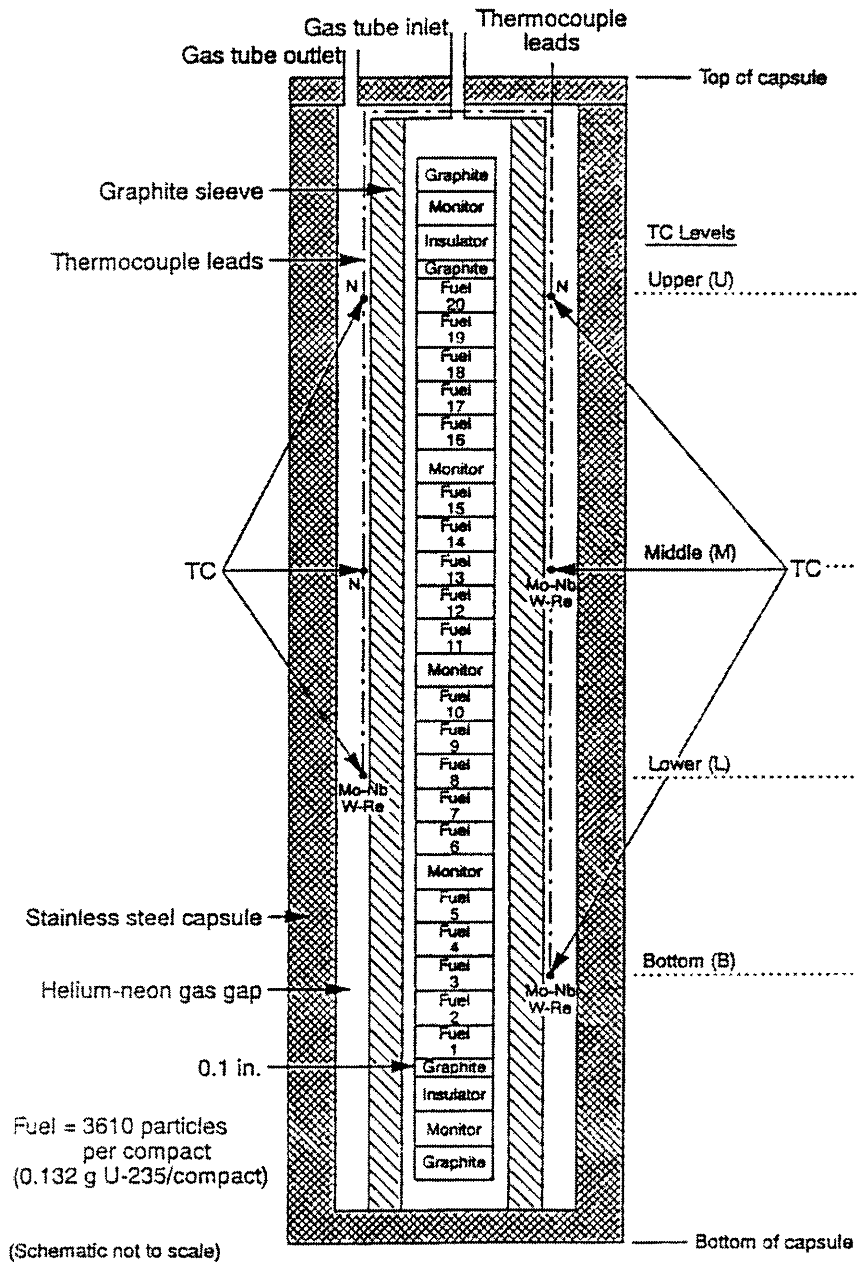


Figure 3-2 Drawing of NPR1A Capsule [5]

Both the NPR1 and NPR2 capsules were irradiated for eight cycles in the HFIR. Figure 3-3 shows the cross section of the HFIR core at its horizontal mid-plane. The NPR1 capsule was irradiated at the positions VXF-5 for three cycles, RB-7A for four cycles, and RB-7B for one cycle. The dotted arrow in Figure 3-3 indicates the irradiation path for the NPR1 capsule. The NPR2 capsule was irradiated at the positions VXF-18 for three cycles and RB-3A for five cycles. The solid arrow in Figure 3-3 depicts the irradiation path of the NPR2 capsule. Placing the capsules in the VXF positions resulted in a higher burnup than placing them in the RA and RB positions. The RA and RB positions were closer to the core, so the capsules at these positions experienced relatively high fast neutron flux but low thermal neutron flux. The capsules in the VXF positions were far from the reactor core and encountered relatively more thermal neutron flux.

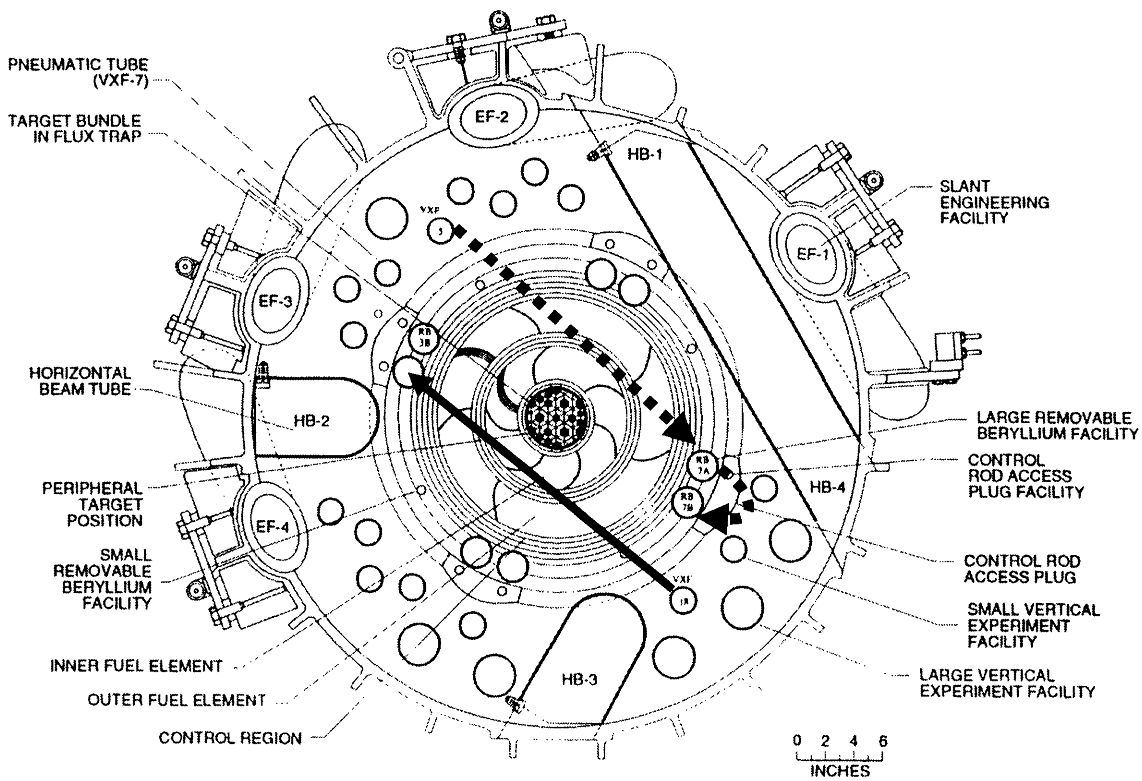


Figure 3-3 Cross section view of the HFIR core at the horizontal midplane [6]

The irradiation of the NPR1 capsule happened between July 25, 1991 and May 29, 1992. During the first 120 full power days, no fuel particle failure occurred as the Kr-

85 R/B ratio stayed low at 1.0×10^{-8}. However, on January 2, 1992, the first failure had been detected as the Kr-85m R/B ratio jumped to 1.7×10^{-7} at a 1.7×10^{21}-peak fluence. The Kr-85m R/B ratio kept rising until it tailed off at 1.0×10^{-4}. The number of particle failures could be approximated as $(1.0\times10^{-4} - 1.0\times10^{-8}) / (1.7\times10^{-7} - 1.0\times10^{-8}) = 625$. The activity spikes recorded by the ionization chambers indicated that 526 fuel particles failed.

The irradiation of the NPR2 capsule took place between August 1991 and May 29, 1992. On February 11, 1992, the first fuel particle failure was registered as the Kr-85 R/B ratio rose to 7.0×10^{-7} at a peak fluence of 1.7×10^{21} neutrons/cm^2. The R/B ratio continued to increase until it reached the final value of 2.0×10^{-5}. The approximated number of fuel particle failure was 135.

The irradiation of the NRR1A capsule started on October 2, 1991 and ended earlier than scheduled due to the unexpectedly high failure rate. The irradiation was terminated after 64.2 full power days. The particle fuel first failed on December 12, 1991 when the Kr-85 R/B ratio increased from 5×10^{-9} to 3.8×10^{-7} after 42 full power days. Upon the termination of the NPR1A irradiation, the Kr-85m R/B ratio increased to 1.79×10^{-5}. The number of fuel particle failures was approximately equal to $(1.79\times10^{-5} - 5\times10^{-9}) / (3.8\times10^{-7} - 5\times10^{-9}) = 48$.

3.2 Benchmarking in This Optimization Study

Before applying TIMCOAT in the optimization study, TIMCOAT itself must be validated. Although Wang has already presented the benchmarking against the experimental data of the NPR1 capsule [1], TIMCOAT has undergone the major modifications in its material database. This thesis presents the re-benchmarking against the very same set of the NPR1 experimental data that Wang used. This will further ensure that the current version of TIMCOAT is legitimate to model fuel performance.

To predict the particle failures for the NPR1 compact, the TIMCOAT simulations under Option 2 (simulations for irradiation tests) were run. Alternatively, Option 3: Simulation under constant irradiation conditions could also be used. However, the predict results would not reflect the actual irradiation histories for the NPR1 capsule. The NPR1 capsule contained 16 compacts labeled A1 to A8 and B1 to B9 (refer to Figure 3-1). Each of these compacts was loaded with essentially the same quality of fuel particles. Based on the compact arrangement in the capsule, the compacts A1 and B1 stayed at the same level and opposite of each other, so they undergo the same irradiation conditions as well as the rest of the pairs A2-B2, A3-B3 and so on. Therefore it suffices to model only the eight compacts A1 to A8 as the failure results should be very similar for the compact group B1 to B8. Figures 3-4A and 3-4B show the irradiation histories for the NPR1 compacts.

The NPR1 benchmarking comprises of eight simulations, one for each A compact. It requires eight general input files and eight irradiation history files. The general input and irradiation history files are included in Appendixes A and B respectively. The various input parameters are shown in Tables 3-1 and 3-2.

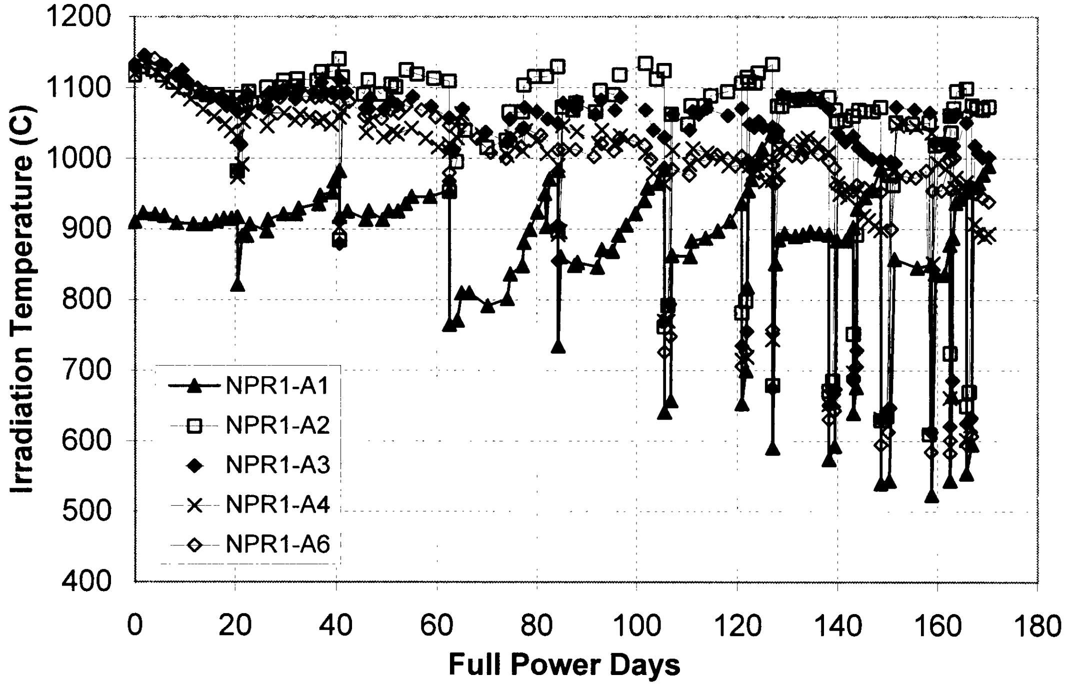


Figure 3-4A Irradiation temperature histories for selected NPR1 compacts

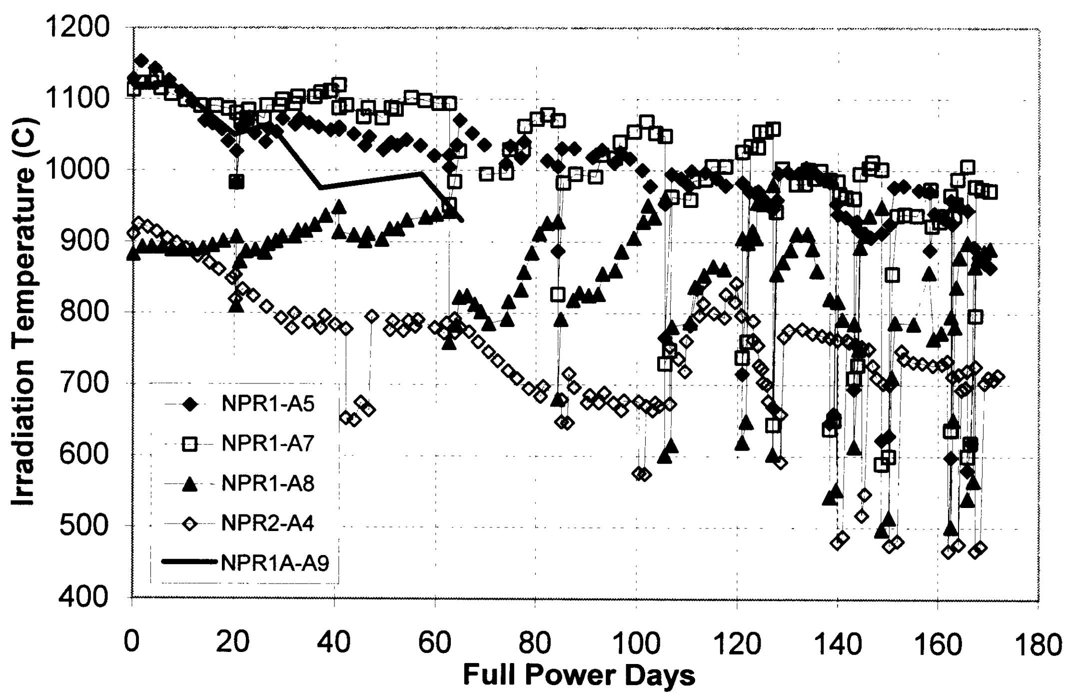


Figure 3-4B Irradiation temperature histories for selected NPR1 compacts

Table 3-1 Properties of each compact in the NPR1 capsule

Compact ID	# Particle Loaded	Time Averaged Temperature (°C)	End-of-life Fluence (10^{21} n/cm^2)	End-of-life Burnup (% FIMA)
NPR1-A1	6126	874	2.4	74.0
NPR1-A2	5266	1050	3.0	77.0
NPR1-A3	4228	1036	3.5	78.5
NPR1-A4	3755	993	3.8	79.0
NPR1-A5	3755	987	3.8	79.0
NPR1-A6	4228	1001	3.5	78.5
NPR1-A7	5266	1003	3.0	77.0
NPR1-A8	6126	845	2.4	72.0

As mentioned earlier, the Kr-85m R/B ratio is an indicator of the particle failure in the NPR1 capsule experiment. TIMCOAT provides the results from the particle failure modeling in term of probability. Equation 3-2 converts the resulting probabilities into the Kr-85m R/B values.

$$N_{failure} = N_i P_i \tag{3-1}$$

$$Kr\text{-}85m\ R/B = N_{failure} \times R/B_{one\,failure} + R/B_{background} \tag{3-2}$$

where

$N_{failure}$ = the number of fuel particle that failed

N_i = the number of fuel particles loaded in each NPR1 compact

$R/B_{one\ failure}$ = the release of Kr-85m for one particle failure (1.7×10^{-7} for NPR1)

$R/B_{background}$ = the background radiation (1.0×10^{-8} for NPR1)

Table 3-2 Input parameters for the NPR1 simulation

Parameter	Mean Value	Standard Deviation	Distribution Type
Fuel Type	UCO	-	-
C:U Ratio, O:U Ratio	0.36, 1.51	-	-
Ambient Pressure (MPa)	0.1	-	-
U235 Enrichment (%)	93.15	0.01	Triangular
Kernel Diameter (μm)	200	5.2	Triangular
Buffer Thickness (μm)	102	10.2	Triangular
IPyC Thickness (μm)	53	3.68	Triangular
SiC Thickness (μm)	35	3.12	Triangular
OPyC Thickness (μm)	39	4.01	Triangular
Kernel Density (g/cm^3)	10.51	0.01	Triangular
Buffer Density (g/cm^3)	0.96	0.05	Triangular
IPyC Density (g/cm^3)	1.923	-	-
OPyC Density (g/cm^3)	1.855	-	-
IPyC BAF_0	1.05788	0.00543	Triangular
OPyC BAF_0	1.05154	0.00622	Triangular
IPyC σ_0 ($MPa.m^{3/\beta}$)	23.6*	9.5 (β)	Weibull

OPyC σ_0 (MPa.m$^{3/\beta}$)	22.4*	9.5 (β)	Weibull
SiC σ_0 (MPa.m$^{3/\beta}$)	9.64*	6.0 (β)	Weibull
SiC K_{IC} (MPa. μm$^{0.5}$)	3500†	530	Triangular

Figure 3-5 shows the comparison between the failure prediction made by TIMCOAT and the actual experiment results. The failure prediction nicely represents the lower bound of the actual experiment results. This is expected because the current version of TIMCOAT has not yet incorporated chemical modeling. Future version of TIMCOAT with the fully integrated mechanical and chemical models should yield a much better failure prediction.

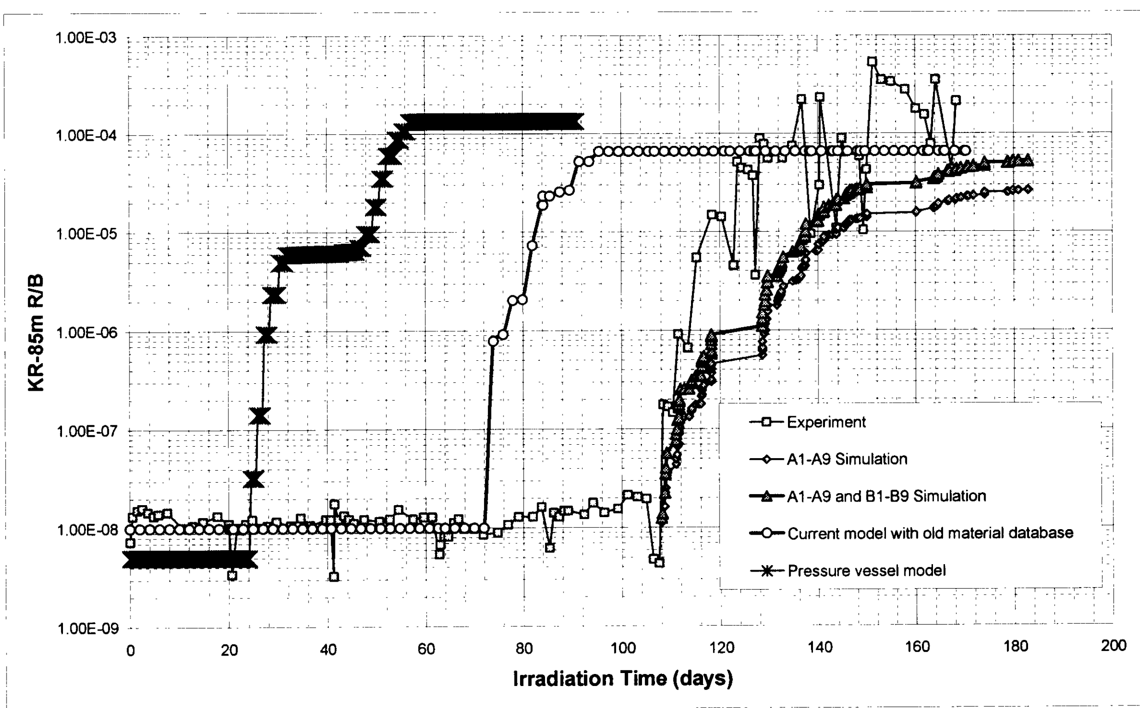


Figure 3-5 The comparison between the actual experiment data and TIMCOAT simulation of the NPR1 capsule

3.3 Summary

Re-benchmarking the predicted failure results against the actual experiment results confirms the validity of the current version of TIMCOAT in predicting fuel performance. Users should feel confident in running TIMCOAT to study performance of coated particle fuel under irradiation. Results from simulations can aid the users to envision how fuel particles behave during irradiation. Further improvement of TIMCOAT includes fully integrated chemical modeling and thus promises much more accurate failure predictions.

Chapter 4

Optimization of Fuel Particles using the TIMCOAT Model

Fuel particle optimization means seeking a set of material parameters for fuel particles to minimize the failure probability. As mentioned earlier, overpressure rupture of the SiC layer and cracking of PyC cause the failure in a fuel particle. Thus the failure probability in a fuel particle can be reduced by minimizing the internal pressure within a fuel particle and minimizing the cracking probability in the PyC layers. Design criteria can be set such that (1) the maximum stresses in the PyC layers are minimized, (2) the strengths in the PyC layers increase, and (3) the SiC layer remains compressive at all times.

4.1 General Comments

Many approaches can be taken in optimizing the fuel performance. While this thesis offers another approach based solely on two important material properties, namely the anisotropy of the pyrolytic carbon layers and fracture toughness of the silicon carbide layer, Wang chooses the optimization procedure based on the parametric study [1]. Table 4-1 shows the results of his study on the relationship between the material parameters and stresses that cause failure. Most of the input parameters in the table are material properties. However, one parameter called BAF_0 (zero subscript denoting initial) deserves some attention.

The Bacon Anisotropy Factor (BAF) measures the degree of anisotropy in graphite (the pyrocarbon layers). Naturally carbon layers in the crystallites tend to lie parallel to the deposition plane. Anisotropy develops as a majority of the crystallites deposit in the same orientation. Thus, a high degree of preferred orientation of a deposit is associated with a high degree of anisotropy. As a result, the carbon deposit, as an aggregate, is isotropic in average. This is due to random orientations of individual crystallites in bulk graphite. A typical BAF value for the pyrocarbon layers ranges from near 1.0 (isotropic) to slightly above 1.1 (anisotropic). The production limit on the BAF ranges from 1.00 to 1.30 as seen from Table 4-1.

Table 4-2 shows how stresses change with the material parameters. In order to design a parameter configuration for a fuel particle, the relationship between stresses in different layers must be known. At a first glance, the study suggests that the SiC layer thickness must be kept as thin as possible while the outer PyC layer thickness must remain as thick as possible. Based on the data in Table 4-1, the SiC and outer PyC layer thicknesses must be set at 20 μm and 80 μm respectively.

Table 4-1 The ranges of the design inputs in current manufacture.

Parameter	**Low**	**Nominal**	**High**
Kernel Dia. (μm)	100	400	700
Buffer Thickness (μm)	40	120	200
IPyC Thickness (μm)	20	40	60
SiC Thickness (μm)	20	40	60
OPyC Thickness (μm)	20	50	80
U235 Enrichment (%)	4	93	96
Kernel Density (g/cc)	10.4	10.5	10.6

Buffer Density (g/cc)	0.9	1.0	1.1
IPyC Density (g/cc)	1.8	1.9	2.0
OPyC Density (g/cc)	1.8	1.9	2.0
IPyC BAF_0	1.00	1.15	1.30
OPyC BAF_0	1.00	1.15	1.30
Irradiation Temp. (°C)	500	900	1300
EOL Fluence (10^{21}nvt)	2.5	3.0	3.5
EOL Burnup (%FIMA)	60	70	80
Reactor Pressure (MPa)	0	6.4	12.8

Table 4-2 Stress changing direction as parametric values increase

Parameter	**Max IPyC Stress**	**Min SiC Stress**	**Max OPyC Stress**
Irradiation T (°C)	+ → -	- → +	+ → -
SiC Thickness (μm)	+	+	+
IPyC Thickness (μm)	+	-	+
OPyC Thickness (μm)	-	-	-
Kernel Diameter (μm)	-	+	+
Buffer Thickness (μm)	+	-	+
IPyC BAF_0	+	-	-
OPyC BAF_0	-	-	+
IPyC Density (g/cm3)	+	+	-
OPyC Density (g/cm3)	-	-	+

(+ = increase - = decrease + → - = increase then decrease - → + = decrease then increase)

Wang proposed the following optimization procedure:

1. Specify irradiation temperature for a given environment. If there is flexibility in the operating temperature limit, it is desirable to go for a higher temperature from mechanical fuel performance viewpoint. Higher temperature helps materials relax and results in lower stresses.
2. Minimize SiC Thickness and maximize OPyC Thickness. This is based on the parametric study (see Table 4-2).
3. Minimize IPyC Thickness and maximize Kernel Diameter, and keep end-of-irradiation stress in SiC non-positive at the same time. Generally stresses in the inner PyC layer are higher than stresses in the outer PyC layer. So the inner PyC layer is more liable to failure.
4. Scan Buffer Thickness for the minimum of maximum IPyC stress, and again keep end-of-irradiation stress in SiC non-positive. There is a strong dependency between the kernel diameter and the buffer layer thickness. Since the kernel diameter has been set in Step 3, the buffer layer thickness must be scanned in the whole range.
5. Increase IPyC BAF_0 from its lower bound for maximum gap between IPyC strength and maximum IPyC stress, and then choose IPyC Density according to BAF_0-Density correlation. The idea behind this is that the inner PyC layer is less

likely to fail when the gap between its strength and stress is widened. Repeat Step 5 for OPyC layer.

4.2 Optimization Based on Bacon Anisotropy Factor of Pyrocarbon

The BAF affects certain properties of the pyrocarbon layers. The strengths of the PyC layers increase with BAF, but high BAF will also accelerate shrinkage of the PyC layers, the cause of local tensile stresses in the layers. For this last reason, most people prefer a low BAF in the PyC layers. In this thesis the BAF is varied from 1.02 to 1.20 for all cases of the modular pebble bed reactors. There are two reactor designs: Old Design (MPBR1) and New Design (MPBR2), and two fuel designs: As Designed (DS) and As Fabricated (MS). Therefore four cases are available, designated as MS MPBR1, DS MPBR1, MS MPBR2, and DS MPBR2. Tables 4-3 and 4-4 show the input parameters for the reactor and fuel designs. The MPBR2 design is larger and capable of generating more power than the MPBR1 design. As a result, their power histories are different. The power histories of a typical fuel particle are illustrated in Figure 4-1. If the model samples one million particle cases, there will be one million power histories. Each fuel particle (if not failed) is recycled ten times in MPBR1 and six times in MPBR2 and the corresponding irradiation time are around 750 days in MPBR1 and 1000 days in MPBR2. Given that MPBR2 generates more power than MPBR1, a particle will experience higher neutron fluence in MPBR2 core than in MPBR1 core. Roughly the end-of-life fluence in MPBR1 and MPBR2 are 1.9×10^{21} neutrons/cm^2 and 2.8×10^{21} neutrons/cm^2, respectively. Figure 4-2 shows the fast neutron fluence of a nominal LEU-TRISO particle in MPBRs.

Table 4-3 Specifications of VSOP Modeled MPBR Cores

Parameter	**MPBR1**	**MPBR2**
Core Height (m)	10.0	11.0
Core Radius (m)	1.75	1.85
Thermal Power (MW)	250	400
Coolant	Helium	Helium
Core Inlet Temperature (°C)	450	500
Core Outlet Temperature (°C)	850	900
Average Power Density (MW/m^3)	3.652	4.777
Max. Power Peaking Factor	5.27	2.74
Min. Power Peaking Factor	4.44E-5	2.70E-5
Coolant Mass Flow Rate (kg/s)	118.0	154.6
No. Pebbles in Core	360,000	451,600
No. Particles per Pebble	11,000	15,000
Pebble Cycling Times	10	6
No. VSOP Blocks	57	93
No. VSOP Batches per Block	11 (10 effective*)	7 (6 effective*)
Pebble Fuel Zone Radius (mm)	25.0	25.0
Pebble Radius (mm)	30.0	30.0

* One additional batch is added for numerical calculation purpose.

Table 4-4 Material parameters in the fuel particles

Parameter	**As Designed (DS)**	**As Manufactured (MS)**
Fuel Type	UO_2	UO_2
U^{235} Enrichment (%)	7.8 ± 0.1	†
Kernel Diameter (μm)	500 ± 20	497 ± 14.1
Kernel Density (g/cm^3)	≥ 10.4	10.81 ± 0.01*
Buffer Thickness (μm)	90 ± 18	94 ± 10.3
Buffer Density (g/cm^3)	≤ 1.05	1.00 ± 0.05*
IPyC Thickness (μm)	40 ± 10	41 ± 4.0
IPyC Density (g/cm^3)	1.90 ± 0.1	Not Measured
SiC Thickness (μm)	35 ± 4.0	36 ± 1.7
SiC Density (g/cm^3)	≥ 3.18	3.20
OPyC Thickness (μm)	40 ± 10	40 ± 2.2
OPyC Density (g/cm^3)	1.90 ± 0.1	1.88
IPyC/OPyC BAF_0	1.058* ± 0.00543*	1.058* ± 0.00543*

*: Values suggested by Wang

†: Minor deviations in this parameter occur due to technical reasons. Its design value is used in simulations.

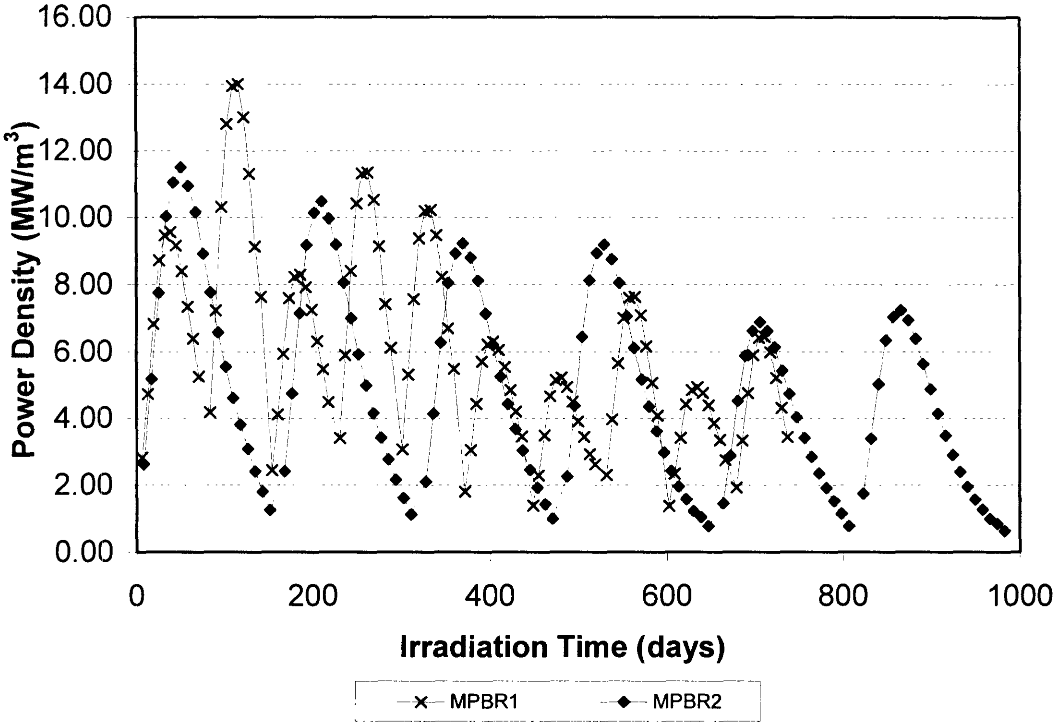


Figure 4-1 Power histories of a nominal LEU-TRISO particle in MPBRs

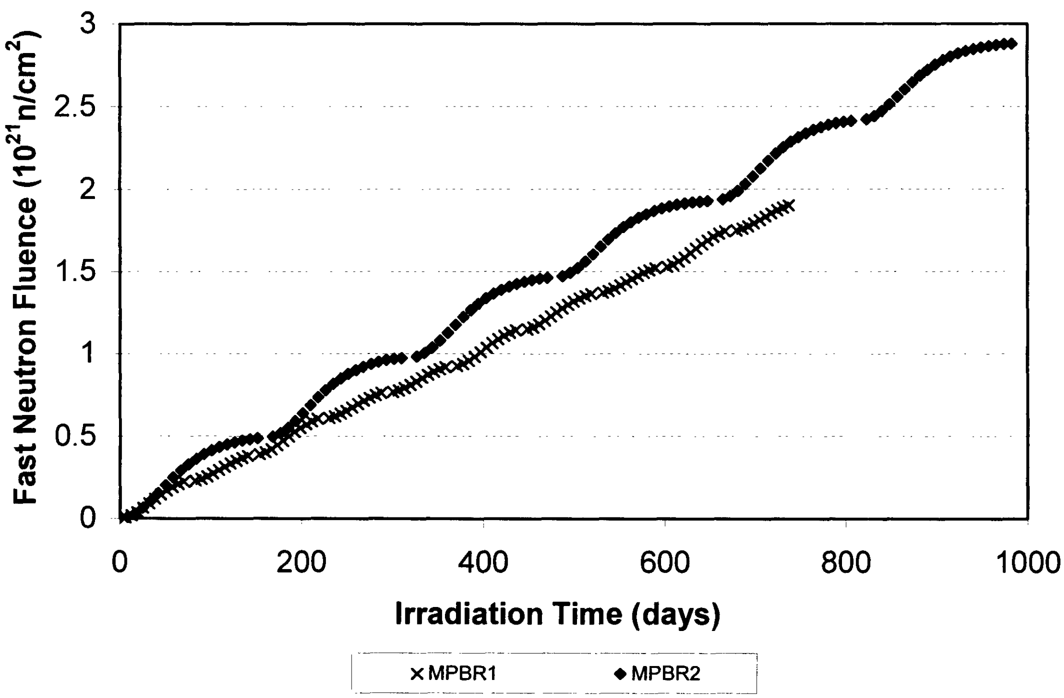


Figure 4-2 Fast neutron fluence received by a nominal LEU-TRISO particle in MPBRs

In order to obtain statistical significance for the results, each Monte Carlo simulation sampled one million particle cases. The Tables 4-5 and 4-6 show the numerical results from the BAF variations. Figure 4-3 clearly exhibits the distinct effect of BAF on the failure probability. In all four cases: MS MPBR1, DS MPBR1, MS MPBR2, and DS MPBR2, a higher BAF leads to a lower failure probability.

Table 4-5 The relationship between the particle failure probability and the initial BAF in MPBR1

BAF_0	Failure Probability	
	MS MPBR1	**DS MPBR1**
1.02000 ± 0.00543	0.238900 ± 0.004095	0.235200 ± 0.004501
1.04000 ± 0.00543	0.061000 ± 0.002242	0.127400 ± 0.003366
1.06000 ± 0.00543	0.009390 ± 0.000887	0.009590 ± 0.001022
1.08000 ± 0.00543	0.001141 ± 0.000351	0.001247 ± 0.000368
1.10000 ± 0.00543	0.000150 ± 0.000135	0.000182 ± 0.000134
1.12000 ± 0.00543	0.000023 ± 0.000045	0.000046 ± 0.000070
1.14000 ± 0.00543	0.000006 ± 0.000024	0.000012 ± 0.000033
1.16000 ± 0.00543	0.000003 ± 0.000017	0.000005 ± 0.000022
1.18000 ± 0.00543	0.000002 ± 0.000014	0.000002 ± 0.000014
1.20000 ± 0.00543	0.000002 ± 0.000014	0.000002 ± 0.000014

Table 4-6 The relationship between the particle failure probability and the initial BAF in MPBR2

BAF_0	**Failure Probability**	
	MS MPBR2	**DS MPBR2**
1.02000 ± 0.00543	0.182800 ± 0.004089	0.197200 ± 0.004261
1.04000 ± 0.00543	0.077010 ± 0.002610	0.078290 ± 0.002530
1.06000 ± 0.00543	0.018170 ± 0.001245	0.018580 ± 0.001308
1.08000 ± 0.00543	0.002574 ± 0.000502	0.000416 ± 0.000192
1.10000 ± 0.00543	0.000401 ± 0.000185	0.000077 ± 0.000093
1.12000 ± 0.00543	0.000082 ± 0.000085	0.000090 ± 0.000081
1.14000 ± 0.00543	0.000016 ± 0.000039	0.000014 ± 0.000035
1.16000 ± 0.00543	0.000002 ± 0.000014	0.000002 ± 0.000014
1.18000 ± 0.00543	0.000001 ± 0.000010	0.000001 ± 0.000010
1.20000 ± 0.00543	0.000000 ± 0.000000	0.000000 ± 0.000000

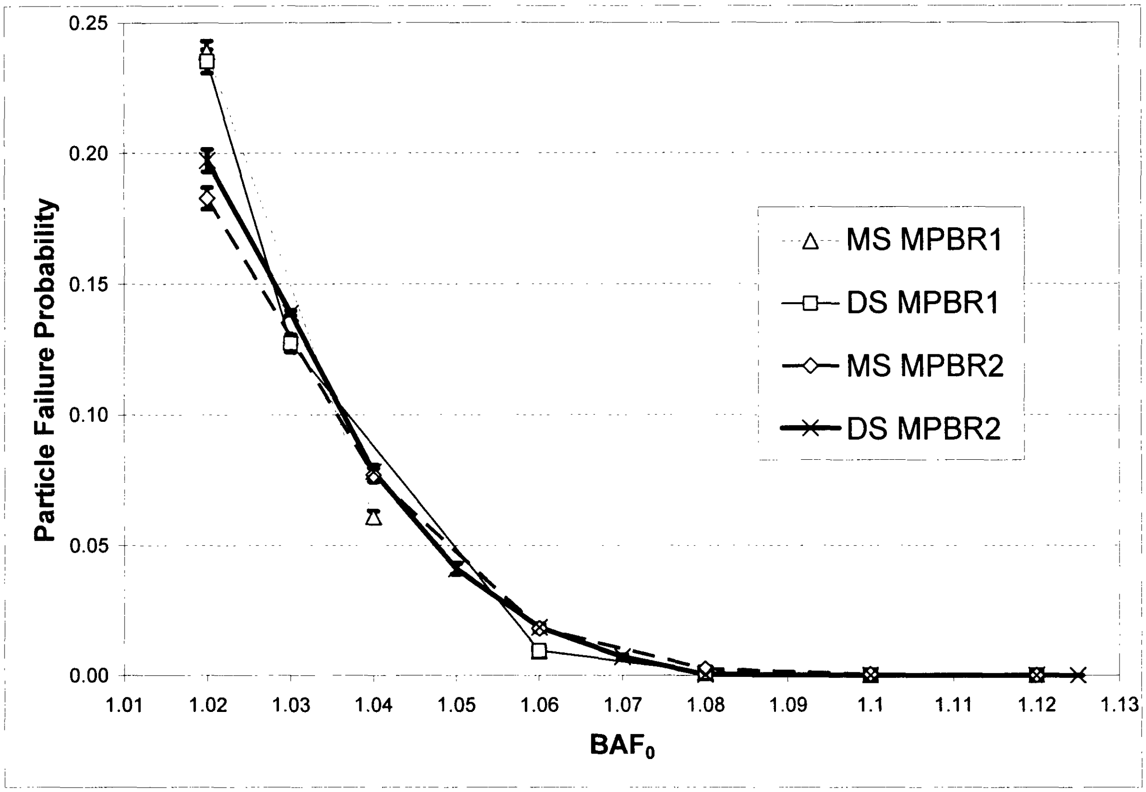


Figure 4-3 The particle failure probability as a function of the initial BAF.

4.3 Optimization Based on Fracture Toughness of Silicon Carbide

The objective is to explore the effects of the silicon carbide fracture toughness and its standard deviation on particle failure probability for all four cases of the reactor and fuel combinations. It is believed that higher fracture toughness reduces the failure probability. Excellent quality control resulting in very minor deviation from target toughness also reduces the failure probability.

In this part of the optimization study, the fracture toughness of the silicon carbide layer was varied from 2000 to 4500 $MPa\sqrt{\mu m}$. The standard deviation was either 100 or 530.72 $MPa\sqrt{\mu m}$ in order to reflect the quality control during the manufacturing. The simulations sampled 100,000 particle cases. Table 4-8 shows the results for K_{IC} of

SiC ($K_{IC} \pm 100\ MPa\sqrt{\mu m}$) and Table 4-9 shows the results for K_{IC} of SiC ($K_{IC} \pm 530.72\ MPa\sqrt{\mu m}$).

Figures 4-4 and 4-5 show the comparisons across all four reactor-fuel combination cases for $K_{IC} \pm 100\ MPa\sqrt{\mu m}$ and $K_{IC} \pm 530.72\ MPa\sqrt{\mu m}$ respectively. In general, failures are smaller in the as-fabricated fuel than in the as-designed fuel at low fracture toughness. Also, MPBR1 generates fewer failures than MPBR2 does at low fracture toughness. A low standard deviation on fracture toughness reduces the failures in a high fracture toughness regime, while in a low fracture toughness regime it creates plateau curve. This suggests that when the standard deviation on fracture toughness is low enough, there exists a certain fracture toughness threshold above which the failure will hardly occur.

Table 4-7 Particle failure probability for K_{IC} of SiC ($K_{IC} \pm 100\ MPa\sqrt{\mu m}$)

K_{IC} of SiC ($MPa\sqrt{\mu m}$)	**Particle Failure Probability**			
	MS MPBR1	**DS MPBR1**	**MS MPBR2**	**DS MPBR2**
2000 ± 100	0.0159 ± 0.0037	0.0291 ± 0.0056	0.0471 ± 0.0066	0.0500 ± 0.0070
2500 ± 100	0.0159 ± 0.0037	0.0175 ± 0.0036	0.0471 ± 0.0026	0.0447 ± 0.0061
3000 ± 100	0.0159 ± 0.0036	0.0155 ± 0.0034	0.0469 ± 0.0025	0.0439 ± 0.0064
3500 ± 100	0.0153 ± 0.0035	0.0148 ± 0.0036	0.0186 ± 0.0013	0.0219 ± 0.0039
4000 ± 100	0.0034 ± 0.0019	0.0060 ± 0.0026	0.0001 ± 0.0001	0.0017 ± 0.0012
4500 ± 100	0.0000 ± 0.0000	0.0007 ± 0.0008	0.0000 ± 0.0000	0.0001 ± 0.0003

Table 4-8 Particle failure probability for K_{IC} of SiC (K_{IC} ± 530.72 $MPa\sqrt{\mu m}$)

K_{IC} of SiC ($MPa\sqrt{\mu m}$)	Particle Failure Probability			
	MS MPBR1	DS MPBR1	MS MPBR2	DS MPBR2
2000.00 ± 530.72	0.0180 ± 0.0042	0.0367 ± 0.0059	0.0473 ± 0.0026	0.0599 ± 0.0076
2500.00 ± 530.72	0.0158 ± 0.0036	0.0225 ± 0.0045	0.0453 ± 0.0026	0.0461 ± 0.0064
3000.00 ± 530.72	0.0146 ± 0.0033	0.0163 ± 0.0036	0.0365 ± 0.0019	0.0363 ± 0.0058
3500.00 ± 530.72	0.0114 ± 0.0034	0.0118 ± 0.0035	0.0219 ± 0.0015	0.0219 ± 0.0039
4000.00 ± 530.72	0.0063 ± 0.0025	0.0070 ± 0.0026	0.0077 ± 0.0007	0.0092 ± 0.0029
4500.00 ± 530.72	0.0023 ± 0.0016	0.0028 ± 0.0018	0.0013 ± 0.0003	0.0020 ± 0.0014

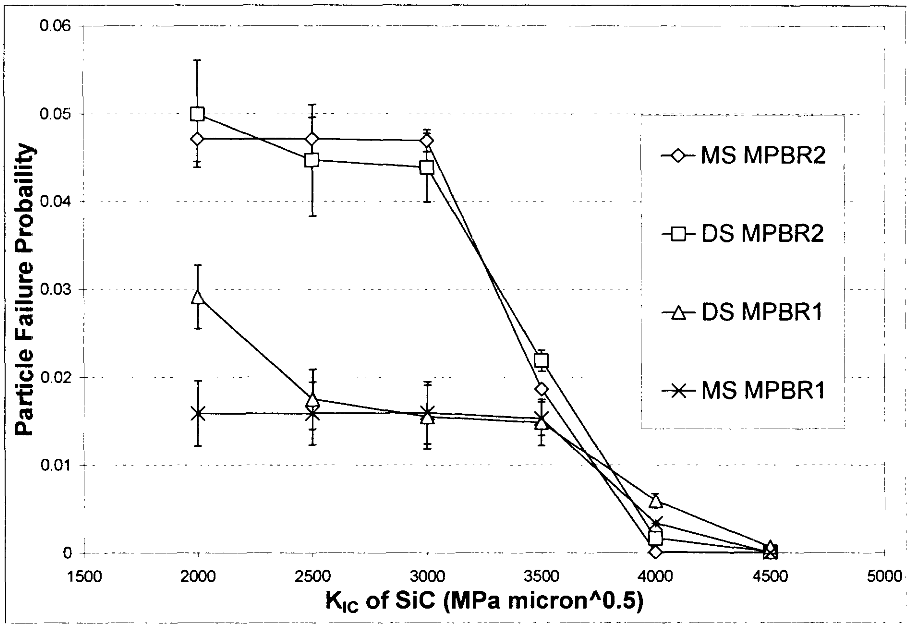


Figure 4-4 Fuel Particle Failure probability as a function of SiC fracture toughness (K_{IC} $\pm$ 100 $MPa\sqrt{\mu m}$).

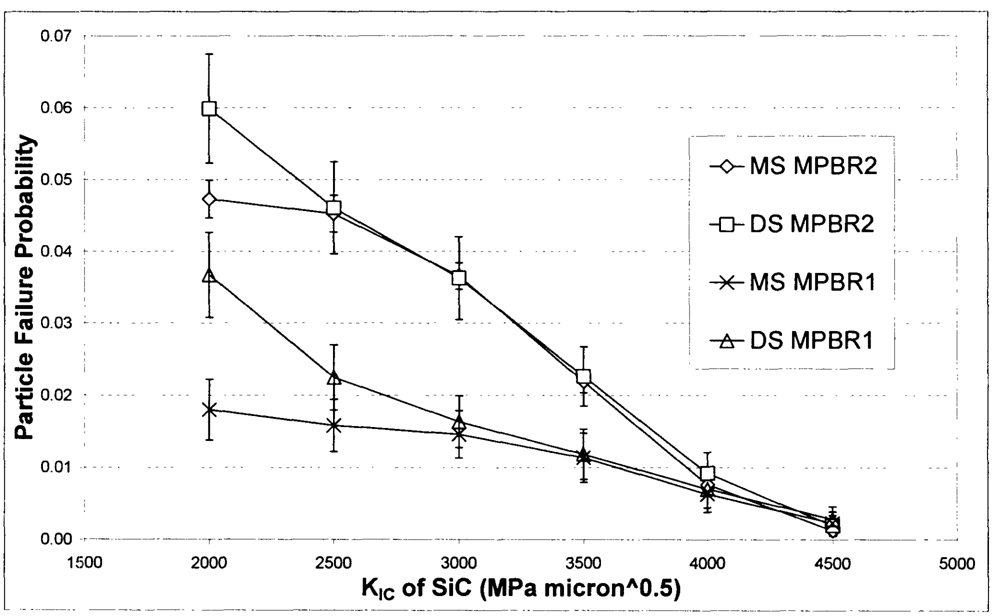


Figure 4-5 Fuel Particle Failure probability as a function of SiC fracture toughness (K_{IC} $\pm$ 530.72 $MPa\sqrt{\mu m}$).

4.4 Failure Characteristics of Fuel Particles

It is worth noting the failure characteristics of all four cases: MS MPBR1, DS MPBR1, MS MPBR2, and DS MPBR2. A low BAF results in failures and so a lower BAF simulation provides a better opportunity to study failure details than a higher BAF simulation does. Therefore a BAF value of 1.02 was chosen. The silicon carbide fracture toughness is 3500 ± 530.72 $MPa\sqrt{\mu m}$. Figures 4-7 shows the cumulative failure evaluation for LEU-TRISO particles in the MPBRs. Each simulation run consisted of 100,000 particle cases.

When a failure occurs, it will follow a certain path. Figure 4-6 shows all the failure paths that any failure can take. First a fuel particle is in a perfect state (no defects of any kinds) and this state is designated with "ISO": I = IPyC, S = SiC, and O = OPyC and starts on top of the diagram. When cracking occurs in a layer, the layer changes its state from the perfect state ("I", "S", or "O") to "C". For example, if both IPyC and OPyC cracks, the particle state will be CSC. Later, if that layer fails, its state designation changes again to "F". In the model, whenever SiC layer in a fuel particle reaches its "F" state, that particle is deemed to fail. This is the case because the SiC carbide layer is the strongest layer among the three layers. Once the SiC layer cannot withstand a tensile stress, it is inevitable that the rest of the layers cannot also maintain their integrity. For example, if a particle reaches the "IFO" state, then the next state the particle will be is "FFF" even though both IPyC and OPyC have not failed or cracked.

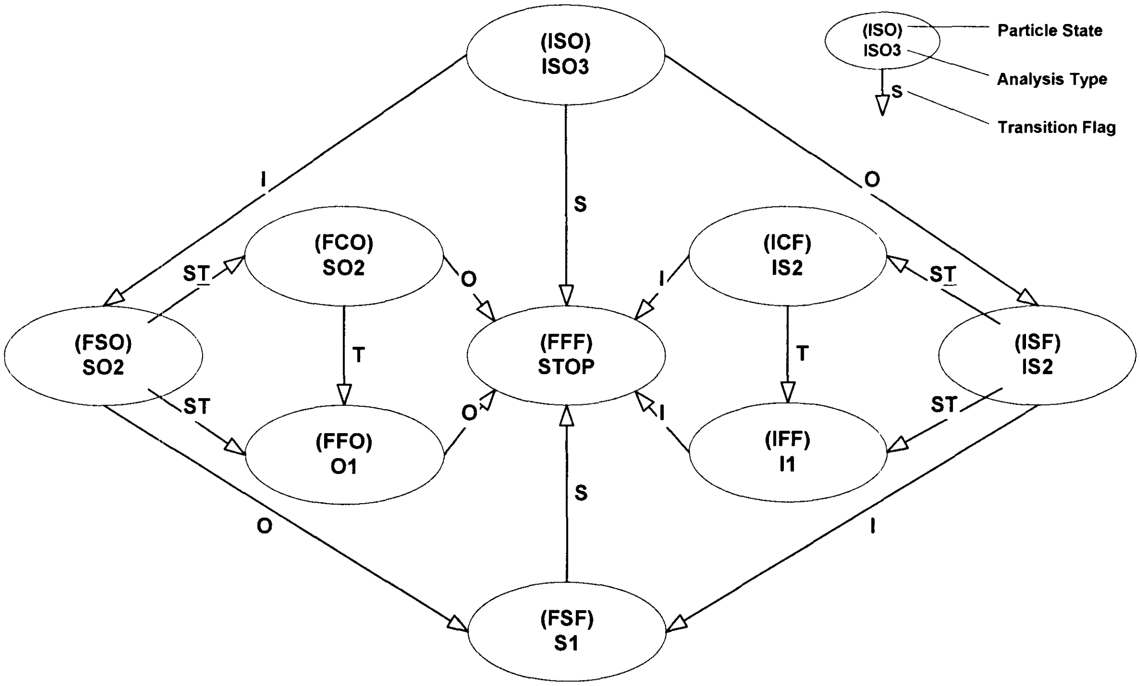


Figure 4-6 Coated fuel particle state diagram

In all four cases, the failures follow two major failure paths. The two major failure paths differ only which pyrocarbon layer (inner or outer) fails first. The two failure paths are described in details below:

- The first failure path: ISO -> CSO -> FSO -> FSC -> FSF -> FFF
    1. The **inner** pyrocarbon layer cracks and fails first.
    2. Then the **outer** pyrocarbon layer cracks and fails second.
    3. Finally the silicon carbide layer fails with a varying delay in failure time.
- The second failure path: ISO -> ISC -> ISF -> CSF -> FSF -> FFF
    1. The **outer** pyrocarbon layer cracks and fails first.
    2. Then the **inner** pyrocarbon layer cracks and fails second.
    3. Finally the silicon carbide layer fails with a varying delay in failure time.

The results also show that most failures (80%) follow the first failure path and about another 20% of the total failures follow the second failure path. Figures 4-8 to 4-11 show the breakdowns of the failures into two major paths. Evidently a tensile stress is larger in the inner pyrocarbon than in the outer pyrocarbon layer.

Besides the two failure paths mentioned above, the DS MPBR1 and DS MPBR2 cases share one special failure path. TIMCOAT gives out this particular failure path as ISO -> CSO -> FSO -> FCO -> FFF. Such the failure path is not found in the MS MPBR1 and MS MPBR2 cases. This might be due to higher standard deviations on the particle fuel physical properties of the DS cases. In the DS MPBR1 case, 38 out of 100,000 failures follow this path and in the DS MPBR2 case, there are 7 out of 100,000 failures. The failure path begins with a crack in the inner pyrocarbon layer leading to its failure. As a result, the inner pyrocarbon layer no longer compresses the silicon carbide layer. The tensile stress begins to intensify at the interface between the inner pyrocarbon and silicon carbide layers, and the silicon carbide layer cracks. Then the crack propagates until the silicon carbide layer breaks apart. The silicon carbide failure means the total failure of that fuel particle. The fuel particle failures by this path occur at times much later during the irradiation. Therefore either over-pressure rupture or neutron fluence causes the failures.

Nevertheless, the simulation results indicate that there is no over-pressure rupture in the MPBR1 cases. The over-pressure failures occur once in the MS MPBR2 case and twice in the DS MPBR2 case. The results suggest that over-pressure failures are likely to occur in the MPBR2 rather than in the MPBR1. This is expected due to the higher operating temperature of the MPBR2 that facilitates a higher fission gas production rate.

Figure 4-7 compares the failure probability across all four simulation cases. The cumulative failure probability curves start off at zero and rapidly rise until they level off after around 500 days in the MPBR1 cases and 400 days in the MPBR2 cases. At the initial BAF = 1.02 ± 0.00543, MPBR1 generates more particle failures than MPBR2 does. In particular, the as-designed fuel performs better than the as-fabricated fuel in MPBR1 and vice versa in MPBR2. The MPBR2 failure probability curves exhibit two humps while the MPBR1 failure probability curves are virtually smooth for the whole irradiation periods. The different in smoothness of the failure probability curves arise from the power histories specific to the simulation cases.

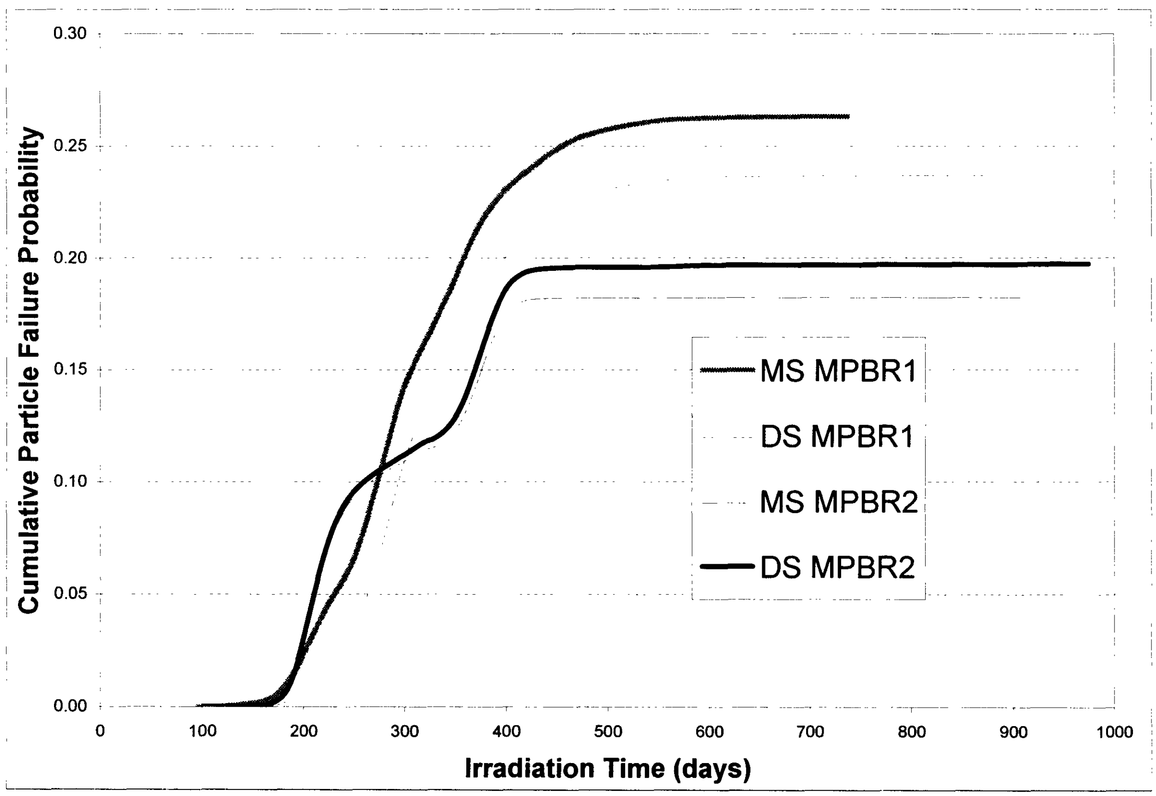


Figure 4-7 Failure developments of LEU-TRISO particles ($BAF_0 = 1.02$, $K_{IC} = 3500 \pm 530.72\ MPa\sqrt{\mu m}$) in the MPBRs.

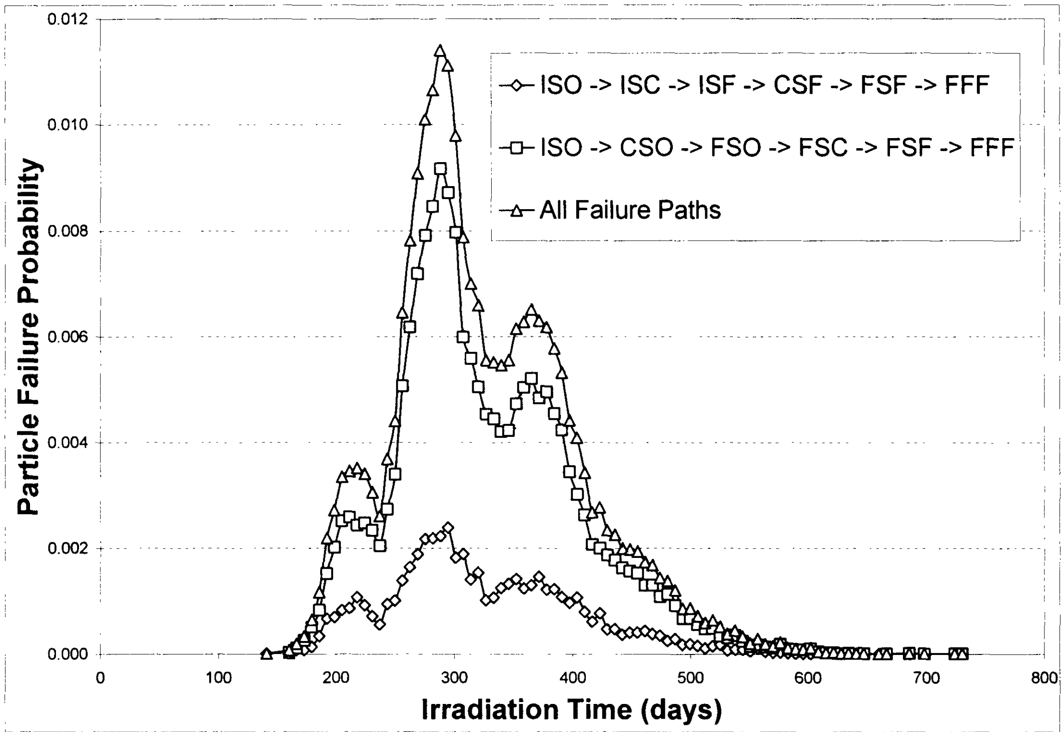


Figure 4-8 Particle failure probability of MS MPBR1 (BAF = 1.02)

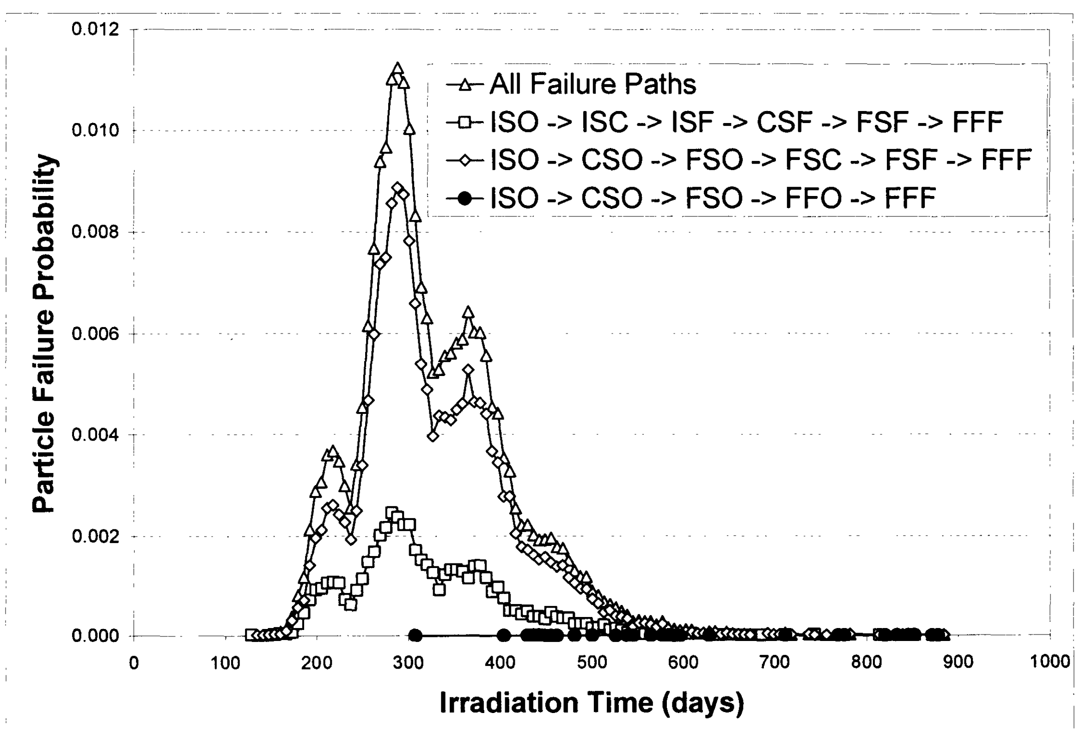


Figure 4-9 Particle failure probability of DS MPBR1 (BAF = 1.02)

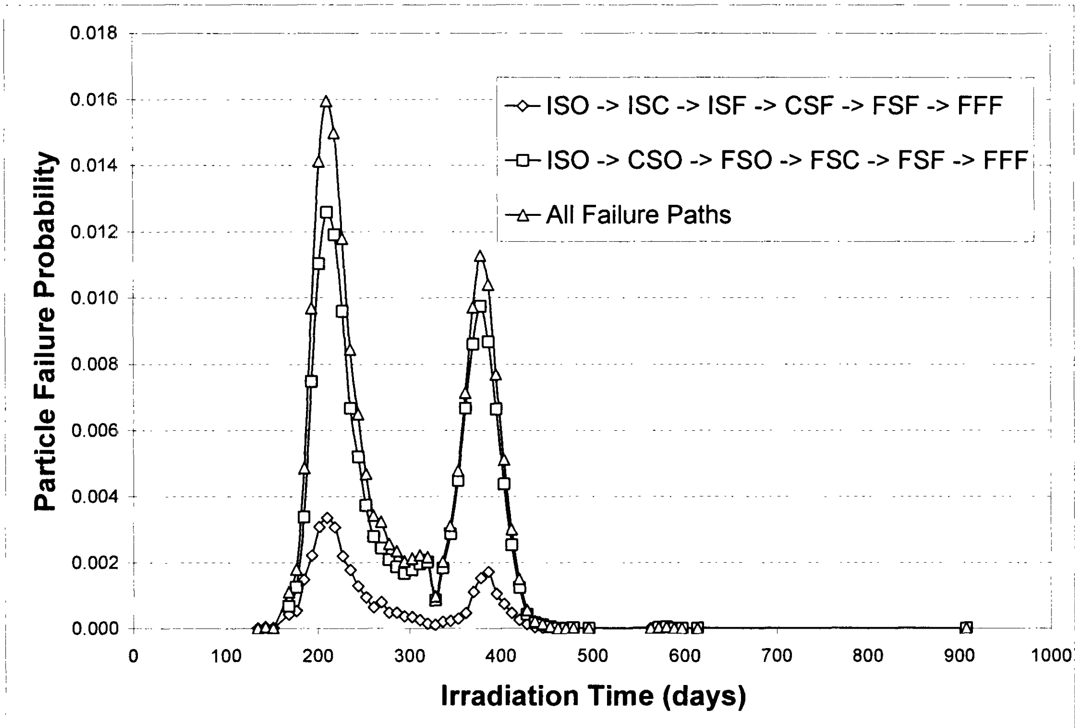


Figure 4-10 Particle failure probability of MS MPBR2 (BAF = 1.02)

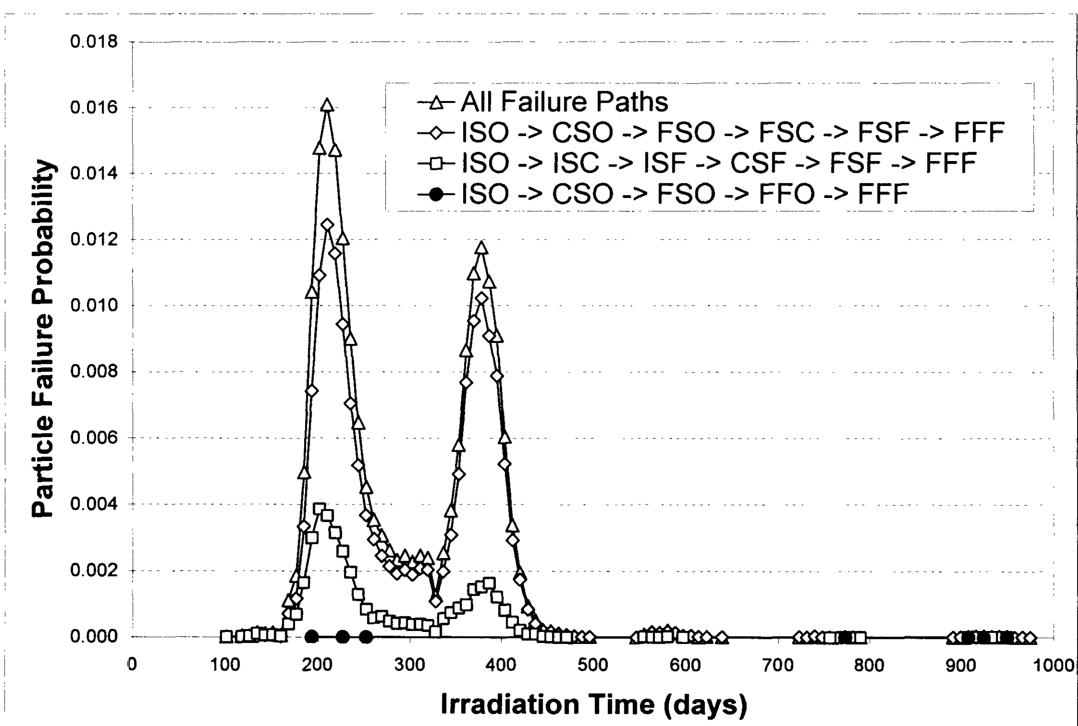


Figure 4-11 Particle failure probability of DS MPBR2 (BAF = 1.02)

The pebble bed reactor fueling schemes significantly affect the shapes of the failure distribution in all four simulation cases. In the MPBR1, each particle goes through the core 10 times and, in the MPBR2, each particle goes through the core 6 times. Each power cycle can be noticed from a step-like change in the neutron fluence as shown in Figure 4-12. The 10 steps in the MPBR1 fluence curve represent 10 power cycles and the MPBR2 fluence curve contains 6 steps for 6 power cycles. From Figure 6 the particle failures in the MPBR1 start when the irradiation time is around 100 days and level off when the irradiation time reaches about 500 days. For the MPBR2, the particle failures begin when the irradiation time is about 100 days, roughly the same as that of the MPBR1. However, the failures in the MPBR2 level off at the irradiation time around 400 days, sooner than those in the MPBR1.

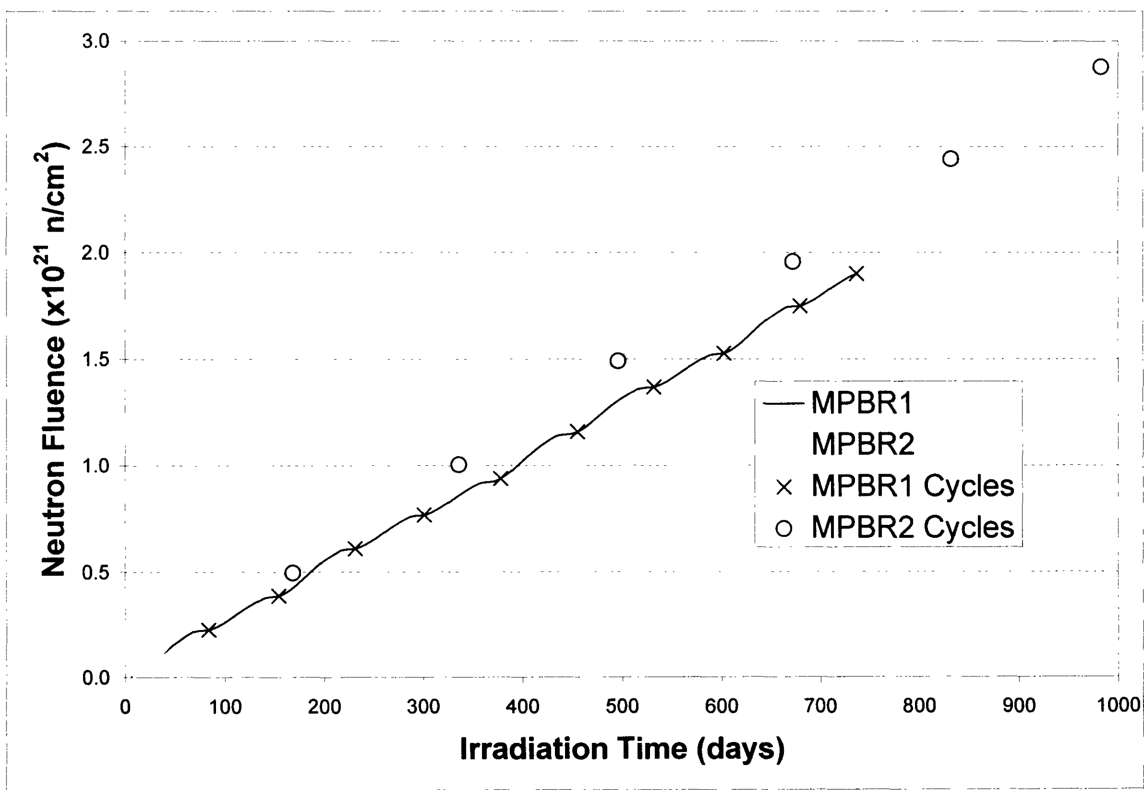


Figure 4-12 Fast neutron fluence in MPBRs with power cycles indicated

Based on the simulation results, the silicon carbide layer fails in one of the following orders:

1. Only the inner pyrocarbon has failed before the silicon carbide failure. The silicon carbide failure instantaneously dictates the outer pyrocarbon layer to fail.

2. All of the pyrocarbon layers have failed before the silicon carbide failure.

In the first case, the silicon carbide and outer pyrocarbon layers fail simultaneously. There is no failure delay between the last remaining pyrocarbon and silicon carbide layers. In the second case, however, failure delays occur in all of the four simulation cases. Figures 4-13 to 4-16 display the time lags between the last remaining pyrocarbon failure and the silicon carbide failure. The plots show that most of the particle failures cluster between 200 to 400 irradiation days. As indicated by the two major failure paths, both inner and outer pyrocarbon layer have failed before the failure of silicon carbide. Thus, the fuel particles that fail at much later times are survived only by the silicon carbide layer alone.

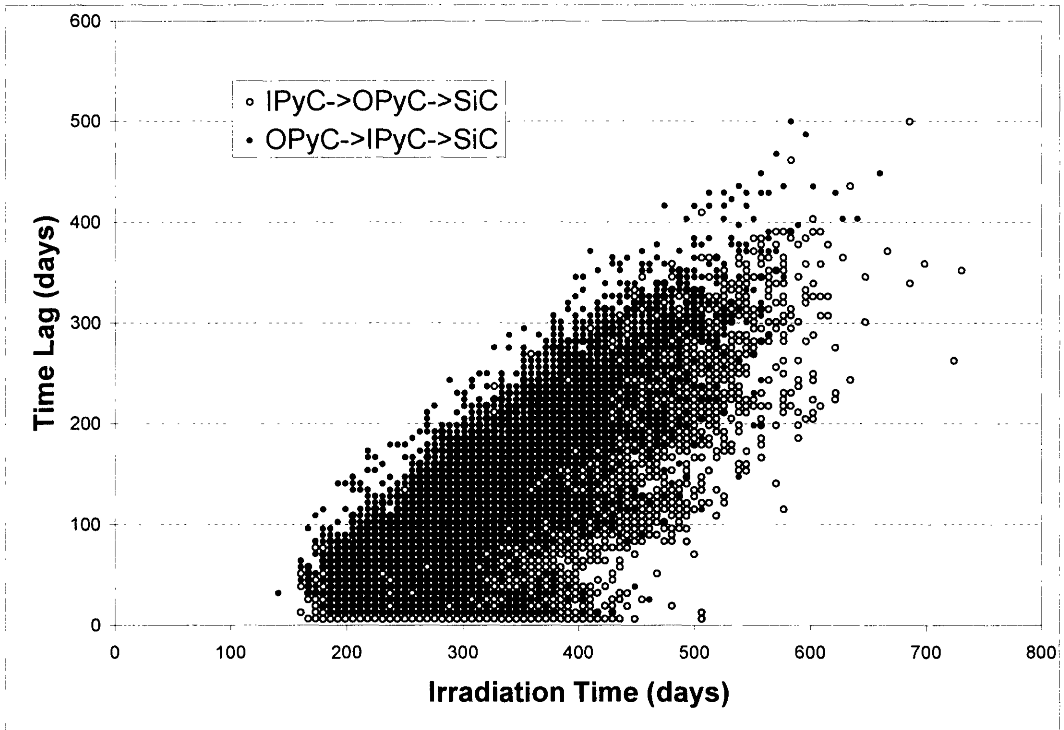


Figure 4-13 Failure delay in SiC layer of MS MPBR1 (BAF = 1.02)

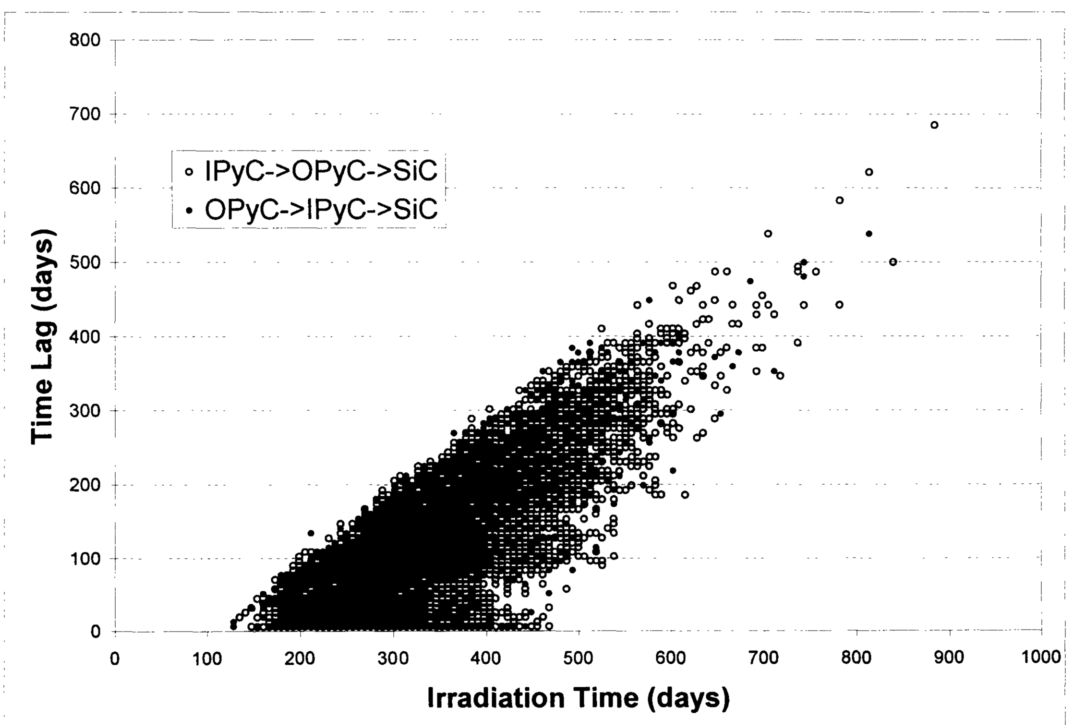


Figure 4-14 Failure delay in SiC layer of DS MPBR1 (BAF = 1.02)

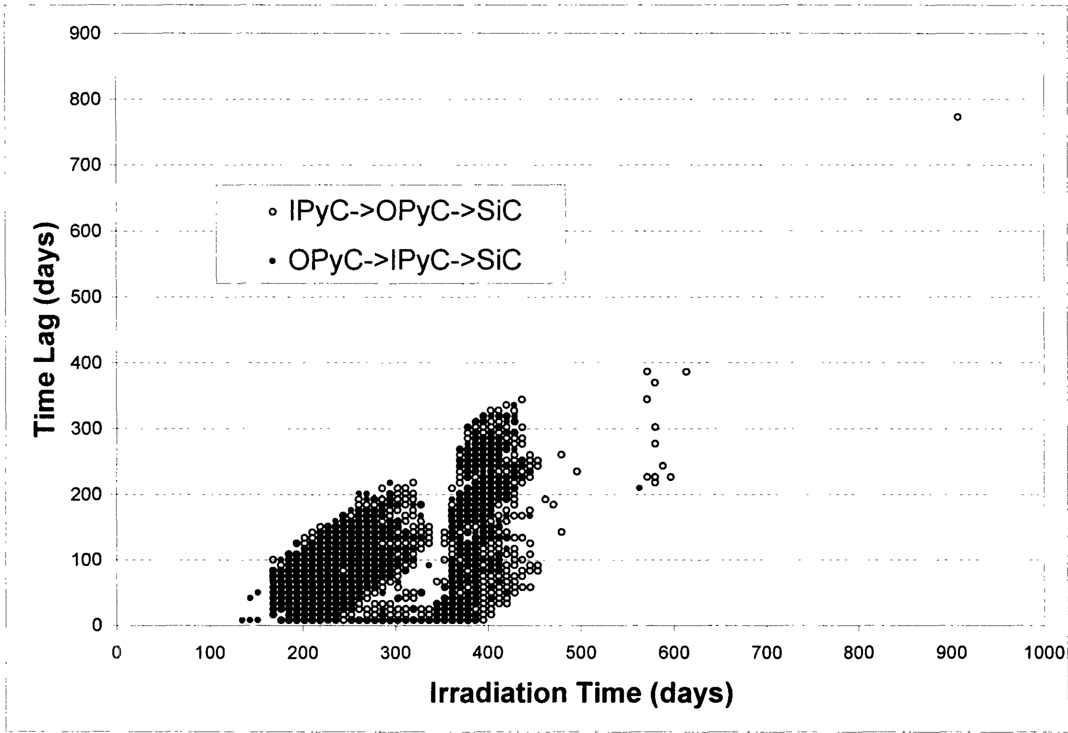


Figure 4-15 Failure delay in SiC layer of MS MPBR2 (BAF = 1.02)

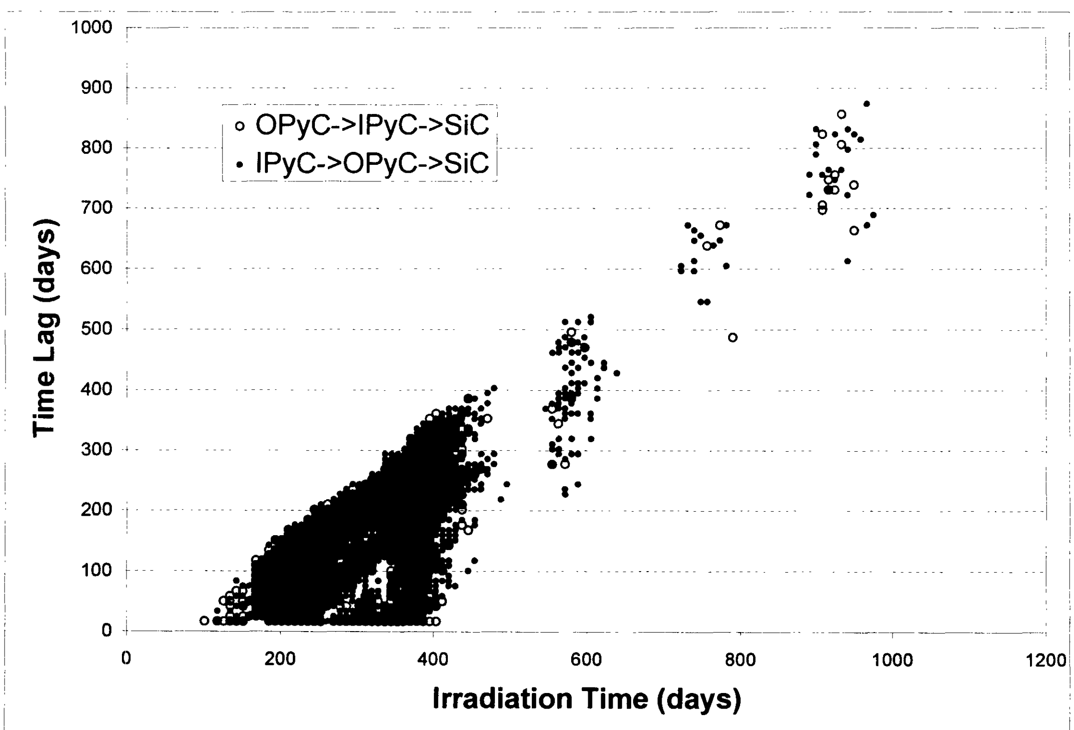


Figure 4-16 Failure delay in SiC layer of DS MPBR2 (BAF = 1.02)

During the failure time intervals, the failure peaks coincide with the early fuel loadings. In the MPBR1, the power cycle numbers 3 to 6 correspond to the failure humps during the irradiation time between 100 and 500 days. Specifically the first failure peak resides within the power cycle number 3. The power cycle number 4 confines the highest peak and the power cycle number 5 matches the remaining peak before the failures fade out in the power cycle number 6. In the MPBR2, only two distinct failure peaks appear. Those peaks correspond to the power cycle number 2 and 3. Although the failures beyond the power cycle number 3 do not intensify and build up as distinct failure peaks, they do concentrate as noticeable groups corresponding to the subsequent fuel loadings, especially in the DS MPBR2 case.

Based on Figures 4-17 to 4-20, neutron fluence ranges from 0.5×10^{21} to 1.5×10^{21} neutrons/cm^2 within the failure clusters in all of the four simulation cases. The stresses in the pyrocarbon layers also reach their peaks within 0.5×10^{21} to 1.5×10^{21} neutrons/cm^2. The MPBR1 power cycles 3 to 5 and MPBR2 power cycles 2 to 3 fall in that range of the neutron fluence. During their peak stresses, almost all of the failed particles lose both of their pyrocarbon layers and their failure occur within the peak stress periods. A few fuel particles fail at quite some time later after they have lost all pyrocarbon layers. These particles mainly have their fracture toughness in the high end of the fracture toughness distribution tails.

Therefore the combinations of the fueling schemes and neutron fluence clearly outline the shapes of the failure distributions as shown in Figure 4-7. For the MPBR1, the relatively frequent fueling generates one failure hump with three distinct peaks. The neutron fluence builds up until around 1.0×10^{21} neutrons/cm^2 when it has the maximum impact on the fuel particle failures. The neutron fluence impact on the particle failure starts to disappear around 1.5×10^{21} neutrons/cm^2. The relative short refueling intervals in the MPBR1 do not allow much time for the pyrocarbon layers to relax. Hence the failures accumulate as one big hump with three heights indicating the three different fuel loadings. The middle failure peak represents the maximum impact of the neutron fluence while first and last failure peaks illustrate the starting and fading off neutron fluence impact. Since all of the three failure heights reside in one big hump, the cumulative failures appear as relatively smooth slopes.

In the MPBR2 cases, the fuel loadings occur relatively less frequent. When combined with the neutron fluence, it results in two separate failure humps during the irradiation period when the neutron fluence takes effect. The MPBR2 fueling scheme also allows longer time for the pyrocarbon layers to relax. Hence, relatively fewer failures result. The first failure hump occurs in the second power cycle and the last failure hump occurs in the third power cycle. Due to these two separate failure humps, the cumulative failure distributions appear protuberant on the slopes.

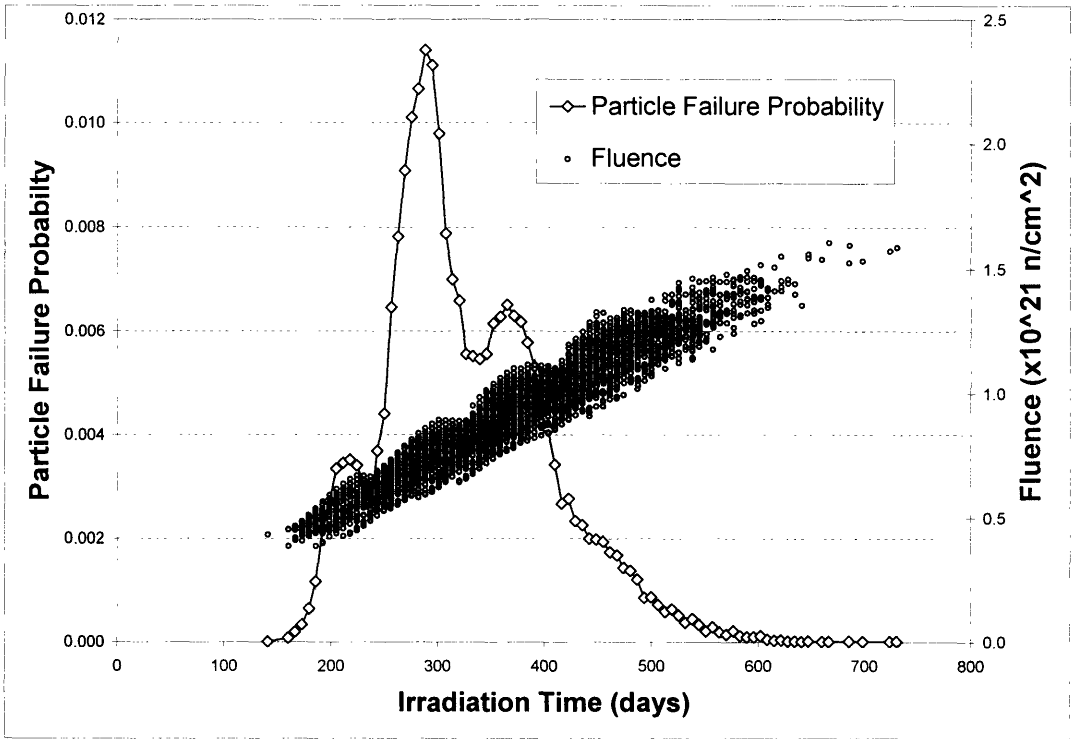


Figure 4-17 Fluence and particle failure probability of MS MPBR1 (BAF = 1.02)

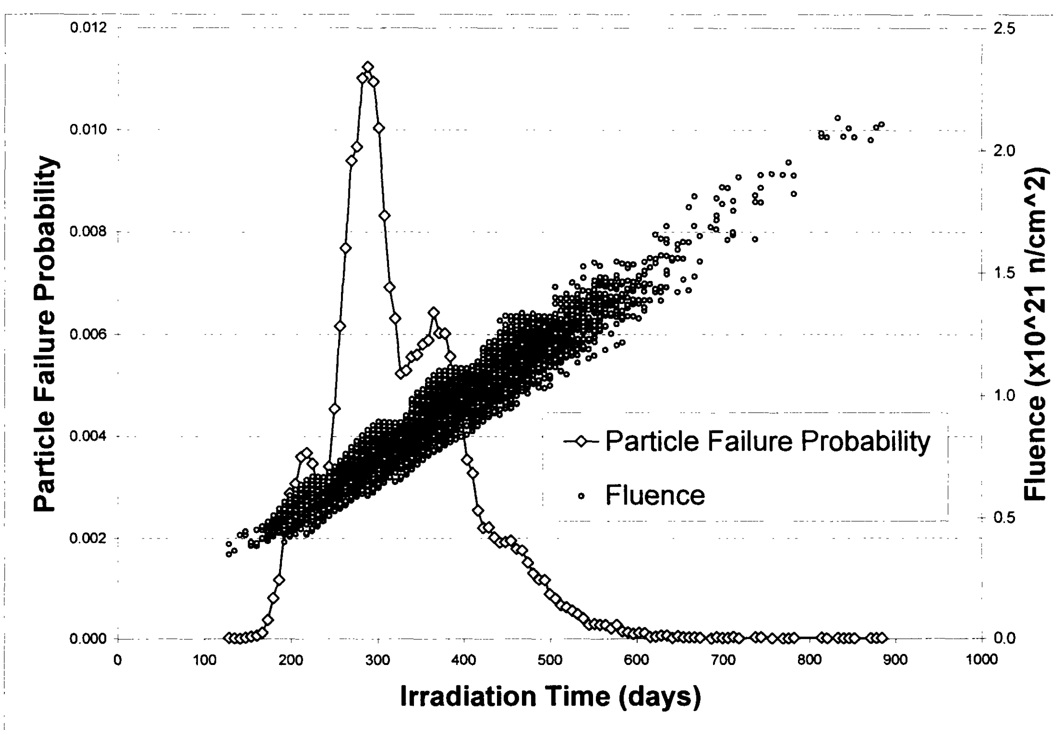


Figure 4-18 Fluence and particle failure probability of DS MPBR1 (BAF = 1.02)

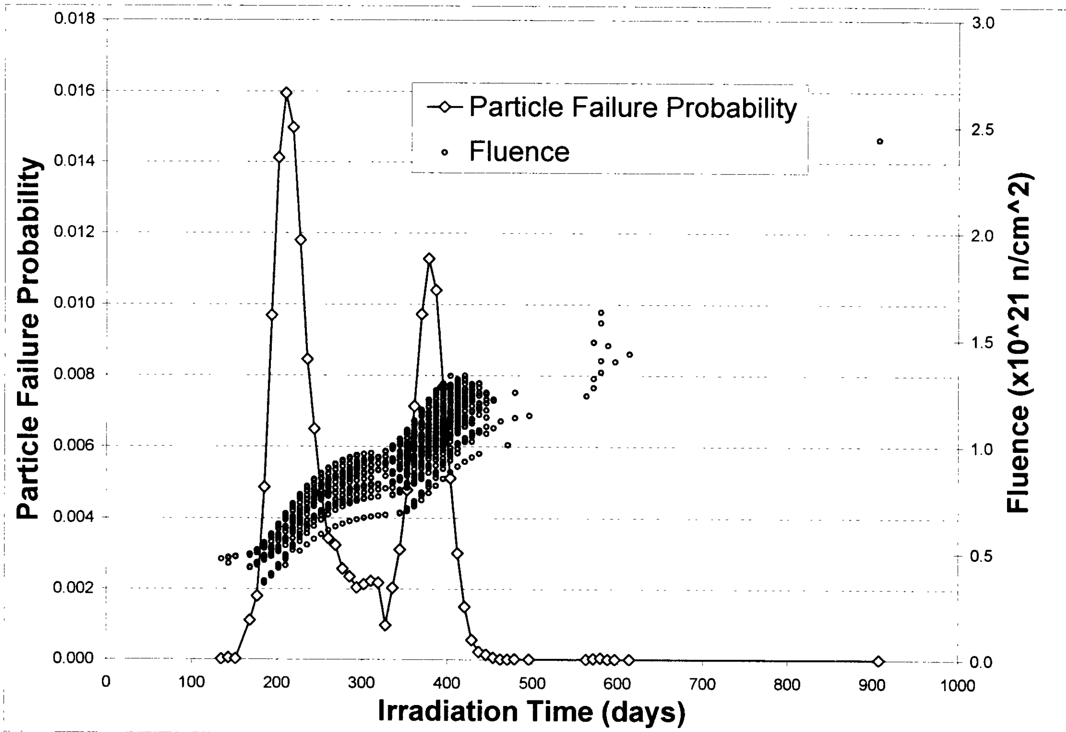


Figure 4-19 Fluence and particle failure probability of MS MPBR2 (BAF = 1.02)

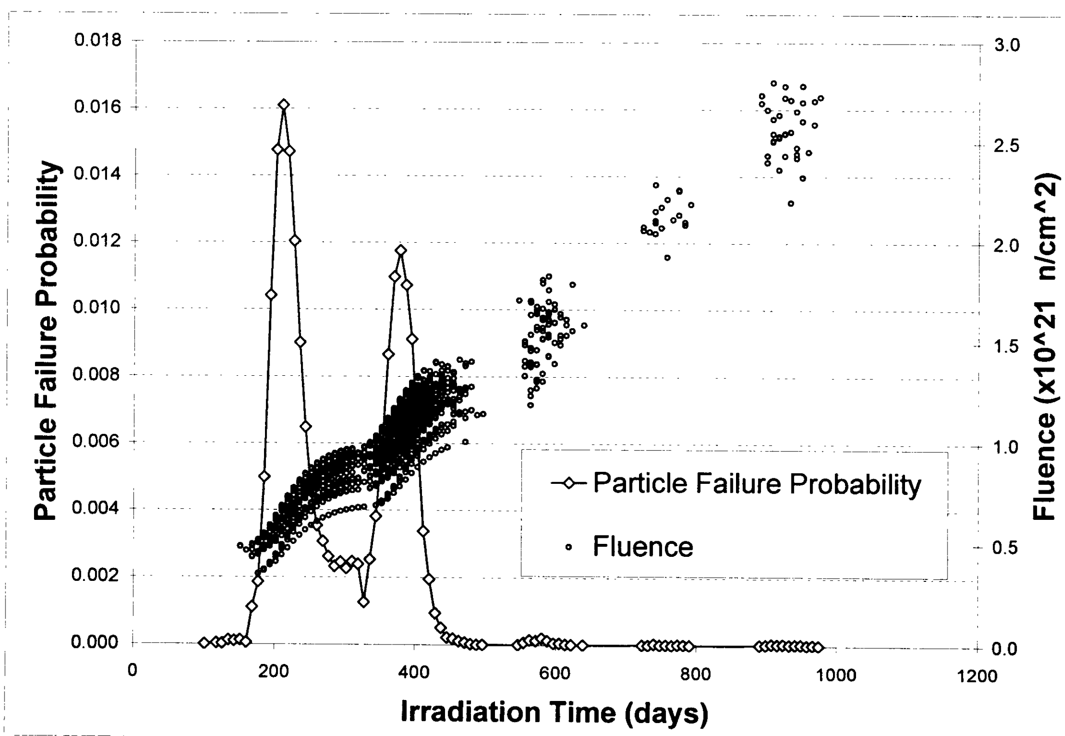


Figure 4-20 Fluence and particle failure probability of DS MPBR2 (BAF = 1.02)

4.5 Summary

The simulation results show the following important points:

- Many have believed that high BAF weakens fuel particles. This new simulation results obviously contradict this notion. The results in fact show that the particle failure probability decreases at high BAF.
- As expected, higher fracture toughness reduces the particle failure probability. The standard deviations on the fracture toughness also affect the failure probability. A combination of high fracture toughness and a low standard deviation provides a great fuel performance. In addition, in the plots show some plateaus in the cases of as manufactured fuel.
- Neutron fluence and power history control the failure characteristics of fuel particles.

Chapter 5

Conclusions and future research

In all four cases high BAF and K_{IC} of SiC provide the best fuel performance. A high BAF value of pyrocarbon increases the strength of pyrocarbon and helps prevent cracks to form on the pyrocarbon layers. In addition, pyrocarbon shrinkage in low fluence regime results in compressive forces on the silicon carbide layer. Hence, the synergic effects due to a high BAF the on silicon carbide layer result in a fewer high local stress intensity points. The probability of sharp crack propagation in the silicon carbide layer declines. It is also inevitable that greater fracture toughness leads to a lower particle failure probability.

Finally, although TIMCOAT yields rather satisfactory simulation results, it still needs work on many areas. Some of the areas include:

- Chemical modeling (fission product attack for pressure vessel failure, palladium attack for crack induced failure, and amoeba effect)
- Higher fluence regime (currently TIMCOAT works well only in low fluence regime, which is less 4×10^{21} neutrons/cm^2) by adding a material database that provides the relations between fast neutron fluence and the properties of pyrocarbon and silicon carbide beyond the current fluence regime
- More user friendly interface.

Appendix A

Input Files for NPR Benchmarking

A-1 The input file for NPR1-A1

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 874.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day) USED IN CONST. IRR. ONLY
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.74D0, ! EOL burnup (FIMA)
    EOLFLU = 2.4D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A1 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_1s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-2 The input file for NPR1-A2

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m3)
    T_IRR = 1050.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.77D0, ! EOL burnup (FIMA)
    EOLFLU = 3.0D0, ! EOL fluence (10^21n/cm2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A2 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_2s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-3 The input file for NPR1-A3

```
$INPUT
      CORE_HEIGHT = 10.0D0, ! core height (m)
      CORE_RADIUS = 1.75D0, ! core radius(m)
      P_CORE = 250.0D0, ! core power (MWth)
      QPPP_AVG = 3.65186D6, ! averaged power density (W/m3)
      T_IRR = 1036.0D0, ! irradiation temperature (Celsius)
      IRRTIME = 170.0D0, ! irradiation time(Day)
      T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
      T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
      MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
      PEBRADIUS = 3.0D-2, ! pebble radius (m)
      PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
      NPEBBLE = 360000, ! number of pebbles in core
      NPARTICLE = 11000, ! number of particles per pebble
      DT = 1.728D5, ! time step size (s)
      OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
      EOLBUP = 0.785D0, ! EOL burnup (FIMA)
      EOLFLU = 3.5D0, ! EOL fluence (10^21n/cm^2)
      SHUFFLE = 10, ! number of fueling cycles
      FUELTYPE = 'UCO', ! fuel kernel type
      CURAT = 0.36D0, ! Carbon to Uranium ratio
      OURAT = 1.51D0, ! Oxygen to Uranium ratio
      U235ENR = 93.15D0, ! U235 enrichment (%)
      U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
      KERND = 10.52D0, ! kernel density (g/cm^3)
      KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
      KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
      KERNDIA = 200.0D0, ! kernel diameter (micron)
      KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
      BUFFD = 0.9577D0, ! buffer density (g/cm^3)
      BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm3)
      BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
      BUFFTHK = 102.0D0, ! buffer thickness (micron)
      BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
      IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
      IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
      IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
      IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
      IPYCD = 1.923D0, ! IPyC density (g/cm^3)
      IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
      IPYCM = 9.5D0, ! IPyC Weibull modulus
      IPYCTHK = 53.0D0, ! IPyC thickness (micron)
      IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
      OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
      OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
      OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
      OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
      OPYCD = 1.855D0, ! OPyC density (g/cm^3)
      OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
      OPYCM = 9.5D0, ! OPyC Weibull modulus
      OPYCTHK = 39.0D0, ! OPyC thickness (micron)
      OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
      SICTHK = 35.0D0, ! SiC thickness (micron)
      SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
      SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
      SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
      SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
      SICM = 6.0D0, ! SiC Weibull modulus
      PAMB = 0.10D0, ! ambient pressure (MPa)
      TITLE = 'Capsule NPR-1#A3 specifications_MC sampling', ! particle description
      OSPEC = 'NPR1_3s', ! output file name
      DEBUG = .TRUE., ! flag for debugging
      ISEED = 30285171, ! initial seed for random number generator
      NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
      NCASES = 1000000, ! number of particles to be sampled
      NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
      DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
      HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
      RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
      USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-4 The input file for NPR1-A4

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 993.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.79D0, ! EOL burnup (FIMA)
    EOLFLU = 3.8D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A4 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_4s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-5 The input file for NPR1-A5

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 987.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.79D0, ! EOL burnup (FIMA)
    EOLFLU = 3.8D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A5 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_5s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-6 The input file for NPR1-A6

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 1001.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.785D0, ! EOL burnup (FIMA)
    EOLFLU = 3.5D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A6 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_6s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-7 The input file for NPR1-A7

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 1003.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 170.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 1.728D5, ! time step size (s)
    OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.77D0, ! EOL burnup (FIMA)
    EOLFLU = 3.0D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UCO', ! fuel kernel type
    CURAT = 0.36D0, ! Carbon to Uranium ratio
    OURAT = 1.51D0, ! Oxygen to Uranium ratio
    U235ENR = 93.15D0, ! U235 enrichment (%)
    U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.52D0, ! kernel density (g/cm3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 200.0D0, ! kernel diameter (micron)
    KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 0.9577D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 102.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.923D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 53.0D0, ! IPyC thickness (micron)
    IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.855D0, ! OPyC density (g/cm^3)
    OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 39.0D0, ! OPyC thickness (micron)
    OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Capsule NPR-1#A7 specifications_MC sampling', ! particle description
    OSPEC = 'NPR1_7s', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

A-8 The input file for NPR1-A8

```
$INPUT
      CORE_HEIGHT = 10.0D0, ! core height (m)
      CORE_RADIUS = 1.75D0, ! core radius(m)
      P_CORE = 250.0D0, ! core power (MWth)
      QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
      T_IRR = 845.0D0, ! irradiation temperature (Celsius)
      IRRTIME = 170.0D0, ! irradiation time(Day)
      T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
      T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
      MF_HE = 118.0D0, ! helium mass flow rate (kg/s)
      PEBRADIUS = 3.0D-2, ! pebble radius (m)
      PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
      NPEBBLE = 360000, ! number of pebbles in core
      NPARTICLE = 11000, ! number of particles per pebble
      DT = 1.728D5, ! time step size (s)
      OUTTIME = 1.728D5, ! time pebble is taken out of the core in each cycle (s)
      EOLBUP = 0.74D0, ! EOL burnup (FIMA)
      EOLFLU = 2.4D0, ! EOL fluence (10^21 n/cm^2)
      SHUFFLE = 10, ! number of fueling cycles
      FUELTYPE = 'UCO', ! fuel kernel type
      CURAT = 0.36D0, ! Carbon to Uranium ratio
      OURAT = 1.51D0, ! Oxygen to Uranium ratio
      U235ENR = 93.15D0, ! U235 enrichment (%)
      U235VAR = 0.01D0, ! standard deviation on U235 enrichment (%)
      KERND = 10.52D0, ! kernel density (g/cm3)
      KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
      KERNT = 11.03D0, ! kernel theoretical density (g/cm^3)
      KERNDIA = 200.0D0, ! kernel diameter (micron)
      KERNVAR = 5.2D0, ! standard deviation on kernel diameter (micron)
      BUFFD = 0.9577D0, ! buffer density (g/cm^3)
      BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
      BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
      BUFFTHK = 102.0D0, ! buffer thickness (micron)
      BUFFVAR = 10.2D0, ! standard deviation on buffer thickness (micron)
      IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
      IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
      IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
      IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
      IPYCD = 1.923D0, ! IPyC density (g/cm^3)
      IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
      IPYCM = 9.5D0, ! IPyC Weibull modulus
      IPYCTHK = 53.0D0, ! IPyC thickness (micron)
      IPYCVAR = 3.68D0, ! standard deviation on IPyC thickness (micron)
      OPYCBAF0I = 1.05154D0, ! OPyC as-fabricated BAF
      OPYCBAFVAR = 0.00622D0, ! standard deviation on OPyC as-fabricated BAF
      OPYCCRATE = 3.0D0, ! OPyC coating rate (micron/min)
      OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
      OPYCD = 1.855D0, ! OPyC density (g/cm^3)
      OPYCF = 20.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
      OPYCM = 9.5D0, ! OPyC Weibull modulus
      OPYCTHK = 39.0D0, ! OPyC thickness (micron)
      OPYCVAR = 4.01D0, ! standard deviation on OPyC thickness (micron)
      SICTHK = 35.0D0, ! SiC thickness (micron)
      SICVAR = 3.12D0, ! standard deviation on SiC thickness (micron)
      SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
      SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
      SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
      SICM = 6.0D0, ! SiC Weibull modulus
      PAMB = 0.10D0, ! ambient pressure (MPa)
      TITLE = 'Capsule NPR-1#A8 specifications_MC sampling', ! particle description
      OSPEC = 'NPR1_8s', ! output file name
      DEBUG = .TRUE., ! flag for debugging
      ISEED = 30285171, ! initial seed for random number generator
      NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
      NCASES = 1000000, ! number of particles to be sampled
      NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
      DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
      HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
      RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
      USERSEED = .FALSE., ! flag determining whether ISEED from users is used
$END
```

Appendix B

Irradiation History Files for NPR Benchmarking

B-1 The irradiation history file for NPR1-A1

0.00000000	0.00000	910.9421154	0.00000	0.00000
1.627056915	1.62706	923.1646794	0.00340	1.15927
4.062608557	4.06261	921.1432213	0.00850	2.89459
5.889465893	5.88947	919.118223	0.01232	4.19622
8.328115216	8.32812	908.9542893	0.01742	5.93375
11.67670832	11.67671	906.9381415	0.02442	8.31961
14.11148554	14.11149	906.9523024	0.02951	10.05438
16.24036677	16.24037	911.0359309	0.03397	11.57120
17.76055369	17.76055	915.1160192	0.03714	12.65433
19.28228945	19.28229	915.1248697	0.04033	13.73856
20.4480000	20.44800	917.1675691	0.04277	14.56913
33.5680000	20.44800	821.5695949	0.04277	14.56913
34.50894013	21.38894	890.785948	0.04471	15.13192
35.42198159	22.30198	890.7912583	0.04660	15.67802
36.02448053	22.90448	907.0797498	0.04784	16.03838
39.37617131	26.25617	896.9211264	0.05477	18.04308
39.6743231	26.55432	913.2078478	0.05539	18.22141
42.71469695	29.59470	921.3680244	0.06167	20.03990
45.14947417	32.02947	921.3821852	0.06670	21.49618
45.75507079	32.63507	929.5282011	0.06795	21.85839
49.70926052	36.58926	935.6580691	0.07612	24.22345
50.00896115	36.88896	947.8735527	0.07674	24.40271
52.44218953	39.32219	951.9589513	0.08177	25.85806
52.74034132	39.62034	968.2456727	0.08239	26.03638
53.8150000	40.69500	982.5003153	0.08461	26.67915
63.9640000	40.69500	917.4206938	0.08461	26.67915
65.53918456	42.27018	925.572020	0.08796	27.37517
69.19599691	45.92700	913.3795478	0.09572	28.99098
69.8000447	46.53104	925.5968014	0.09700	29.25788
72.54381559	49.27482	913.3990189	0.10283	30.47025
73.75655768	50.48756	925.6198128	0.10541	31.00612
75.5826406	52.31364	925.6304334	0.10929	31.81299
77.10050426	53.83150	935.8173784	0.11251	32.48368
78.31402077	55.04502	946.0025534	0.11509	33.01989
81.9661866	58.69719	946.0237946	0.12284	34.63364
85.8090000	62.54000	954.1875115	0.13100	36.33164
96.6180000	62.54000	764.9369069	0.13100	36.33164
98.16318583	64.08519	771.0543842	0.16214	37.28358
99.06151331	64.98351	809.7364537	0.18024	37.83701
100.5832491	66.50525	809.7453042	0.21090	38.77450
104.2423847	70.16438	791.4459753	0.28462	41.02877
108.1950256	74.11703	801.6470812	0.36426	43.46387
108.7905547	74.71255	836.2561428	0.37626	43.83075
111.2206854	77.14269	848.4840171	0.42522	45.32788

111.5126419	77.43464	881.0556897	0.43110	45.50774
112.7230607	78.64506	899.3833402	0.45549	46.25344
114.2355034	80.15750	923.8196176	0.48596	47.18521
115.7471717	81.66917	950.2915139	0.51642	48.11649
116.0693305	81.99133	903.4740492	0.52291	48.31497
116.652469	82.57447	970.6530133	0.53466	48.67422
118.2140000	84.31600	982.8755772	0.56612	49.63623
128.6180000	84.31600	734.5902543	0.56612	49.63623
129.1725209	84.87052	860.8021666	0.57722	49.87801
131.9162918	87.61429	848.6043841	0.63213	51.07433
132.5234373	88.22144	852.6791621	0.64428	51.33905
136.4822735	92.18027	846.5953167	0.72351	53.06516
137.3860219	93.08402	871.0280539	0.74160	53.45920
139.5172264	95.21523	869.0048257	0.78425	54.38844
140.7260964	96.42410	891.4037141	0.80845	54.91552
142.2424112	97.94041	905.661897	0.83879	55.57665
144.0622988	99.76030	921.9574688	0.87522	56.37015
145.8814119	101.57941	940.2886596	0.91162	57.16331
146.4831364	102.18114	958.612770	0.92367	57.42566
148.6112433	104.30924	964.7320174	0.96626	58.35355
150.0210000	105.53900	985.0952869	0.99447	58.96822
158.7570000	105.53900	641.1270248	0.99447	58.96822
159.9890254	106.77103	657.4190565	1.01927	59.35104
160.2151561	106.99716	863.0183361	1.02382	59.42130
163.8680963	110.65010	861.0039584	1.09736	60.55635
164.1639249	110.94592	883.3975365	1.10331	60.64827
166.9015004	113.68350	887.4847052	1.15842	61.49890
169.3324055	116.11441	897.6769606	1.20736	62.25423
171.7617618	118.54376	911.9404537	1.25626	63.00909
174.1240000	120.90600	936.3820414	1.30382	63.74309
176.8090000	120.90600	653.4451744	1.30382	63.74309
177.6248974	121.72190	700.2697195	1.31977	63.97356
177.8843282	121.98133	818.3373861	1.32484	64.04684
178.1367892	122.23379	954.7256229	1.32977	64.11816
178.7392881	122.83629	971.0141144	1.34155	64.28835
179.9481581	124.04516	993.4130027	1.36518	64.62984
180.8534554	124.95046	1013.774502	1.38288	64.88556
182.8990000	126.99600	1036.176931	1.42287	65.46339
249.6750000	126.99600	590.7658131	1.42287	65.46339
250.3065598	127.62756	851.3285732	1.43637	65.59253
250.9020889	128.22309	885.9376348	1.44911	65.71430
252.1163799	129.43738	894.0871909	1.47508	65.96259
254.2483588	131.56936	890.0283438	1.52067	66.39853
255.7693201	133.09032	892.0728132	1.55320	66.70953
257.289507	134.61051	896.1529015	1.58571	67.02038
259.1163644	136.43736	894.1279032	1.62477	67.39393

260.9520000	138.27300	892.102905	1.66403	67.76927
263.5730000	138.27300	574.5605165	1.66403	67.76927
264.7092273	139.40923	592.8881671	1.68778	67.99376
265.2071795	139.90718	883.9852108	1.69819	68.09215
267.0332625	141.73326	883.9958314	1.73636	68.45294
268.4380000	143.13800	902.3252521	1.76572	68.73049
271.0760000	143.13800	639.742804	1.76572	68.73049
271.6774606	143.73946	676.3892546	1.77865	68.85602
271.8857797	143.94778	928.807769	1.78313	68.89950
273.4013201	145.46332	945.1015707	1.81573	69.21581
274.9191837	146.98118	955.2885158	1.84837	69.53261
276.6000000	148.66200	985.8316499	1.88452	69.88342
281.0460000	148.66200	540.055891	1.88452	69.88342
282.6842954	150.30030	544.1377494	1.91779	70.11242
283.7824233	151.39842	857.6301413	1.94009	70.26591
288.3522771	155.96828	845.4429794	2.03290	70.90465
291.0898527	158.70585	849.5301482	2.08850	71.28730
291.2137599	158.82976	523.8311233	2.09101	71.30462
292.0075406	159.62354	837.3217451	2.10713	71.41557
293.834398	161.45040	835.2967468	2.14423	71.67091
294.8780000	162.49400	878.0500541	2.16543	71.81678
297.7530000	162.49400	544.2244845	2.16543	71.81678
298.1603094	162.90131	664.3295401	2.17385	71.88814
298.3794703	163.12047	888.2493899	2.17838	71.92653
298.9695786	163.71058	937.1077838	2.19058	72.02991
299.8802968	164.62130	943.2199508	2.20940	72.18946
301.0510000	165.79200	953.4051258	2.23360	72.39455
303.7790000	165.79200	554.4379811	2.23360	72.39455
304.8822771	166.89528	595.1574396	2.25583	72.53713
305.048003	167.06100	959.5349938	2.25917	72.55855
306.2630683	168.27607	965.648931	2.28365	72.71557
307.1714633	169.18446	977.8679547	2.30196	72.83296
308.2740000	170.28700	990.0869785	2.32417	72.97545

B-2 The irradiation history file for NPR1-A2

0.00000000	0.00000	1117.795556	0.00000	0.00000
1.568294308	1.56829	1129.851514	0.00443	1.40762
3.69251667	3.69252	1125.877995	0.01044	3.31420
5.516750533	5.51675	1117.889296	0.01560	4.95154
7.645529683	7.64553	1107.900818	0.02162	6.86222
10.07581626	10.07582	1099.922535	0.02849	9.04351
12.20155755	12.20156	1093.94403	0.03450	10.95146
14.32577992	14.32578	1089.970511	0.04051	12.85805
16.44696442	16.44696	1090.006965	0.04651	14.76191
18.57118678	18.57119	1086.033447	0.05252	16.66850
20.4480000	20.44800	1086.064693	0.057822657	18.35302348
33.5680000	20.44800	982.0293327	0.057822657	18.35302348
34.33767096	21.21767	1074.274332	0.05986	18.88532
35.24371218	22.12371	1078.299928	0.06226	19.51194
35.83761346	22.71761	1094.350235	0.06383	19.92268
38.88002847	25.76003	1078.362421	0.07187	22.02680
39.46937296	26.34937	1100.427687	0.07343	22.43439
42.19661018	29.07661	1100.474557	0.08065	24.32053
42.79506825	29.67507	1110.509905	0.08223	24.73442
45.22535483	32.10535	1102.531621	0.08866	26.41520
45.52078654	32.40079	1112.561761	0.08944	26.61952
49.46164812	36.34165	1110.624475	0.09986	29.34500
50.36161362	37.24161	1122.670017	0.10224	29.96741
52.48279813	39.36280	1122.706471	0.10785	31.43442
53.8150000	40.69500	1140.77218	0.111377069	32.3557614
63.9640000	40.69500	884.3057734	0.111377069	32.3557614
64.60992815	41.34093	1114.894836	0.11311	32.70273
68.87052431	45.60152	1090.907907	0.12450	34.99135
69.76441409	46.49541	1110.973395	0.12689	35.47151
72.20381425	48.93481	1090.965193	0.13342	36.78185
74.31436625	51.04537	1105.036552	0.13907	37.91555
75.22648318	51.95748	1101.042202	0.14151	38.40551
77.32944054	54.06044	1125.138494	0.14713	39.53513
79.45518183	56.18618	1119.159989	0.15282	40.67699
82.79302855	59.52403	1113.202315	0.16175	42.46995
85.8090000	62.54000	1109.24442	0.169817145	44.09000175
96.6180000	62.54000	953.0377497	0.169817145	44.09000175
98.03396325	63.95596	995.1685035	0.20632	45.10209
99.81870496	65.74070	1039.309451	0.25232	46.37777
104.0793011	70.00130	1015.322523	0.36215	49.42311
108.0110491	73.93305	1025.415156	0.46349	52.23340
108.5867233	74.50872	1065.5253	0.47833	52.64487182
111.3139605	77.23596	1065.57217	0.54863	54.26196
111.5881272	77.51013	1103.67212	0.55570	54.42452

113.7001981	79.62220	1115.738492	0.61014	55.67685
116.124409	82.04641	1115.780155	0.67263	57.11426
118.2140000	84.31600	1129.851514	0.726494445	58.3532647
128.6180000	84.31600	897.4449442	0.726494445	58.3532647
129.4909852	85.18899	1071.899594	0.74909	58.84721
131.6152075	87.31321	1067.926076	0.80408	60.04912
132.2136656	87.91167	1077.961424	0.81957	60.38773
136.1621218	91.86012	1065.999206	0.92178	62.62181
137.048417	92.74642	1096.089625	0.94472	63.12328503
139.780211	95.47821	1090.121536	1.01543	63.88780
140.9710514	96.66905	1118.212177	1.04626	64.22106
146.110348	101.80835	1134.3406	1.17929	65.65933
148.2482408	103.94624	1112.322204	1.23463	66.25763
150.0210000	105.53900	1124.383369	1.280520869	66.75374957
158.7570000	105.53900	761.6214351	1.280520869	66.75374957
159.4002183	106.18222	791.7118548	1.29669	66.90646
160.1042419	106.88624	1062.400646	1.31438	67.07360
163.4481644	110.23016	1048.423026	1.39841	67.86749
164.034471	110.81647	1074.498265	1.41314	68.00669
166.7617082	113.54371	1074.545135	1.48168	68.65417
167.9631812	114.74518	1088.600871	1.51187	68.93941
171.2919143	118.07391	1094.673116	1.59553	69.72969
174.1240000	120.90600	1106.749904	1.666696494	70.4020649
176.8090000	120.90600	781.9837648	1.666696494	70.4020649
177.577243	121.67424	798.0392795	1.68689	70.57193
177.9433049	122.04030	1114.837551	1.69651	70.65287
178.250888	122.34789	1108.827799	1.70460	70.72087
179.4645124	123.56151	1106.843644	1.73650	70.98921
180.0599326	124.15693	1120.888964	1.75215	71.12086
182.8990000	126.99600	1132.965752	1.826782574	71.74859335
249.6750000	126.99600	678.9743323	1.826782574	71.74859335
250.4303994	127.75140	1031.872774	1.84763	71.86555
250.7015283	128.02253	1073.982697	1.85511	71.90753
251.6106073	128.93161	1073.99832	1.88020	72.04828
251.9045201	129.22552	1086.033447	1.88832	72.09379
254.0287425	131.34974	1082.059928	1.94694	72.42268
256.1484081	133.46941	1084.101369	2.00545	72.75086
258.5726189	135.89362	1084.143031	2.07235	73.12620
260.9520000	138.27300	1086.18968	2.13802229	73.4945935
263.5730000	138.27300	671.1939434	2.13802229	73.4945935
264.3293602	139.02936	685.2444716	2.15663	73.61483
264.9483239	139.64832	1068.212503	2.17187	73.71322
265.2635017	139.96350	1052.177819	2.17962	73.76333
266.7771145	141.47711	1054.208844	2.21687	74.00394
268.4380000	143.13800	1060.249842	2.25774123	74.26796688
271.0760000	143.13800	751.5235944	2.25774123	74.26796688

271.7485695	143.81057	891.8882676	2.27594	74.33963
272.2209564	144.28296	1068.337489	2.28872	74.38996
273.4345808	145.49658	1066.353333	2.32156	74.51928
274.9497126	147.01171	1066.379372	2.36256	74.68072
276.6000000	148.66200	1072.42037	2.407210383	74.85656047
281.0460000	148.66200	629.3912783	2.407210383	74.85656047
282.2458886	149.86189	635.4270686	2.43955	74.97600
282.8967497	150.51275	976.2903845	2.45709	75.04080
283.5134349	151.12943	962.2658951	2.47371	75.10218
284.0526548	151.66865	1050.495713	2.48824	75.15586
287.3874636	155.00346	1048.548012	2.57811	75.48783
290.7192346	158.33523	1050.610284	2.66790	75.81949
290.7503727	158.36637	609.5080623	2.66873	75.82259
291.9556429	159.57164	1018.551332	2.70122	75.94257
293.4692558	161.08526	1020.582357	2.74201	76.09325
294.8780000	162.49400	1060.708125	2.779970561	76.2334835
297.7530000	162.49400	723.912067	2.779970561	76.2334835
298.0024997	162.74350	1036.700365	2.78624	76.24867
298.5827306	163.32373	1070.79555	2.80082	76.28398
299.1705562	163.91156	1094.865803	2.81559	76.31975
301.0510000	165.79200	1098.907022	2.862832254	76.43418426
303.7790000	165.79200	649.8317244	2.862832254	76.43418426
304.3409909	166.35399	669.8920041	2.87813	76.48365
304.9432463	166.95625	1074.914886	2.89452	76.53665
305.8553632	167.86836	1070.920536	2.91934	76.61693
307.0689876	169.08199	1068.936381	2.95237	76.72374
308.2740000	170.28700	1072.967185	2.985161804	76.82979634

B-3 The irradiation history file for NPR1-A3

0.00000000	0.00000	1132.825764	0.00000	0.00000
2.191213922	2.19121	1145.076401	0.00692	2.23028
5.549992042	5.54999	1132.921265	0.01753	5.64894
8.302936651	8.30294	1118.719935	0.02623	8.45097
9.51228247	9.51228	1124.847906	0.03005	9.68188
10.44540535	10.44541	1106.543577	0.03299	10.63164
13.19834996	13.19835	1092.342247	0.04169	13.43367
15.0297777	15.02978	1086.267332	0.04747	15.29775
16.85656303	16.85656	1084.263582	0.05324	17.15710
18.38855581	18.38856	1074.112196	0.05808	18.71641
20.4480000	20.44800	1066.007003	0.064586995	20.81257274
33.5680000	20.44800	982.7709394	0.064586995	20.81257274
34.26325074	21.14325	1019.427349	0.06680	21.36489
35.70239548	22.58240	1090.699278	0.07140	22.50817
39.36989336	26.24989	1074.478282	0.08309	25.42169
39.95715726	26.83716	1092.80914	0.08497	25.88822
41.48218644	28.36219	1088.764502	0.08983	27.09972
42.68921106	29.56921	1096.928056	0.09368	28.05860
45.13111471	32.01111	1088.828169	0.10147	29.99849
45.72766341	32.60766	1099.016695	0.10338	30.47239
48.77540057	35.65540	1092.963002	0.11310	32.89356
50.27953894	37.15954	1107.238611	0.11790	34.08847
50.90394206	37.78394	1093.000141	0.11989	34.58451
52.42432884	39.30433	1093.026669	0.12474	35.79233
53.8150000	40.69500	1111.368138	0.129173989	36.89709864
63.9640000	40.69500	879.4867714	0.129173989	36.89709864
64.58974427	41.32074	1091.203311	0.13120	37.26578
65.49965514	42.23066	1093.25481	0.13415	37.80189
69.17411662	45.90512	1070.927066	0.14605	39.96686
70.07010028	46.80110	1085.192063	0.14895	40.49476
72.82536609	49.55637	1068.95515	0.15787	42.11815
74.33182566	51.06283	1081.195175	0.16275	43.00574
75.55509868	52.28610	1075.109649	0.16671	43.72648
78.58194503	55.31295	1087.376203	0.17651	45.50988
82.24712171	58.97812	1073.190789	0.18838	47.66937
85.8090000	62.54000	1056.964488	0.199912127	49.76800005
96.6180000	62.54000	967.5898415	0.199912127	49.76800005
97.52062553	63.44263	1012.388582	0.22678	50.34976
99.28009603	65.20210	1069.416737	0.27915	51.48378
103.8783956	69.80040	1036.926995	0.41601	54.44748
108.151727	74.07373	1022.752193	0.54321	57.20173
108.7227425	74.64474	1055.332131	0.56020	57.5697598
111.1716097	77.09361	1041.125495	0.63309	59.04484
111.7449464	77.66695	1071.66985	0.65016	59.39019

114.1845289	80.10653	1065.605546	0.72277	60.85968
116.3246764	82.24668	1055.464771	0.78647	62.14880
118.2140000	84.31600	1049.389856	0.842706503	63.28683685
128.6180000	84.31600	905.038554	0.842706503	63.28683685
129.6785468	85.37655	1078.089629	0.87441	63.82552
132.1204504	87.81845	1069.989743	0.94739	65.06583
132.4129218	88.11092	1080.172963	0.95613	65.21439
136.0827409	91.78074	1061.916384	1.06582	67.07839
137.2758383	92.97384	1082.293435	1.10148	67.68440287
140.0287829	95.72678	1068.092105	1.18377	68.34738
141.2242015	96.92220	1086.433574	1.21950	68.63527
146.1103300	101.80833	1068.198217	1.36554	69.81198
147.6632136	103.36121	1039.726585	1.41195	70.18596
150.0210000	105.53900	1029.591115	1.482425308	70.75377369
158.7570000	105.53900	769.1797538	1.482425308	70.75377369
159.8030958	106.58510	793.6279711	1.51341	70.96416
160.4089293	107.19093	1062.340832	1.53136	71.08601
163.7793135	110.56131	1040.007782	1.63119	71.76386
164.3572926	111.13929	1066.480971	1.64831	71.88010
165.5782444	112.36024	1062.431027	1.68448	72.12566
167.0893463	113.87135	1070.599887	1.72924	72.42957
171.3580353	118.14004	1060.496251	1.85568	73.28808
174.1240000	120.90600	1070.721916	1.937609842	73.84437248
176.8090000	120.90600	734.8878749	1.937609842	73.84437248
177.7877626	121.88476	755.2649264	1.96826	74.00069
178.3657417	122.46274	1048.404782	1.98635	74.09300
179.2826162	123.37962	1044.349533	2.01506	74.23943
180.1855635	124.28256	1052.507782	2.04333	74.38364
181.1070803	125.20408	1044.381367	2.07219	74.53081
182.8990000	126.99600	1044.407895	2.128295255	74.81699926
249.6750000	126.99600	675.0937323	2.128295255	74.81699926
250.1419249	127.46292	1037.443407	2.14281	74.86606
250.7477584	128.06876	1039.489601	2.16165	74.92972
251.6019604	128.92296	1090.395091	2.18821	75.01947
254.3456202	131.66662	1084.336092	2.27351	75.30775
255.866007	133.18701	1084.36262	2.32078	75.46751
257.077674	134.39867	1088.455008	2.35845	75.59482
259.2155003	136.53650	1080.349816	2.42492	75.81945
260.9520000	138.27300	1070.203735	2.478910369	76.00190569
263.5730000	138.27300	650.9107951	2.478910369	76.00190569
263.9391447	138.63914	671.2719298	2.49025	76.04620
264.8490556	139.54906	673.3234295	2.51844	76.15629
265.3481139	140.04811	1035.673104	2.53390	76.21667
266.8824278	141.58243	1023.486135	2.58143	76.40230
268.4380000	143.13800	1031.654994	2.629613357	76.59049928
271.0760000	143.13800	685.6483447	2.629613357	76.59049928

271.7801624	143.84216	728.4061969	2.65118	76.64179
272.0610277	144.12303	1015.433998	2.65978	76.66225
273.2866219	145.34862	1007.312889	2.69731	76.75152
274.8162935	146.87829	999.1970855	2.74415	76.86294
276.6000000	148.66200	997.1933362	2.798769772	76.99286572
281.0460000	148.66200	630.8573854	2.798769772	76.99286572
282.8197952	150.43580	647.1738823	2.85399	77.12192
283.0310245	150.64702	995.2691709	2.86056	77.13729
283.9455778	151.56158	993.2495048	2.88903	77.20384
284.1591283	151.77513	1072.642544	2.89568	77.21937
287.812699	155.42870	1068.635045	3.00941	77.48520
290.8581149	158.47411	1064.616935	3.10421	77.70678
291.0693442	158.68534	612.7122241	3.11079	77.72215
291.8190922	159.43509	1021.885611	3.13413	77.77670
293.6435563	161.25956	1021.917445	3.19092	77.90945
294.8780000	162.49400	1060.609437	3.229349736	77.99926426
297.7530000	162.49400	620.971279	3.229349736	77.99926426
298.2836375	163.02464	686.1205433	3.24716	78.03218
298.5134364	163.25444	1017.931169	3.25488	78.04643
299.0705247	163.81152	1062.724604	3.27358	78.08098
301.0510000	165.79200	1050.54294	3.340070299	78.20382465
303.7790000	165.79200	625.1485569	3.340070299	78.20382465
304.7296132	166.74261	633.3068053	3.36804	78.24780
305.5072156	167.52022	1018.053198	3.39092	78.28377
306.1269763	168.13998	1007.885894	3.40915	78.31244
307.046172	169.05917	1001.795062	3.43620	78.35496
308.2740000	170.28700	1001.816285	3.472319859	78.41176222

B-4 The irradiation history file for NPR1-A4

0.00000000	0.00000	1120.00	0.00000	0.00000
1.554174067	1.55417	1130.301954	0.00543	1.81199
4.351687389	4.35169	1122.178804	0.01520	5.07356
6.527531083	6.5275	1109.934873	0.02280	7.61035
8.703374778	8.7033	1095.639659	0.03040	10.14713
11.19005329	11.19005	1083.404837	0.03908	13.04631
13.67673179	13.67673	1069.118732	0.04776	15.94549
15.85257549	15.85258	1058.926083	0.05536	18.48227
18.02841918	18.02842	1048.733434	0.06296	21.01905
19.27175844	19.27176	1038.513458	0.06730	22.46864
20.4480000	20.44800	1030.344765	0.071412828	23.84000
33.5680000	20.44800	973.2823245	0.071412828	23.84000
34.5026643	21.38266	991.7802979	0.07467	24.61748
34.81349911	21.69350	1051.276586	0.07576	24.87604
36.05683837	22.93684	1065.671995	0.08009	25.91028
39.47602131	26.35602	1045.259371	0.09202	28.75445
40.09769094	26.97769	1063.739126	0.09419	29.27157
42.89520426	29.77520	1063.821105	0.10395	31.59862
45.07104796	31.95105	1053.628456	0.11154	33.40855
46.0035524	32.88355	1061.86091	0.11479	34.18423
47.86856128	34.74856	1057.812998	0.12130	35.73559
49.73357016	36.61357	1051.713804	0.12780	37.28696
50.6660746	37.54607	1055.843694	0.13106	38.06264
52.22024867	39.10025	1047.68411	0.13648	39.35544
53.8150000	40.69500	1057.995172	0.142041976	40.68200
63.9640000	40.69500	902.3801066	0.142041976	40.68200
64.65364121	41.38464	1066.509997	0.14423	41.04654
69.31616341	46.04716	1035.877397	0.15905	43.51109
69.93783304	46.66883	1052.305871	0.16103	43.83970
72.73534636	49.46635	1029.823746	0.16992	45.31843
74.60035524	51.33136	1038.083527	0.17585	46.30425
75.53285968	52.26386	1034.008289	0.17881	46.79716
78.33037300	55.06137	1042.295396	0.18770	48.27589
81.12788632	57.85889	1028.0184	0.19659	49.75462
83.61456483	60.34556	1015.783577	0.20449	51.06905
85.8090000	62.54000	1009.693492	0.211468888	52.22900
96.6180000	62.54000	1020.268707	0.211468888	52.22900
98.22380107	64.14580	1028.519379	0.26365	53.21563
99.15630551	65.07831	1063.4185	0.29395	53.78858
103.1971581	69.11916	1032.767682	0.42526	56.27134
108.1705151	74.09252	1004.195473	0.58688	59.32705
109.1030195	75.02502	1030.889466	0.61718	59.90000
111.2788632	77.20086	1010.440406	0.68788	61.20799
111.9005329	77.82253	1039.176572	0.70808	61.58170

114.0763766	79.99838	1024.881359	0.77879	62.88970
116.2522202	82.17422	1006.483582	0.84950	64.19769
118.2140000	84.31600	990.1279774	0.913245303	65.37700
128.6180000	84.31600	891.9670265	0.913245303	65.37700
128.9964476	84.69445	896.087808	0.92552	65.50249
129.6181172	85.31612	1045.849615	0.94568	65.70863
132.4156306	88.11363	1037.726465	1.03639	66.63625
136.7673179	92.46532	1021.443731	1.17750	68.07922
137.3889876	93.08699	1039.923487	1.19766	68.28536
140.1865009	95.88450	1019.492645	1.28838	69.21299
141.1190053	96.81701	1031.827663	1.31862	69.52220
146.0923623	101.79036	1007.358018	1.47989	71.17131
147.6465364	103.34454	978.6856128	1.53029	71.68665
150.0210000	105.53900	964.3995081	1.607282879	72.47400
158.7570000	105.53900	769.7736485	1.607282879	72.47400
159.4582593	106.24026	769.8009746	1.62940	72.58927
160.3907638	107.17276	1011.879583	1.65880	72.74256
163.8099467	110.59195	991.4669581	1.76663	73.30459
164.4316163	111.21362	1014.049278	1.78624	73.40678
167.2291297	114.01113	1007.97741	1.87446	73.86663
170.026643	116.80864	999.8542606	1.96268	74.32648
171.5808171	118.36282	989.6433939	2.01169	74.58196
174.1240000	120.90600	989.7162636	2.091890917	75.00000
176.8090000	120.90600	714.9173384	2.091890917	75.00000
177.7975133	121.89451	719.0563374	2.12485	75.12758
178.4191829	122.51618	989.8437856	2.14557	75.20782
179.0408526	123.13785	979.6055927	2.16630	75.28805
179.973357	124.07036	983.735483	2.19738	75.40840
181.5275311	125.62453	967.3707701	2.24920	75.60899
182.8990000	126.99600	969.458487	2.294917435	75.78600
249.6750000	126.99600	743.7245525	2.294917435	75.78600
250.8436945	128.16469	977.6071412	2.33497	75.92891
251.4653641	128.78636	1010.445871	2.35627	76.00493
252.7087034	130.02970	1020.738717	2.39888	76.15697
255.5062167	132.82722	1016.718131	2.49474	76.49907
255.8170515	133.13805	1024.932368	2.50539	76.53708
256.749556	134.07056	1029.062258	2.53735	76.65111
258.9253996	136.24640	1020.920891	2.61191	76.91718
260.9520000	138.27300	1008.667851	2.681360664	77.16500
263.5730000	138.27300	651.8176436	2.681360664	77.16500
264.5204263	139.22043	658.0079246	2.71265	77.24309
265.4529307	140.15293	965.7275584	2.74345	77.31995
265.7637655	140.46377	949.3264107	2.75372	77.34557
267.3179396	142.01794	945.2693902	2.80505	77.47368
268.4380000	143.13800	953.5018445	2.842041753	77.56600
271.0760000	143.13800	697.1735665	2.842041753	77.56600

272.2912966	144.35330	929.0048732	2.88446	77.61374
273.2238011	145.28580	918.775789	2.91700	77.65037
274.1563055	146.21831	912.649269	2.94955	77.68700
275.3996448	147.46164	904.4805757	2.99294	77.73585
276.6000000	148.66200	898.3540557	3.034835906	77.78300
281.0460000	148.66200	631.8240197	3.034835906	77.78300
282.2380107	149.85401	638.0143007	3.07450	77.85375
283.4813499	151.09735	982.6661201	3.11587	77.92755
284.4138544	152.02985	1046.28319	3.14690	77.98290
285.3463588	152.96236	1050.41308	3.17793	78.03825
288.1438721	155.75987	1044.341212	3.27102	78.20430
291.2522202	158.86822	1036.227171	3.37445	78.38879
291.5630551	159.17906	851.6208954	3.38479	78.40724
292.4955595	160.11156	993.1866831	3.41582	78.46259
294.0497336	161.66573	985.0270984	3.46754	78.55484
294.8780000	162.49400	1011.711983	3.495096435	78.60400
297.7530000	162.49400	661.0338389	3.495096435	78.60400
298.7122558	163.45326	958.4970624	3.52770	78.66363
299.0230906	163.76409	972.8651455	3.53826	78.68295
300.2664298	165.00743	958.542606	3.58052	78.76023
301.0510000	165.79200	966.7659516	3.607189372	78.80900
303.7790000	165.79200	601.7197249	3.607189372	78.80900
304.6181172	166.63112	622.2598716	3.63582	78.84839
305.5506217	167.56362	907.4154028	3.66763	78.89216
306.1722913	168.18529	893.0746459	3.68883	78.92134
307.4156306	169.42863	889.0085166	3.73125	78.97971
308.2740000	170.28700	893.1384069	3.760532368	79.02000

B-5 The irradiation history file for NPR1-A5

0.00000000	0.00000	1128.389709	0.00000	0.00000
1.550406693	1.55041	1152.995557	0.00541	1.80477
4.312607496	4.31261	1142.862262	0.01504	5.02014
7.077159775	7.07716	1126.590942	0.02468	8.23826
9.535236312	9.53524	1110.308872	0.03325	11.09961
11.68605328	11.68605	1096.062061	0.04075	13.60330
14.14804895	14.14805	1069.54995	0.04933	16.46921
15.68199531	15.68200	1065.511681	0.05468	18.25482
17.52398506	17.52399	1057.392146	0.06111	20.39901
18.75615863	18.75616	1041.067078	0.06540	21.83334
20.4800000	20.44800	1026.798767	0.071412828	23.84000
33.5680000	20.44800	982.2488175	0.071412828	23.84000
34.37936703	21.25937	1060.029382	0.07424	24.51492
35.90782661	22.78783	1070.313172	0.07958	25.78633
37.14078400	24.02078	1051.942095	0.08388	26.81194
39.29081715	26.17082	1039.741293	0.09138	28.60039
39.8967142	26.77671	1058.176867	0.09349	29.10439
41.43066056	28.31066	1054.138598	0.09884	30.38037
42.6495091	29.52951	1072.595671	0.10309	31.39424
45.10445034	31.98445	1064.497635	0.11166	33.43633
46.02074226	32.90074	1072.713917	0.11485	34.19853
47.86194819	34.74195	1066.64039	0.12128	35.73009
49.70315411	36.58315	1060.566863	0.12770	37.26166
52.1565277	39.03653	1056.560843	0.13626	39.30244
53.8150000	40.69500	1060.706607	0.142041976	40.68200
63.9640000	40.69500	1056.980077	0.142041976	40.68200
66.86971478	43.60071	1050.938799	0.15128	42.21793
69.02131557	45.75232	1034.64598	0.15811	43.35524
69.93603985	46.66704	1046.954278	0.16102	43.83875
72.70137595	49.43238	1028.63695	0.16981	45.30047
74.22983553	50.96084	1038.92074	0.17467	46.10840
75.45730615	52.18831	1034.871721	0.17857	46.75722
77.2930253	54.02403	1043.120252	0.18440	47.72756
80.05444227	56.78544	1035.032965	0.19318	49.18721
82.81821073	59.54921	1020.807654	0.20196	50.64811
85.8090000	62.54000	1004.547083	0.211468888	52.22900
96.6180000	62.54000	1021.291386	0.211468888	52.22900
98.13651104	64.05851	1035.667192	0.26081	53.25657
98.73613749	64.65814	1070.470833	0.28030	53.66234
101.1949979	67.11700	1052.142755	0.36020	55.32625
103.6530744	69.57507	1035.860685	0.44008	56.98962
107.9539245	73.87592	1009.413072	0.57984	59.90000
108.8639458	74.78595	1033.99742	0.60941	60.38578
111.0155466	76.93755	1017.704601	0.67933	61.53435

111.619876	77.54188	1040.232191	0.69896	61.85695
116.2272019	82.14920	1013.795328	0.84868	64.31641
118.2140000	84.31600	1005.686541	0.913245303	65.37700
128.6180000	84.31600	887.3727963	0.913245303	65.37700
129.3993882	85.09739	1030.625627	0.93858	65.63610
131.8511941	87.54919	1030.711624	1.01809	66.44909
135.533606	91.23161	1018.564569	1.13750	67.67014
137.3685413	93.06654	1028.859108	1.19700	68.27858
139.8274016	95.52540	1010.531031	1.27673	69.09391
141.0478178	96.74582	1024.896087	1.31631	69.49859
142.8898076	98.58781	1016.776552	1.37604	70.10937
145.3478841	101.04588	1000.494482	1.45575	70.92445
146.8888849	102.58688	978.0421385	1.50572	71.43542
150.0210000	105.53900	953.5975348	1.607282879	72.47400
158.7570000	105.53900	765.6657589	1.607282879	72.47400
160.0610712	106.84307	994.872438	1.64841	72.68836
161.9022771	108.68428	988.7989107	1.70647	72.99102
163.438575	110.22057	978.6226172	1.75492	73.24355
164.0436882	110.82569	999.1041995	1.77400	73.34302
166.8027537	113.58475	997.1549377	1.86101	73.79655
168.9512192	115.73322	989.0461516	1.92876	74.14971
170.7939928	117.57599	978.8806077	1.98688	74.45262
174.1240000	120.90600	983.09087	2.091890917	75.00000
176.8090000	120.90600	715.1390282	2.091890917	75.00000
178.1525459	122.24955	970.954565	2.13668	75.17340
179.3792327	123.47623	968.9515551	2.17758	75.33172
179.9914003	124.08840	971.0190626	2.19798	75.41073
180.9147467	125.01175	960.8212699	2.22877	75.52990
182.1445688	126.24157	950.6342267	2.26977	75.68863
182.8990000	126.99600	946.5637093	2.294917435	75.78600
249.6750000	126.99600	668.5932349	2.294917435	75.78600
250.4863077	127.80731	959.1694138	2.32272	75.88521
250.7786746	128.09967	996.008313	2.33274	75.92096
252.6167452	129.93775	998.118819	2.39573	76.14573
254.7628592	132.08386	996.1480579	2.46927	76.40817
256.2921026	133.61310	1004.385839	2.52167	76.59517
257.8268328	135.14783	998.3015623	2.57427	76.78284
259.0558711	136.37687	990.1605274	2.61638	76.93313
260.9520000	138.27300	984.0870001	2.681360664	77.16500
263.5730000	138.27300	646.5816253	2.681360664	77.16500
264.3929384	139.09294	658.889924	2.70844	77.23258
264.893019	139.59302	953.5366203	2.72496	77.27380
265.2049815	139.90498	939.2253117	2.73526	77.29952
266.7389279	141.43893	935.1870431	2.78592	77.42595
268.4380000	143.13800	927.0567579	2.842041753	77.56600
271.0760000	143.13800	693.8978071	2.842041753	77.56600

271.6448912	143.70689	929.2210119	2.86190	77.58835
271.9560699	144.01807	916.9557116	2.87276	77.60057
273.1835406	145.24554	912.9066934	2.91560	77.64879
274.411795	146.47380	906.8116669	2.95846	77.69704
276.6000000	148.66200	913.0034399	3.034835906	77.78300
281.0460000	148.66200	622.6422531	3.034835906	77.78300
282.4867645	150.10276	628.8340261	3.08278	77.86852
282.6795856	150.29559	925.5159811	3.08919	77.87996
283.5794172	151.19542	976.6984377	3.11914	77.93337
285.4174878	153.03349	978.8089437	3.18030	78.04247
288.4845967	156.10060	972.7784148	3.28236	78.22452
290.6307107	158.24671	970.8076537	3.35377	78.35190
290.6620637	158.27806	888.9673212	3.35481	78.35376
291.5618953	159.17790	940.1497778	3.38475	78.40717
293.4031013	161.01910	934.0762505	3.44602	78.51646
294.8780000	162.49400	958.6820983	3.495096435	78.60400
297.7530000	162.49400	598.6706321	3.495096435	78.60400
298.0033727	162.74437	926.0534614	3.50361	78.61956
298.6053506	163.34635	954.719077	3.52407	78.65698
299.5271293	164.26813	948.6133008	3.55540	78.71428
301.0510000	165.79200	944.5750322	3.607189372	78.80900
303.7790000	165.79200	580.4715494	3.607189372	78.80900
304.5569371	166.56994	619.3779561	3.63373	78.84552
305.064856	167.07786	893.5645693	3.65106	78.86936
305.9897700	168.00277	879.2747599	3.68261	78.91278
307.2188082	169.23181	871.1337251	3.72454	78.97047
308.2740000	170.28700	865.027949	3.760532368	79.02000

B-6 The irradiation history file for NPR1-A6

0.00000000	0.00000	1131.314042	0.00000	0.00000
1.879001577	1.87900	1145.487082	0.00594	1.91250
4.025548235	4.02555	1141.483848	0.01272	4.09732
6.176734404	6.17673	1131.420088	0.01951	6.28686
8.331013578	8.33101	1117.315977	0.02631	8.47955
10.48065324	10.48065	1109.272392	0.03310	10.66752
12.63183941	12.63184	1099.208632	0.03990	12.85706
14.16751724	14.16752	1093.174618	0.04475	14.42011
15.39698741	15.39699	1087.135301	0.04863	15.67150
18.1574959	18.15750	1081.122496	0.05735	18.48123
20.4480000	20.44800	1067.018386	0.064586995	20.81257274
33.5680000	20.44800	982.3937221	0.064586995	20.81257274
34.12668955	21.00669	1020.792959	0.06637	21.25640
34.6988958	21.57890	1073.328119	0.06819	21.71097
35.60669327	22.48669	1087.485253	0.07109	22.43214
38.9873496	25.86735	1071.382176	0.08187	25.11779
39.58893941	26.46894	1085.534008	0.08379	25.59570
42.03860072	28.91860	1085.576426	0.09161	27.54175
42.64637654	29.52638	1091.647556	0.09355	28.02457
45.10222387	31.98222	1083.609274	0.10138	29.97554
47.24258452	34.12258	1087.68674	0.10821	31.67587
49.08137701	35.96138	1085.698379	0.11407	33.13664
50.30466116	37.18466	1087.739763	0.11798	34.10843
52.14345365	39.02345	1085.751402	0.12384	35.56920
53.8150000	40.69500	1095.878789	0.129173989	36.89709864
63.9640000	40.69500	1077.87749	0.129173989	36.89709864
65.92743806	42.65844	1079.929479	0.13553	38.05394
69.00497974	45.73598	1059.78075	0.14550	39.86720
69.91587022	46.64687	1069.897533	0.14845	40.40389
72.37635706	49.10736	1055.798725	0.15641	41.85359
74.20432402	50.93532	1067.95159	0.16233	42.93062
75.73845535	52.46946	1063.937751	0.16730	43.83451
77.26176116	53.99276	1074.065139	0.17223	44.73203
80.32847731	57.05948	1068.057636	0.18217	46.53892
83.09207881	59.82308	1058.00448	0.19111	48.16721
85.8090000	62.54000	1045.93115	0.199912127	49.76800005
96.6180000	62.54000	979.4456448	0.199912127	49.76800005
97.21474746	63.13675	1009.76418	0.21767	50.17922
99.02260988	64.94461	1048.179324	0.27148	51.42500
102.1001516	68.02215	1028.030594	0.36309	53.54572
104.8714856	70.79349	1007.876563	0.44557	55.45544
107.9397482	73.86175	999.8488845	0.53690	57.5697598
108.8367202	74.75872	1028.147245	0.56360	58.06888
110.9894528	76.91145	1016.063309	0.62767	59.26676

111.5817636	77.50376	1042.336192	0.64530	59.59635
114.9577805	80.87978	1032.293641	0.74579	61.47492
118.2140000	84.31600	1012.150214	0.842706503	63.28683685
128.6180000	84.31600	854.7515211	0.842706503	63.28683685
129.6712134	85.36921	1012.346399	0.87419	63.70187
132.1208747	87.81887	1012.388817	0.94740	64.66718
135.8030992	91.50110	1002.351569	1.05746	66.11820
137.320219	93.01822	1020.559657	1.10281	66.71604
139.7776128	95.47561	1010.5012	1.17626	67.68440287
140.9885249	96.68652	1028.703986	1.21245	68.04725
143.7474869	99.44549	1024.711356	1.29491	68.87395
145.8955801	101.59358	1018.687947	1.35912	69.51762
147.1358758	102.83388	998.5074033	1.39619	69.88926
150.0210000	105.53900	986.4287703	1.482425308	70.75377369
158.7570000	105.53900	725.9799308	1.482425308	70.75377369
159.8821564	106.66416	748.2230676	1.51575	70.98006
160.3136309	107.09563	984.5941754	1.52853	71.06684
163.6881012	110.47010	976.5717997	1.62849	71.74551
163.9772973	110.75930	998.7990297	1.63706	71.80368
166.7347128	113.51671	996.8265751	1.71873	72.35824
169.1781881	115.96019	1004.949694	1.79111	72.84967
171.3262813	118.10828	998.9262848	1.85474	73.28170
174.1240000	120.90600	1003.009054	1.937609842	73.84437248
176.8090000	120.90600	706.0910139	1.937609842	73.84437248
177.6592125	121.75621	726.3086732	1.96423	73.98016
178.0643964	122.16140	997.0227601	1.97692	74.04487
178.9876589	123.08466	990.9781413	2.00583	74.19232
179.9000959	123.99710	999.0747491	2.03440	74.33805
181.1280195	125.22502	995.0556078	2.07284	74.53416
182.8990000	126.99600	991.0417688	2.128295255	74.81699926
249.6750000	126.99600	757.8573417	2.128295255	74.81699926
250.3541493	127.67515	965.9512984	2.14941	74.88836
250.6309734	127.95197	1004.33993	2.15802	74.91745
252.1558257	129.47683	1012.447143	2.20543	75.07767
253.6930500	131.01405	1004.392953	2.25322	75.23919
255.5318425	132.85284	1002.404592	2.31039	75.43239
256.1380718	133.45907	1010.495897	2.32924	75.49609
258.8970338	136.21803	1006.503268	2.41502	75.78598
260.9520000	138.27300	996.4342051	2.478910369	76.00190569
263.5730000	138.27300	630.8249049	2.478910369	76.00190569
264.6871424	139.38714	642.9671655	2.51342	76.13670
264.7304445	139.43044	986.4022588	2.51476	76.14194
265.0552102	139.75521	962.1654582	2.52482	76.18123
266.5893415	141.28934	958.1516192	2.57235	76.36684
268.4380000	143.13800	954.1377802	2.629613357	76.59049928
271.0760000	143.13800	691.5627195	2.629613357	76.59049928

271.681977	143.74398	705.7145508	2.64817	76.63464
271.7917788	143.85378	962.2821087	2.65153	76.64264
273.3259101	145.38791	958.2682697	2.69851	76.75438
274.8600414	146.92204	954.2544307	2.74549	76.86613
276.6000000	148.66200	952.260767	2.798769772	76.99286572
281.0460000	148.66200	594.7639815	2.798769772	76.99286572
282.4703845	150.08638	612.9720701	2.84311	77.09650
283.169404	150.78540	899.8528613	2.86487	77.14736
284.0308063	151.64681	974.6152521	2.89168	77.21004
286.1742600	153.79026	974.6523681	2.95841	77.36599
288.0130525	155.62905	972.6640067	3.01565	77.49978
290.1487736	157.76477	982.801999	3.08213	77.65517
291.0658501	158.68185	584.8380811	3.11068	77.72190
291.3952553	159.01126	954.5407548	3.12093	77.74586
293.2325013	160.84850	954.5725686	3.17813	77.87954
294.8780000	162.49400	997.0174578	3.229349736	77.99926426
297.7530000	162.49400	582.9292541	3.229349736	77.99926426
297.7900467	162.53105	601.1161336	3.23059	78.00156
298.1302774	162.87128	956.6775806	3.24202	78.02267
298.7086697	163.44967	1001.13204	3.26143	78.05854
301.0510000	165.79200	1061.779716	3.340070299	78.20382465
303.7790000	165.79200	595.1563515	3.340070299	78.20382465
304.8281835	166.84118	607.2986121	3.37094	78.25236
304.8652996	166.87830	958.8144063	3.37203	78.25408
305.7901086	167.80311	950.7496123	3.39924	78.29686
307.0195787	169.03258	944.7102957	3.43541	78.35373
308.2740000	170.28700	938.6709792	3.472319859	78.41176222

B-7 The irradiation history file for NPR1-A7

0.00000000	0.00000	1112.689777	0.00000	0.00000
1.493694541	1.49369	1122.868636	0.00422	1.34066
3.625997619	3.62600	1122.905746	0.01025	3.25450
4.542161196	4.54216	1129.013062	0.01284	4.07680
5.450593435	5.45059	1114.815674	0.01541	4.89216
7.579803977	7.57980	1106.730903	0.02143	6.80322
10.31824397	10.31824	1098.656735	0.02918	9.26110
13.36129869	13.36130	1090.587869	0.03778	11.99238
16.40744594	16.40745	1090.640884	0.04640	14.72644
18.84281748	18.84282	1086.622355	0.05328	16.91230
20.4480000	20.44800	1080.557452	0.057822657	18.35302348
33.5680000	20.44800	983.3228408	0.057822657	18.35302348
34.3719834	21.25198	1070.648969	0.05995	18.90905
35.59121543	22.47122	1072.700645	0.06317	19.75227
35.90046896	22.78047	1084.888768	0.06399	19.96615
38.94197741	25.82198	1072.758961	0.07204	22.06964
39.55816507	26.43817	1091.043797	0.07367	22.49580
41.99508287	28.87508	1091.086209	0.08011	24.18116
42.60740485	29.48740	1099.218693	0.08173	24.60464
45.04200326	31.92200	1093.169694	0.08817	26.28839
45.65509838	32.53510	1103.332649	0.08979	26.71241
49.00586035	35.88586	1103.390965	0.09866	29.02978
50.22663866	37.10664	1109.503582	0.10189	29.87407
52.05510014	38.93510	1111.565861	0.10672	31.13862
53.8150000	40.69500	1119.71425	0.111377069	32.3557614
63.9640000	40.69500	1087.406975	0.111377069	32.3557614
65.45041672	42.18142	1091.494423	0.11535	33.15420
68.79499363	45.52599	1075.308977	0.12430	34.95077
69.71347661	46.44448	1087.507704	0.12676	35.44415
72.4495972	49.18060	1073.342125	0.13408	36.91388
74.28269749	51.01370	1087.587226	0.13898	37.89854
75.19576853	51.92677	1085.57266	0.14142	38.38901
78.24810085	54.97910	1101.869438	0.14959	40.02860
80.98808711	57.71909	1097.85621	0.15692	41.50040
83.72807337	60.45907	1093.842983	0.16425	42.97221
85.8090000	62.54000	1093.874792	0.169817145	44.09000175
96.6180000	62.54000	951.9327241	0.169817145	44.09000175
97.69860151	63.62060	984.441455	0.19767	44.85630
98.6286815	64.55068	1027.097236	0.22165	45.51585
104.0993764	70.02138	994.7051378	0.36266	49.39534
108.060141	73.98214	996.8045275	0.46476	52.20407
108.6817406	74.60374	1029.302655	0.48078	52.64487182
111.4232731	77.34527	1029.350369	0.55145	54.28664
111.740258	77.66226	1061.843195	0.55962	54.47646

114.1810414	80.10304	1072.037959	0.62254	55.93813
116.3156639	82.23766	1078.16648	0.67756	57.21645
118.2140000	84.31600	1070.076408	0.726494445	58.3532647
128.6180000	84.31600	826.6002213	0.726494445	58.3532647
129.6823745	85.38037	982.967641	0.75405	58.79728
132.1239311	87.82193	995.1928748	0.81725	59.81581
136.0823763	91.78038	991.2008535	0.91971	61.46713
137.3124322	93.01043	1021.679114	0.95155	61.98026
140.0524185	95.75042	1017.665887	1.02248	63.12328503
140.9747671	96.67277	1040.016965	1.04636	63.45920
143.7217116	99.41971	1054.27797	1.11746	64.45961
146.1640413	101.86204	1068.533674	1.18068	65.34908
147.9855446	103.68354	1052.321721	1.22783	66.01246
150.0210000	105.53900	1048.292589	1.280520869	66.75374957
158.7570000	105.53900	729.6677954	1.280520869	66.75374957
159.7495488	106.53155	747.9579327	1.30546	66.98939
160.1361157	106.91812	963.1930869	1.31518	67.08117
163.7899462	110.57195	959.1957641	1.40700	67.94863
164.4092264	111.19123	985.6024811	1.42256	68.09566
166.8469173	113.62892	987.6753633	1.48382	68.67440
168.0723344	114.85433	1005.970802	1.51462	68.96532
170.8138669	117.59587	1006.018515	1.58351	69.61620
174.1240000	120.90600	1026.376233	1.666696494	70.4020649
176.8090000	120.90600	738.1024645	1.666696494	70.4020649
177.7264564	121.82346	760.4535424	1.69081	70.60492
178.4400589	122.53706	1034.577637	1.70957	70.76270
179.9623594	124.05936	1032.573674	1.74959	71.09929
180.2754786	124.37248	1054.914149	1.75782	71.16852
181.4939375	125.59094	1054.935355	1.78985	71.43793
182.8990000	126.99600	1059.017502	1.826782574	71.74859335
249.6750000	126.99600	643.9374159	1.826782574	71.74859335
250.2935700	127.61457	942.4271542	1.84385	71.84437
251.5352229	128.85622	1003.362469	1.87812	72.03661
254.2682509	131.58925	981.0750094	1.95355	72.45976
256.0959393	133.41694	981.1068184	2.00400	72.74274
256.7129001	134.03390	1001.422124	2.02103	72.83826
257.9267202	135.24772	989.2605085	2.05453	73.02619
259.1490447	136.47004	999.434066	2.08826	73.21544
260.9520000	138.27300	987.2777516	2.13802229	73.4945935
263.5730000	138.27300	638.0898735	2.13802229	73.4945935
264.4991308	139.19913	650.2885998	2.16081	73.64182
265.2359273	139.93593	985.3268037	2.17894	73.75894
265.5335838	140.23358	967.0578724	2.18627	73.80626
266.7504965	141.45050	963.0181377	2.21621	73.99971
268.4380000	143.13800	961.0141749	2.25774123	74.26796688
271.0760000	143.13800	709.28357	2.25774123	74.26796688

271.8392633	143.90126	727.5737073	2.27839	74.34929
272.2459317	144.30793	995.6010895	2.28940	74.39263
274.0767125	146.13871	1003.75478	2.33893	74.58770
274.6890345	146.75103	1011.887264	2.35550	74.65294
276.6000000	148.66200	1001.766721	2.407210383	74.85656047
281.0460000	148.66200	589.660771	2.407210383	74.85656047
282.4520712	150.06807	599.83963	2.44510	74.99653
283.1587155	150.77472	855.6894918	2.46415	75.06687
284.1034851	151.71949	936.9242086	2.48961	75.16092
285.6273318	153.24333	938.9811863	2.53067	75.31261
288.0634765	155.67948	936.9931279	2.59633	75.55512
290.8189254	158.43493	973.5893069	2.67058	75.82942
291.1042118	158.72021	922.8328507	2.67827	75.85782
292.6296048	160.24560	928.950769	2.71938	76.00966
293.8511563	161.46716	937.0938562	2.75230	76.13127
294.8780000	162.49400	965.536345	2.779970561	76.2334835
297.7530000	162.49400	636.65317	2.779970561	76.2334835
298.4203772	163.16138	937.1733786	2.79674	76.27410
298.731177	163.47218	953.4224425	2.80455	76.29301
299.048935	163.78993	987.9457393	2.81253	76.31235
301.0510000	165.79200	1006.251781	2.862832254	76.43418426
303.7790000	165.79200	600.2107342	2.862832254	76.43418426
304.3912897	166.40429	618.4955699	2.87950	76.48807
305.3731696	167.38617	797.1928615	2.90622	76.57449
305.4419785	167.45498	977.904719	2.90809	76.58055
306.6588911	168.67189	973.8649843	2.94121	76.68765
308.2740000	170.28700	971.8610215	2.985161804	76.82979634

B-8 The irradiation history file for NPR1-A8

0.00000000	0.00000	882.90155	0.00000	0.00000
1.85022000	1.85022	893.26425	0.00387	1.31814
3.70044000	3.70044	893.26425	0.00774	2.63627
5.85903000	5.85903	893.26425	0.01225	4.17409
7.70925000	7.70925	889.11917	0.01612	5.49223
9.86784000	9.86784	889.11917	0.02064	7.03005
11.7180600	11.71806	889.11917	0.02451	8.34819
13.8766500	13.87665	891.19171	0.02902	9.88601
15.7268700	15.72687	895.33679	0.03289	11.20415
17.8854600	17.88546	901.55440	0.03741	12.74197
20.4480000	20.44800	907.77202	0.04277	14.56913
33.5680000	20.44800	810.36269	0.04277	14.56913
34.2290700	21.10907	872.53886	0.04413	14.96325
35.4625600	22.34256	887.04663	0.04668	15.70109
37.3127800	24.19278	889.11917	0.05050	16.80784
39.1630000	26.04300	884.97409	0.05433	17.91460
39.7797400	26.65974	897.40933	0.05560	18.28351
41.3215900	28.20159	901.55440	0.05879	19.20581
42.5550700	29.43507	907.77202	0.06134	19.94365
45.0220300	31.90203	907.77202	0.06644	21.41932
45.6387700	32.51877	916.06218	0.06771	21.78824
47.1806200	34.06062	916.06218	0.07090	22.71053
49.0308400	35.91084	924.35233	0.07472	23.81729
51.1894300	38.06943	936.78756	0.07918	25.10850
53.8150000	40.69500	949.22280	0.08461	26.67915
63.9640000	40.69500	913.98964	0.08461	26.67915
66.9163000	43.64730	909.84456	0.09088	27.98374
69.0748900	45.80589	901.55440	0.09546	28.93763
69.6916300	46.42263	911.91710	0.09677	29.21017
72.4669600	49.19796	903.62694	0.10267	30.43660
74.0088100	50.73981	918.13472	0.10594	31.11795
75.5506600	52.28166	918.13472	0.10922	31.79930
77.4008800	54.13188	930.56995	0.11315	32.61692
81.1013200	57.83232	934.71503	0.12101	34.25217
83.2599100	59.99091	938.86010	0.12559	35.20606
85.8090000	62.54000	943.00518	0.13100	36.33164
96.6180000	62.54000	758.54922	0.13100	36.33164
98.0616700	63.98367	783.41969	0.16009	37.22116
98.6784100	64.60041	822.79793	0.17252	37.60112
100.220260	66.14226	824.87047	0.20358	38.55099
101.762110	67.68411	812.43523	0.23465	39.50087
102.995590	68.91759	802.07254	0.25950	40.26078
104.537440	70.45944	785.49223	0.29057	41.21065
108.237890	74.15989	791.70984	0.36512	43.49036

108.546260	74.46826	816.58031	0.37134	43.68034
111.013220	76.93522	833.16062	0.42104	45.20014
111.629960	77.55196	858.03109	0.43347	45.58010
113.171810	79.09381	884.97409	0.46453	46.52997
114.713660	80.63566	911.91710	0.49560	47.47985
116.255510	82.17751	926.42487	0.52666	48.42973
118.214000	84.31600	928.49741	0.56612	49.63623
128.618000	84.31600	679.79275	0.56612	49.63623
129.207050	84.90505	791.70984	0.57791	49.89310
131.674010	87.37201	818.65285	0.62728	50.96873
132.907490	88.60549	829.01554	0.65197	51.50654
134.757710	90.45571	824.87047	0.68900	52.31325
136.607930	92.30593	826.94301	0.72603	53.11997
137.533040	93.23104	855.95855	0.74454	53.52333
140.000000	95.69800	860.10363	0.79392	54.59895
141.233480	96.93148	887.04663	0.81860	55.13676
143.700440	99.39844	905.69948	0.86797	56.21238
145.550660	101.24866	928.49741	0.90500	57.01910
146.475770	102.17377	951.29534	0.92352	57.42246
147.709250	103.40725	934.71503	0.94820	57.96027
150.021000	105.53900	961.65803	0.99447	58.96822
158.757000	105.53900	601.03627	0.99447	58.96822
160.044050	106.82605	615.54404	1.02038	59.36814
160.144050	106.92605	781.34715	1.02239	59.39921
163.744490	110.52649	787.56477	1.09487	60.51795
164.669600	111.45160	837.30570	1.11350	60.80540
166.519820	113.30182	853.88601	1.15074	61.38030
168.370040	115.15204	866.32124	1.18799	61.95521
170.528630	117.31063	862.17617	1.23144	62.62593
174.124000	120.90600	905.69948	1.30382	63.74309
176.809000	120.90600	619.68912	1.30382	63.74309
177.621150	121.71815	648.70466	1.31970	63.97250
177.929520	122.02652	899.48187	1.32572	64.05961
178.854630	122.95163	916.06218	1.34381	64.32094
179.471370	123.56837	905.69948	1.35587	64.49515
179.779740	123.87674	955.44041	1.36189	64.58226
181.013220	125.11022	953.36788	1.38601	64.93069
182.899000	126.99600	980.31088	1.42287	65.46339
249.675000	126.99600	603.10881	1.42287	65.46339
250.396480	127.71748	855.95855	1.43830	65.61091
251.629960	128.95096	872.53886	1.46468	65.86313
253.171810	130.49281	889.11917	1.49765	66.17840
254.405290	131.72629	911.91710	1.52403	66.43062
256.563880	133.88488	911.91710	1.57019	66.87200
257.488990	134.80999	891.19171	1.58997	67.06117
258.414100	135.73510	860.10363	1.60976	67.25033

260.952000	138.27300	820.72539	1.66403	67.76927
263.573000	138.27300	543.00518	1.66403	67.76927
264.889870	139.58987	553.36788	1.69156	68.02945
265.198240	139.89824	816.58031	1.69800	68.09038
266.123350	140.82335	791.70984	1.71734	68.27316
268.438000	143.13800	785.49223	1.76572	68.73049
271.076000	143.13800	613.47150	1.76572	68.73049
271.982380	144.04438	750.25907	1.78521	68.91966
272.290750	144.35275	893.26425	1.79184	68.98402
273.215860	145.27786	909.84456	1.81174	69.17711
274.140970	146.20297	936.78756	1.83164	69.37019
276.600000	148.66200	949.22280	1.88452	69.88342
281.046000	148.66200	497.40933	1.88452	69.88342
282.466960	150.08296	513.98964	1.91338	70.08203
283.083700	150.69970	710.88083	1.92590	70.16824
283.700440	151.31644	787.56477	1.93843	70.25444
287.400880	155.01688	785.49223	2.01358	70.77167
290.484580	158.10058	858.03109	2.07621	71.20269
291.409690	159.02569	764.76684	2.09499	71.33200
292.951540	160.56754	773.05699	2.12631	71.54751
294.878000	162.49400	795.85492	2.16543	71.81678
297.753000	162.49400	501.55440	2.16543	71.81678
298.193830	162.93483	650.77720	2.17454	71.89401
298.502200	163.24320	781.34715	2.18092	71.94803
298.810570	163.55157	837.30570	2.18729	72.00205
299.427310	164.16831	878.75648	2.20004	72.11010
301.051000	165.79200	899.48187	2.23360	72.39455
303.779000	165.79200	540.93264	2.23360	72.39455
304.977970	166.99097	565.80311	2.25776	72.54119
305.286340	167.29934	866.32124	2.26397	72.57891
305.903080	167.91608	878.75648	2.27640	72.65434
307.136560	169.14956	887.04663	2.30125	72.80520
308.274000	170.28700	891.19171	2.32417	72.97545

Appendix C

Input files for MPBR1 simulations

C-1 The 'blocks.dat' file for MPBR1

Layers 1 to 57

z (cm)	FLUX 1	FLUX 2	FLUX 3	FLUX 4
325.8662	4.06017E+12	9.78204E+12	3.3256E+12	7.07992E+13
391.5263	6.82129E+12	1.66895E+13	5.72995E+12	1.28405E+14
457.4383	9.69167E+12	2.37536E+13	8.17565E+12	1.84172E+14
523.4468	1.20728E+13	2.97102E+13	1.02598E+13	2.32887E+14
590.028	1.32014E+13	3.25597E+13	1.12702E+13	2.59145E+14
658.3862	1.34469E+13	3.32364E+13	1.15305E+13	2.67799E+14
728.9344	1.2761E+13	3.16695E+13	1.10314E+13	2.57237E+14
803.4993	1.18409E+13	2.99387E+13	1.04872E+13	2.33088E+14
1066.2	1.22791E+13	3.01595E+13	1.05507E+13	1.83549E+14
325.9992	1.03545E+13	1.79321E+13	5.11465E+12	5.13683E+13
391.1913	1.85412E+13	3.30302E+13	9.53047E+12	9.01219E+13
456.7378	2.66364E+13	4.77133E+13	1.38243E+13	1.31767E+14
522.6889	3.35077E+13	6.03921E+13	1.7518E+13	1.68707E+14
589.1911	3.66154E+13	6.63261E+13	1.93527E+13	1.90012E+14
656.5009	3.70598E+13	6.74071E+13	1.97765E+13	1.97532E+14
725.3721	3.54085E+13	6.42618E+13	1.87955E+13	1.89148E+14
797.0067	3.28091E+13	5.96613E+13	1.72231E+13	1.68811E+14
870.4246	2.91272E+13	5.39106E+13	1.51996E+13	1.46625E+14
1066.2	2.36744E+13	4.37109E+13	1.28399E+13	1.13412E+14
328.1101	1.2924E+13	2.10973E+13	5.06225E+12	3.65613E+13
394.5977	2.36285E+13	4.00745E+13	9.73853E+12	6.2034E+13
460.6103	3.46117E+13	5.86497E+13	1.41914E+13	9.15951E+13
526.1077	4.46828E+13	7.58473E+13	1.82214E+13	1.20183E+14
591.0684	4.91446E+13	8.34927E+13	1.99985E+13	1.33498E+14
655.4955	5.00792E+13	8.52448E+13	2.03882E+13	1.37726E+14
719.5168	4.73618E+13	8.10627E+13	1.95284E+13	1.34364E+14
783.4268	4.31558E+13	7.44648E+13	1.80959E+13	1.24975E+14
846.7093	3.78726E+13	6.6835E+13	1.63851E+13	1.10187E+14
911.2618	3.36146E+13	5.99617E+13	1.47702E+13	9.54515E+13
1066.2	2.65619E+13	4.68216E+13	1.17724E+13	7.86835E+13
327.7736	1.1411E+13	1.87037E+13	4.40855E+12	3.09315E+13
393.1451	2.05065E+13	3.50399E+13	8.37042E+12	5.08574E+13
458.4412	3.08515E+13	5.22091E+13	1.24079E+13	7.85294E+13
524.1719	4.08041E+13	6.86461E+13	1.61726E+13	1.07004E+14
590.2695	4.52789E+13	7.62581E+13	1.79297E+13	1.20098E+14
656.0625	4.62957E+13	7.81829E+13	1.83534E+13	1.23617E+14
720.2756	4.40172E+13	7.46297E+13	1.74988E+13	1.18313E+14
781.3543	4.03091E+13	6.85744E+13	1.60987E+13	1.09015E+14
838.8892	3.60632E+13	6.22924E+13	1.46944E+13	9.52204E+13
896.3219	3.27717E+13	5.79615E+13	1.37508E+13	8.35561E+13
952.4894	2.86183E+13	5.19487E+13	1.23999E+13	7.07473E+13
1066.2	2.39696E+13	4.20728E+13	1.00884E+13	6.35667E+13

329.0798	9.05196E+12	1.47594E+13	3.67249E+12	2.88938E+13
397.1589	1.63792E+13	2.77149E+13	6.97098E+12	4.84066E+13
465.1485	2.56439E+13	4.23462E+13	1.05687E+13	8.03789E+13
532.6207	3.40439E+13	5.54806E+13	1.37263E+13	1.115E+14
599.045	3.74538E+13	6.1099E+13	1.51044E+13	1.25155E+14
663.8527	3.76045E+13	6.14599E+13	1.52003E+13	1.27593E+14
727.6718	3.53212E+13	5.79077E+13	1.43269E+13	1.21851E+14
791.0222	3.17951E+13	5.22455E+13	1.29525E+13	1.11049E+14
846.8144	2.77213E+13	4.57894E+13	1.14143E+13	9.74819E+13
889.1656	2.55122E+13	4.29221E+13	1.0599E+13	8.39483E+13
922.5213	2.31072E+13	3.9394E+13	9.64417E+12	7.24135E+13
948.9672	2.17417E+13	3.72468E+13	9.05541E+12	6.61806E+13
971.4881	1.99492E+13	3.39607E+13	8.22238E+12	6.07901E+13
993.743	1.83766E+13	3.12986E+13	7.75588E+12	6.09025E+13
1066.2	1.56745E+13	2.63824E+13	6.94083E+12	6.30413E+13

C-2 The ‘channels.dat’ file for MPBR1

z-position (cm)				r-position (cm)		
	channel 0	channel 1	channel 2	channel 3	channel 4	channel 5
261.2	0.0	72.8	106.4	133.5	155.1	175.0
368.8	0.0	72.2	105.7	133.1	155.1	175.0
476.3	0.0	71.6	105	132.8	155.1	175.0
580.8	0.0	70.2	103.5	131.8	154.4	175.0
685.4	0.0	68.7	101.9	130.8	153.7	175.0
810.9	0.0	61.6	95.4	125.7	151.7	175.0
841.3	0.0	53.9	90.2	121.7	149	175.0
871.7	0.0	45.3	81.7	115.2	142.3	175.0
902.1	0.0	37.9	70.7	104.9	136	175.0
932.5	0.0	28.9	57.7	90.3	123.5	175.0
962.9	0.0	22.7	47.7	73.5	109.8	175.0
993.3	0.0	17.3	37.4	60.3	91.5	150.0
1019.4	0.0	13.9	30.2	49.1	72.1	110.0
1044.4	0.0	12.2	23.4	38.5	50.3	75.0
1066.2	0.0	11.5	18.5	22.4	25.9	35.0

C-3 The 'pdistr.dat' file for MPBR1

1	636.417	0.674755	1.64737	397.16	0.11215
2	637.963	0.180719	1.54798	11499.7	2.11E+20
3	638.863	0.206653	1.40508	21962.6	4.21E+20
4	639.764	0.237325	1.26455	31567.7	6.31E+20
5	640.666	0.269026	1.13857	40343.1	8.42E+20
6	641.569	0.300583	1.02835	48376.8	1.05E+21
7	642.474	0.331727	0.932485	55763.1	1.27E+21
8	643.38	0.362424	0.849251	62589.5	1.48E+21
9	644.287	0.392625	0.777106	68935.8	1.69E+21
10	645.195	0.422213	0.714685	74862.9	1.91E+21
11	1.27E+06	0.786948	1.18E-04	36.5205	1.12E+18
12	636.417	8.74E-02	2.92252	1499.84	4.13E+18
13	637.963	0.106299	2.74197	12538.7	2.14E+20
14	638.863	0.127311	2.48557	22908.5	4.24E+20
15	639.764	0.151158	2.23539	32422.5	6.34E+20
16	640.666	0.175135	2.01158	41116.5	8.45E+20
17	641.569	0.198444	1.81593	49079.5	1.06E+21
18	642.474	0.220987	1.64583	56404.8	1.27E+21
19	643.38	0.24284	1.49822	63178.8	1.48E+21
20	644.287	0.264071	1.37033	69480.3	1.70E+21
21	645.195	0.284667	1.25975	75367.1	1.91E+21
22	1.27E+06	0.96463	2.19E-04	140.599	4.13E+18
23	636.417	9.68E-02	4.0623	3185.41	8.70E+18
24	637.963	0.110167	3.79121	14119.1	2.18E+20
25	638.863	0.132518	3.42874	24342.7	4.29E+20
26	639.764	0.1574	3.07942	33715.2	6.39E+20
27	640.666	0.182331	2.76803	42283.2	8.50E+20
28	641.569	0.206597	2.49615	50136.5	1.06E+21
29	642.474	0.230129	2.25997	57366.9	1.27E+21
30	643.38	0.253008	2.05519	64059.1	1.49E+21
31	644.287	0.275293	1.8779	70290.5	1.70E+21
32	645.195	0.296956	1.72477	76114.9	1.92E+21
33	1.27E+06	0.974093	3.26E-04	309.07	8.70E+18
34	636.417	0.104759	4.94107	5357.72	1.47E+19
35	637.963	0.120472	4.57802	16141.8	2.24E+20
36	638.863	0.144994	4.12768	26172.4	4.35E+20
37	639.764	0.171768	3.70047	35360.6	6.45E+20
38	640.666	0.198549	3.3214	43765.1	8.56E+20
39	641.569	0.224715	2.99102	51476.2	1.07E+21
40	642.474	0.250223	2.70436	58583.6	1.28E+21
41	643.38	0.27515	2.45608	65169.7	1.49E+21
42	644.287	0.299539	2.24137	71310.2	1.71E+21
43	645.195	0.323324	2.05617	77054.3	1.92E+21
44	1.27E+06	0.940926	4.34E-04	544.461	1.47E+19
45	636.417	0.11407	5.26559	7818.87	2.17E+19
46	637.963	0.1333	4.84012	18415.5	2.32E+20
47	638.863	0.160381	4.34953	28222	4.42E+20
48	639.764	0.189424	3.89185	37199.9	6.52E+20
49	640.666	0.218443	3.48779	45418.5	8.63E+20

50	641.569	0.246918	3.13633	52968.2	1.08E+21
51	642.474	0.274832	2.83178	59936.1	1.29E+21
52	643.38	0.302254	2.56836	66402.1	1.50E+21
53	644.287	0.329203	2.34081	72439.4	1.72E+21
54	645.195	0.355573	2.14485	78093.2	1.93E+21
55	1.27E+06	0.909056	5.09E-04	837.216	2.17E+19
56	636.417	0.122631	5.20956	10343.8	2.91E+19
57	637.963	0.145414	4.75235	20729.8	2.39E+20
58	638.863	0.174994	4.25717	30301.4	4.49E+20
59	639.764	0.206229	3.80232	39062.2	6.60E+20
60	640.666	0.237405	3.4027	47090.1	8.71E+20
61	641.569	0.26811	3.05578	54474.4	1.08E+21
62	642.474	0.29835	2.75558	61299.6	1.30E+21
63	643.38	0.328187	2.49624	67642.7	1.51E+21
64	644.287	0.357618	2.27249	73574.6	1.72E+21
65	645.195	0.386488	2.08009	79136.6	1.94E+21
66	1.27E+06	0.875	5.53E-04	1167.29	2.91E+19
67	636.417	0.131985	4.80058	12755.8	3.64E+19
68	637.963	0.158087	4.35092	22925.2	2.46E+20
69	638.863	0.190072	3.88728	32268.4	4.56E+20
70	639.764	0.223452	3.46689	40821.1	6.67E+20
71	640.666	0.256755	3.09906	48666.9	8.78E+20
72	641.569	0.289662	2.78028	55893.8	1.09E+21
73	642.474	0.3222	2.50475	62583.3	1.30E+21
74	643.38	0.354416	2.26701	68809.8	1.52E+21
75	644.287	0.386283	2.06211	74641.5	1.73E+21
76	645.195	0.417598	1.88616	80117	1.95E+21
77	1.27E+06	0.85575	5.53E-04	1511.05	3.64E+19
78	636.417	0.14329	4.1931	14922.6	4.32E+19
79	637.963	0.172439	3.78096	24886.4	2.53E+20
80	638.863	0.206781	3.37131	34021.7	4.63E+20
81	639.764	0.242335	3.00363	42387.3	6.74E+20
82	640.666	0.277825	2.68294	50070.2	8.85E+20
83	641.569	0.313004	2.40538	57156.2	1.10E+21
84	642.474	0.347907	2.16572	63724.6	1.31E+21
85	643.38	0.382561	1.95913	69847.1	1.52E+21
86	644.287	0.416915	1.78124	75589.7	1.74E+21
87	645.195	0.450713	1.62865	80988.5	1.95E+21
88	1.27E+06	0.8579	5.18E-04	1843.95	4.32E+19
89	636.417	0.165289	3.35976	16742.2	4.99E+19
90	637.963	0.198177	3.0038	26523	2.60E+20
91	638.863	0.236024	2.6651	35480.5	4.70E+20
92	639.764	0.275348	2.36541	43688.1	6.81E+20
93	640.666	0.315055	2.10555	51233.8	8.92E+20
94	641.569	0.354947	1.88135	58201.9	1.10E+21
95	642.474	0.39504	1.68822	64668.9	1.32E+21
96	643.38	0.43531	1.52209	70704.7	1.53E+21
97	644.287	0.475638	1.3793	76372.8	1.75E+21
98	645.195	0.515665	1.25704	81708.3	1.96E+21
99	1.27E+06	0.964399	4.26E-04	2137.28	4.99E+19
100	63641.7	0.111123	1.21962	293.796	2.86E+18

101	63729.4	0.261713	1.14527	11402.4	2.13E+20
102	63819.3	0.293809	1.0392	21874.1	4.23E+20
103	63909.3	0.332426	0.935082	31488	6.33E+20
104	63999.4	0.372993	0.841824	40271.3	8.44E+20
105	64089.6	0.414006	0.760268	48311.9	1.06E+21
106	64180	0.45504	0.689345	55704.2	1.27E+21
107	64270.5	0.495939	0.627777	62535.9	1.48E+21
108	64361.1	0.53653	0.574417	68886.6	1.70E+21
109	64451.9	0.57656	0.528252	74817.7	1.91E+21
110	632370	1.2932	8.85E-05	27.2808	2.86E+18
111	63641.7	0.152023	2.11031	1096.74	1.09E+19
112	63729.4	0.175322	1.98145	12159.8	2.21E+20
113	63819.3	0.201269	1.79706	22564.6	4.31E+20
114	63909.3	0.23159	1.61694	32113	6.41E+20
115	63999.4	0.26282	1.45579	40838.1	8.52E+20
116	64089.6	0.293869	1.31491	48828.1	1.06E+21
117	64180	0.324496	1.19243	56177	1.28E+21
118	64270.5	0.354672	1.08612	62971.4	1.49E+21
119	64361.1	0.384357	0.994009	69290.6	1.70E+21
120	64451.9	0.413426	0.914352	75192.7	1.92E+21
121	632370	1.6536	1.61E-04	104.239	1.09E+19
122	63641.7	0.16691	3.01806	2333.74	2.34E+19
123	63729.4	0.181339	2.82567	13322.8	2.33E+20
124	63819.3	0.208412	2.56048	23622.3	4.43E+20
125	63909.3	0.239604	2.30337	33068.4	6.54E+20
126	63999.4	0.271619	2.07378	41702.2	8.65E+20
127	64089.6	0.303431	1.87319	49613.1	1.08E+21
128	64180	0.334814	1.69885	56893.5	1.29E+21
129	64270.5	0.365738	1.5476	63629.1	1.50E+21
130	64361.1	0.396155	1.41659	69898.1	1.72E+21
131	64451.9	0.42592	1.30338	75754.9	1.93E+21
132	632370	1.62056	2.51E-04	231.539	2.34E+19
133	63641.7	0.178314	3.76357	3969.62	4.00E+19
134	63729.4	0.194432	3.50792	14854	2.50E+20
135	63819.3	0.223443	3.17444	25012.2	4.60E+20
136	63909.3	0.256317	2.85461	34322.2	6.70E+20
137	63999.4	0.289948	2.56986	42835.1	8.82E+20
138	64089.6	0.323377	2.32133	50640.6	1.09E+21
139	64180	0.356392	2.10547	57830.1	1.31E+21
140	64270.5	0.388948	1.91833	64487.3	1.52E+21
141	64361.1	0.420983	1.75631	70689.3	1.73E+21
142	64451.9	0.452316	1.61643	76486.4	1.95E+21
143	632370	1.50386	3.50E-04	417.735	4.00E+19
144	63641.7	0.190119	4.11832	5870.61	5.94E+19
145	63729.4	0.209425	3.81831	16623.9	2.69E+20
146	63819.3	0.240684	3.44989	26615.8	4.79E+20
147	63909.3	0.275478	3.10102	35767.7	6.90E+20
148	63999.4	0.310936	2.79154	44140.3	9.01E+20
149	64089.6	0.346179	2.52179	51824	1.11E+21
150	64180	0.381011	2.28769	58908.1	1.33E+21
151	64270.5	0.415375	2.08491	65474.4	1.54E+21

152	64361.1	0.449186	1.90948	71598.5	1.75E+21
153	64451.9	0.482225	1.75817	77327	1.97E+21
154	632370	1.38459	4.33E-04	660.817	5.94E+19
155	63641.7	0.199903	4.1619	7867.52	7.98E+19
156	63729.4	0.222572	3.83769	18473	2.90E+20
157	63819.3	0.255972	3.46173	28288.2	5.00E+20
158	63909.3	0.292504	3.11034	37274.3	7.10E+20
159	63999.4	0.329566	2.79985	45500.4	9.22E+20
160	64089.6	0.36638	2.52961	53057	1.13E+21
161	64180	0.402767	2.29532	60031.2	1.35E+21
162	64270.5	0.438658	2.09255	66503	1.56E+21
163	64361.1	0.473952	1.91727	72545.9	1.78E+21
164	64451.9	0.50839	1.76626	78203.4	1.99E+21
165	632370	1.27397	4.90E-04	947.768	7.98E+19
166	63641.7	0.211474	3.88282	9807.38	9.99E+19
167	63729.4	0.237444	3.56264	20259.9	3.10E+20
168	63819.3	0.273049	3.20902	29902	5.20E+20
169	63909.3	0.311423	2.88242	38727.6	7.31E+20
170	63999.4	0.350211	2.59486	46812.5	9.42E+20
171	64089.6	0.388718	2.34495	54246.7	1.15E+21
172	64180	0.426782	2.12847	61115.3	1.37E+21
173	64270.5	0.464314	1.94129	67496.4	1.58E+21
174	64361.1	0.501196	1.77961	73461.4	1.80E+21
175	64451.9	0.537132	1.64046	79051.1	2.01E+21
176	632370	1.20357	5.05E-04	1257.45	9.99E+19
177	63641.7	0.226645	3.39165	11561.6	1.19E+20
178	63729.4	0.255802	3.09928	21868.8	3.29E+20
179	63819.3	0.293768	2.78858	31353.6	5.39E+20
180	63909.3	0.334235	2.50444	40034.9	7.50E+20
181	63999.4	0.375043	2.25505	47993.3	9.61E+20
182	64089.6	0.415557	2.03856	55318	1.17E+21
183	64180	0.455615	1.8512	62092.4	1.39E+21
184	64270.5	0.495108	1.68931	68392.4	1.60E+21
185	64361.1	0.533894	1.54957	74287.8	1.82E+21
186	64451.9	0.571631	1.42941	79817.6	2.03E+21
187	632370	1.17682	4.79E-04	1563.79	1.19E+20
188	63641.7	0.252112	2.73429	13039.2	1.36E+20
189	63729.4	0.289527	2.50194	23222.4	3.46E+20
190	63819.3	0.336032	2.25678	32575.9	5.56E+20
191	63909.3	0.384445	2.03258	41137.5	7.67E+20
192	63999.4	0.432371	1.83553	48991.3	9.78E+20
193	64089.6	0.479191	1.66427	56225.4	1.19E+21
194	64180	0.524828	1.51592	62921.9	1.40E+21
195	64270.5	0.569251	1.38767	69155.2	1.62E+21
196	64361.1	0.612392	1.27691	74992.9	1.83E+21
197	64451.9	0.653942	1.18165	80473.9	2.05E+21
198	632370	1.17759	4.26E-04	1845.38	1.36E+20
199	63641.7	0.253039	2.31375	14258.3	1.51E+20
200	63729.4	0.288342	2.09068	24334.1	3.61E+20
201	63819.3	0.330982	1.87113	33578.3	5.71E+20
202	63909.3	0.375912	1.67486	42041.4	7.82E+20

203	63999.4	0.421398	1.50402	49809.3	9.93E+20
204	64089.6	0.466932	1.3563	56969.4	1.21E+21
205	64180	0.512343	1.22879	63602.4	1.42E+21
206	64270.5	0.55745	1.11888	69781.4	1.63E+21
207	64361.1	0.602034	1.02419	75572.1	1.85E+21
208	64451.9	0.645635	0.942926	81013.9	2.06E+21
209	632370	1.21382	3.53E-04	2087.74	1.51E+20
210	127283	0.158945	0.772045	185.839	3.57E+18
211	127463	0.39412	0.731902	11302.7	2.13E+20
212	127643	0.447662	0.667869	21784.6	4.23E+20
213	127823	0.511798	0.603477	31408	6.34E+20
214	128003	0.578133	0.545264	40199.7	8.45E+20
215	128184	0.643987	0.494125	48247.6	1.06E+21
216	128365	0.708716	0.449533	55646.3	1.27E+21
217	128545	0.772218	0.41075	62483.5	1.48E+21
218	128727	0.834392	0.377086	68838.9	1.70E+21
219	120779	0.895003	0.347927	74774.1	1.91E+21
220	1	1.85001	5.68E-05	17.4896	3.57E+18
221	127283	0.229547	1.29699	684.518	1.37E+19
222	127463	0.266325	1.23225	11779.4	2.23E+20
223	127643	0.310954	1.12556	22223.1	4.33E+20
224	127823	0.362786	1.01826	31808.2	6.44E+20
225	128003	0.415212	0.921163	40565.6	8.55E+20
226	128184	0.466233	0.835786	48583.7	1.07E+21
227	128365	0.515508	0.761277	55956.8	1.28E+21
228	128545	0.563138	0.696436	62772.2	1.49E+21
229	128727	0.609218	0.640125	69109.6	1.71E+21
230	120779	0.653702	0.59134	75027.4	1.92E+21
231	1	2.49539	1.00E-04	65.9485	1.37E+19
232	127283	0.253615	1.87058	1448.27	2.98E+19
233	127463	0.274467	1.77864	12508.6	2.40E+20
234	127643	0.319511	1.62718	22893.2	4.50E+20
235	127823	0.371266	1.47474	32418.8	6.60E+20
236	128003	0.423365	1.33658	41122.5	8.71E+20
237	128184	0.47391	1.21489	49093.8	1.08E+21
238	128365	0.522599	1.10856	56426.5	1.30E+21
239	128545	0.56954	1.01594	63207.3	1.51E+21
240	128727	0.614829	0.935441	69515.3	1.72E+21
241	120779	0.658411	0.865676	75405.7	1.94E+21
242	1	2.44358	1.59E-04	145.883	2.98E+19
243	127283	0.268975	2.39048	2475.85	5.18E+19
244	127463	0.290625	2.27159	13488.7	2.62E+20
245	127643	0.336841	2.08106	23793.9	4.72E+20
246	127823	0.389184	1.88979	33239.7	6.82E+20
247	128003	0.44159	1.71629	41871.4	8.93E+20
248	128184	0.492289	1.56325	49779.5	1.11E+21
249	128365	0.541017	1.42936	57057.5	1.32E+21
250	128545	0.587889	1.31261	63791	1.53E+21
251	128727	0.632993	1.21106	70058.8	1.75E+21
252	120779	0.676255	1.12303	75912.5	1.96E+21
253	1	2.21977	2.29E-04	265.741	5.18E+19

254	127283	0.290453	2.59236	3677.76	7.77E+19
255	127463	0.315393	2.4583	14632.7	2.88E+20
256	127643	0.363458	2.2542	24845.8	4.98E+20
257	127823	0.41703	2.05072	34199.6	7.08E+20
258	128003	0.470397	1.86622	42748	9.19E+20
259	128184	0.52193	1.70332	50583.1	1.13E+21
260	128365	0.571404	1.56066	57797.6	1.34E+21
261	128545	0.618924	1.43617	64476.2	1.56E+21
262	128727	0.664566	1.32781	70696.9	1.77E+21
263	120779	0.708219	1.23386	76508.4	1.99E+21
264	1	2.03408	2.84E-04	425.078	7.77E+19
265	127283	0.305331	2.62063	4935.67	1.05E+20
266	127463	0.334009	2.47776	15826.7	3.15E+20
267	127643	0.383573	2.27314	25944.2	5.25E+20
268	127823	0.437822	2.07112	35203.4	7.36E+20
269	128003	0.491527	1.88821	43666.3	9.47E+20
270	128184	0.543249	1.72665	51426.3	1.16E+21
271	128365	0.592815	1.58505	58575.4	1.37E+21
272	128545	0.640333	1.46142	65197.4	1.59E+21
273	128727	0.685869	1.35377	71369.5	1.80E+21
274	120779	0.729291	1.26043	77137.7	2.02E+21
275	1	1.84196	3.26E-04	615.084	1.05E+20
276	127283	0.316208	2.51078	6174.13	1.32E+20
277	127463	0.348574	2.36631	16998.7	3.42E+20
278	127643	0.399435	2.17138	27022.9	5.52E+20
279	127823	0.454106	1.98093	36190.6	7.63E+20
280	128003	0.507878	1.80885	44571	9.74E+20
281	128184	0.559507	1.65685	52258.5	1.19E+21
282	128365	0.608883	1.52356	59344.4	1.40E+21
283	128545	0.656117	1.40715	65911.8	1.61E+21
284	128727	0.701278	1.30575	72036.8	1.83E+21
285	120779	0.744214	1.21784	77763.5	2.04E+21
286	1	1.68213	3.49E-04	825.54	1.32E+20
287	127283	0.326653	2.30211	7335.91	1.57E+20
288	127463	0.362387	2.1629	18095	3.67E+20
289	127643	0.414433	1.98481	28032.2	5.77E+20
290	127823	0.469501	1.81258	37115.5	7.88E+20
291	128003	0.523364	1.6573	45420	1.00E+21
292	128184	0.574956	1.52016	53040.9	1.21E+21
293	128365	0.624222	1.39989	60068.8	1.42E+21
294	128545	0.671274	1.29482	66586.1	1.64E+21
295	128727	0.716179	1.20328	72667.6	1.85E+21
296	120779	0.758768	1.12392	78356.7	2.07E+21
297	1	1.57076	3.51E-04	1043.66	1.57E+20
298	127283	0.342564	2.01223	8377.75	1.80E+20
299	127463	0.38141	1.88502	19075.4	3.90E+20
300	127643	0.434884	1.72953	28935.2	6.00E+20
301	127823	0.4908	1.58061	37944.1	8.11E+20
302	128003	0.545314	1.44666	46182	1.02E+21
303	128184	0.597495	1.3284	53744.4	1.23E+21
304	128365	0.647314	1.22468	60721.4	1.45E+21

305	128545	0.694877	1.13407	67194.7	1.66E+21
306	128727	0.740233	1.05512	73238.1	1.88E+21
307	120779	0.783191	0.986694	78894.6	2.09E+21
308	1	1.52251	3.30E-04	1255.73	1.80E+20
309	127283	0.354377	1.75233	9287.36	2.00E+20
310	127463	0.395567	1.63562	19929.1	4.09E+20
311	127643	0.449761	1.49932	29721.6	6.20E+20
312	127823	0.505953	1.37018	38666.4	8.31E+20
313	128003	0.560688	1.25441	46847.2	1.04E+21
314	128184	0.613158	1.1523	54359.5	1.25E+21
315	128365	0.663341	1.06279	61293	1.47E+21
316	128545	0.711316	0.984622	67729	1.68E+21
317	128727	0.757104	0.916527	73739.4	1.90E+21
318	120779	0.800484	0.857525	79368.8	2.11E+21
319	1	1.49145	3.03E-04	1452.74	2.00E+20
320	127283	0.36214	1.43986	10059.3	2.16E+20
321	127463	0.405104	1.3411	20652	4.26E+20
322	127643	0.459802	1.22904	30387.5	6.37E+20
323	127823	0.516076	1.12359	39278.9	8.47E+20
324	128003	0.570767	1.02924	47412	1.06E+21
325	128184	0.623165	0.946072	54882.7	1.27E+21
326	128365	0.673268	0.873174	61780.3	1.48E+21
327	128545	0.721146	0.80952	68185.3	1.70E+21
328	128727	0.766812	0.754076	74168	1.91E+21
329	120779	0.810042	0.706032	79775.7	2.13E+21
330	1	1.45223	2.60E-04	1628.12	2.16E+20
331	127283	0.163263	0.654751	157.584	3.15E+18
332	127463	0.437618	0.6207	11275.9	2.13E+20
333	127643	0.49414	0.56638	21760.1	4.23E+20
334	127823	0.562279	0.511756	31385.9	6.33E+20
335	128003	0.633109	0.462379	40179.7	8.44E+20
336	128184	0.703747	0.419004	48229.5	1.06E+21
337	128365	0.773455	0.381183	55629.9	1.27E+21
338	128545	0.842063	0.34829	62468.4	1.48E+21
339	128727	0.909404	0.319741	68825.1	1.70E+21
340	120781	0.975177	0.295011	74761.4	1.91E+21
341	1	1.90336	4.82E-05	14.84	3.15E+18
342	127283	0.239875	1.0681	572.807	1.20E+19
343	127463	0.280597	1.01511	11673.4	2.22E+20
344	127643	0.326087	0.927266	22126.3	4.32E+20
345	127823	0.37919	0.838845	31720.7	6.42E+20
346	128003	0.43308	0.758828	40486.5	8.53E+20
347	128184	0.485672	0.688469	48511.9	1.07E+21
348	128365	0.536588	0.627073	55891.5	1.28E+21
349	128545	0.585901	0.573645	62712.5	1.49E+21
350	128727	0.633685	0.527247	69054.8	1.71E+21
351	120781	0.679874	0.48705	74976.7	1.92E+21
352	1	2.63486	8.22E-05	55.0586	1.20E+19
353	127283	0.257112	1.60928	1218.34	2.62E+19
354	127463	0.277517	1.53182	12290.7	2.36E+20
355	127643	0.322558	1.4018	22694.2	4.46E+20

356	127823	0.374568	1.27054	32238.8	6.57E+20
357	128003	0.427018	1.1515	40959.6	8.68E+20
358	128184	0.477949	1.04664	48946	1.08E+21
359	128365	0.527034	0.955018	56291.8	1.29E+21
360	128545	0.574371	0.875208	63084	1.51E+21
361	128727	0.620056	0.805843	69401.9	1.72E+21
362	120781	0.66403	0.745725	75301	1.94E+21
363	1	2.53775	1.34E-04	121.811	2.62E+19
364	127283	0.267874	2.13367	2120.94	4.60E+19
365	127463	0.288277	2.0312	13153.3	2.56E+20
366	127643	0.334062	1.86177	23487.6	4.66E+20
367	127823	0.386228	1.69084	32962.5	6.77E+20
368	128003	0.438527	1.53558	41620.3	8.88E+20
369	128184	0.489123	1.3986	49551.5	1.10E+21
370	128365	0.537734	1.27874	56849.5	1.31E+21
371	128545	0.584469	1.17424	63600.5	1.53E+21
372	128727	0.62943	1.08333	69883.5	1.74E+21
373	120781	0.672547	1.00452	75750.4	1.96E+21
374	1	2.29275	1.99E-04	224.664	4.60E+19
375	127283	0.289718	2.33843	3199.62	6.99E+19
376	127463	0.313	2.22265	14182.5	2.80E+20
377	127643	0.360587	2.03938	24434.9	4.90E+20
378	127823	0.414045	1.85546	33827.3	7.00E+20
379	128003	0.467403	1.68841	42410.5	9.12E+20
380	128184	0.518941	1.54086	50276.2	1.12E+21
381	128365	0.568407	1.41162	57517.4	1.34E+21
382	128545	0.615901	1.29884	64219.3	1.55E+21
383	128727	0.661512	1.20066	70460.2	1.77E+21
384	120781	0.705135	1.11554	76289.2	1.98E+21
385	1	2.12134	2.47E-04	363.019	6.99E+19
386	127283	0.306595	2.36029	4333.41	9.52E+19
387	127463	0.333354	2.23764	15261.7	3.05E+20
388	127643	0.382538	2.05428	25428.8	5.15E+20
389	127823	0.436895	1.87182	34736	7.26E+20
390	128003	0.490861	1.70627	43242.1	9.37E+20
391	128184	0.542871	1.55998	51040.1	1.15E+21
392	128365	0.592721	1.43175	58222.3	1.36E+21
393	128545	0.640508	1.31978	64873.3	1.58E+21
394	128727	0.686312	1.22226	71070.5	1.79E+21
395	120781	0.730001	1.13771	76860.5	2.01E+21
396	1	1.94172	2.82E-04	527.659	9.52E+19
397	127283	0.322394	2.22271	5439.5	1.20E+20
398	127463	0.352722	2.10106	16311.8	3.30E+20
399	127643	0.403513	1.9294	26396.3	5.40E+20
400	127823	0.458766	1.76021	35621.9	7.51E+20
401	128003	0.513333	1.60698	44054.2	9.62E+20
402	128184	0.565813	1.47154	51787.4	1.17E+21
403	128365	0.616046	1.35277	58913.2	1.39E+21
404	128545	0.664129	1.24903	65515.5	1.60E+21
405	128727	0.710135	1.15864	71670.8	1.82E+21
406	120781	0.753908	1.08028	77423.7	2.03E+21

407	1	1.80372	2.96E-04	707.696	1.20E+20
408	127283	0.334011	2.02179	6464.15	1.44E+20
409	127463	0.367571	1.90575	17282.1	3.54E+20
410	127643	0.419628	1.75023	27290.7	5.64E+20
411	127823	0.475433	1.59837	36442	7.74E+20
412	128003	0.530268	1.46112	44807.4	9.86E+20
413	128184	0.582891	1.33981	52481.8	1.20E+21
414	128365	0.633188	1.23339	59556.6	1.41E+21
415	128545	0.681258	1.14042	66114.6	1.62E+21
416	128727	0.727173	1.0594	72231.7	1.84E+21
417	120781	0.77076	0.989158	77951.4	2.05E+21
418	1	1.68977	2.95E-04	891.675	1.44E+20
419	127283	0.353026	1.75504	7376.28	1.65E+20
420	127463	0.389685	1.64969	18143.8	3.75E+20
421	127643	0.443404	1.51483	28085.4	5.85E+20
422	127823	0.500389	1.38436	37171.8	7.96E+20
423	128003	0.556241	1.26669	45478.8	1.01E+21
424	128184	0.609831	1.16272	53102	1.22E+21
425	128365	0.661066	1.07152	60132.2	1.43E+21
426	128545	0.710029	0.991838	66651.9	1.65E+21
427	128727	0.756777	0.922391	72735.7	1.86E+21
428	120781	0.801105	0.862188	78427	2.08E+21
429	1	1.65128	2.75E-04	1069.09	1.65E+20
430	127283	0.366939	1.55264	8175.57	1.84E+20
431	127463	0.406074	1.45408	18896.9	3.94E+20
432	127643	0.460732	1.33389	28780.1	6.04E+20
433	127823	0.518255	1.21889	37810.3	8.15E+20
434	128003	0.57461	1.11552	46067.2	1.03E+21
435	128184	0.628781	1.02429	53646.5	1.24E+21
436	128365	0.680679	0.944301	60638.5	1.45E+21
437	128545	0.730358	0.874433	67125.5	1.67E+21
438	128727	0.777842	0.813554	73180.3	1.88E+21
439	120781	0.822893	0.760792	78848.1	2.10E+21
440	1	1.62478	2.56E-04	1234.48	1.84E+20
441	127283	0.389712	1.32065	8870.37	2.01E+20
442	127463	0.431377	1.23368	19550	4.11E+20
443	127643	0.48771	1.13114	29382.5	6.21E+20
444	127823	0.546693	1.0338	38364.6	8.32E+20
445	128003	0.604497	0.94651	46578.6	1.04E+21
446	128184	0.660162	0.869527	54120.5	1.26E+21
447	128365	0.713591	0.802047	61080.1	1.47E+21
448	128545	0.764804	0.743117	67539.5	1.68E+21
449	128727	0.813791	0.69178	73569.4	1.90E+21
450	120781	0.860284	0.647287	79217.9	2.11E+21
451	1	1.64525	2.28E-04	1385.32	2.01E+20
452	127283	0.374351	1.17948	9475.48	2.15E+20
453	127463	0.416539	1.10029	20118	4.25E+20
454	127643	0.471681	1.00889	29906.9	6.36E+20
455	127823	0.528818	0.922547	38847.8	8.47E+20
456	128003	0.584507	0.845208	47025.2	1.06E+21
457	128184	0.637931	0.777019	54535.2	1.27E+21

458	128365	0.689053	0.717248	61467.4	1.48E+21
459	128545	0.737924	0.66505	67903.4	1.70E+21
460	128727	0.784554	0.619579	73911.9	1.91E+21
461	120781	0.828721	0.580159	79544.6	2.13E+21
462	1	1.51168	2.12E-04	1522.48	2.15E+20
463	127283	0.147535	0.607095	146.112	2.50E+18
464	127463	0.442091	0.575864	11265.2	2.12E+20
465	127643	0.498791	0.525627	21750.3	4.22E+20
466	127823	0.567241	0.475027	31377.1	6.33E+20
467	128003	0.638397	0.42926	40171.8	8.44E+20
468	128184	0.709339	0.389046	48222.3	1.06E+21
469	128365	0.77932	0.353976	55623.3	1.27E+21
470	128545	0.848167	0.323471	62462.4	1.48E+21
471	128727	0.915713	0.296992	68819.7	1.70E+21
472	120784	0.981657	0.274054	74756.4	1.91E+21
473	1	1.72296	4.44E-05	13.6994	2.50E+18
474	127283	0.213509	1.0067	535.064	9.54E+18
475	127463	0.255193	0.957593	11637.9	2.19E+20
476	127643	0.298951	0.875062	22094.1	4.29E+20
477	127823	0.349788	0.791792	31691.7	6.40E+20
478	128003	0.401116	0.716373	40460.3	8.51E+20
479	128184	0.450943	0.650034	48488.3	1.06E+21
480	128365	0.498946	0.592132	55870	1.28E+21
481	128545	0.545243	0.541738	62692.9	1.49E+21
482	128727	0.589953	0.497969	69036.8	1.70E+21
483	120784	0.633054	0.460045	74960.1	1.92E+21
484	1	2.37023	7.66E-05	51.0468	9.54E+18
485	127283	0.218962	1.62555	1169.76	2.12E+19
486	127463	0.23877	1.54892	12245.6	2.31E+20
487	127643	0.281345	1.41798	22653.4	4.41E+20
488	127823	0.330094	1.28541	32202.1	6.52E+20
489	128003	0.378864	1.16505	40926.6	8.63E+20
490	128184	0.425845	1.05898	48916.1	1.07E+21
491	128365	0.470796	0.96628	56264.7	1.29E+21
492	128545	0.513883	0.885512	63059.2	1.50E+21
493	128727	0.555264	0.815304	69379.2	1.72E+21
494	120784	0.594945	0.754449	75280.1	1.93E+21
495	1	2.21415	1.32E-04	115.516	2.12E+19
496	127283	0.226884	2.18792	2089.41	3.77E+19
497	127463	0.246826	2.08458	13125.3	2.47E+20
498	127643	0.290186	1.91107	23462.7	4.58E+20
499	127823	0.339115	1.73553	32940.3	6.68E+20
500	128003	0.387765	1.57593	41600.3	8.79E+20
501	128184	0.434458	1.43505	49533.4	1.09E+21
502	128365	0.479006	1.31175	56833.2	1.30E+21
503	128545	0.52159	1.20422	63585.6	1.52E+21
504	128727	0.562375	1.11067	69869.8	1.73E+21
505	120784	0.601359	1.02956	75737.7	1.95E+21
506	1	2.01655	1.97E-04	217.263	3.77E+19
507	127283	0.245522	2.39048	3193.69	5.75E+19
508	127463	0.268438	2.27319	14179.5	2.67E+20

509	127643	0.313633	2.08554	24432.9	4.77E+20
510	127823	0.363884	1.89682	33825.8	6.88E+20
511	128003	0.413638	1.72527	42409.1	8.99E+20
512	128184	0.461344	1.57368	50274.9	1.11E+21
513	128365	0.506849	1.44087	57516	1.32E+21
514	128545	0.550331	1.32496	64217.9	1.54E+21
515	128727	0.591939	1.22404	70458.7	1.75E+21
516	120784	0.631639	1.13654	76287.7	1.97E+21
517	1	1.88957	2.41E-04	353.24	5.75E+19
518	127283	0.260237	2.38145	4345.04	7.83E+19
519	127463	0.286668	2.25793	15275.7	2.88E+20
520	127643	0.333555	2.07204	25442.1	4.98E+20
521	127823	0.384834	1.88677	34748	7.09E+20
522	128003	0.435357	1.71858	43252.5	9.20E+20
523	128184	0.483731	1.5699	51049	1.13E+21
524	128365	0.529852	1.43953	58229.8	1.35E+21
525	128545	0.573896	1.32569	64879.5	1.56E+21
526	128727	0.616001	1.22653	71075.6	1.77E+21
527	120784	0.656101	1.14056	76864.6	1.99E+21
528	1	1.74963	2.69E-04	512.08	7.83E+19
529	127283	0.272234	2.22953	5457.73	9.85E+19
530	127463	0.302193	2.10704	16331.9	3.08E+20
531	127643	0.350667	1.93347	26414.7	5.19E+20
532	127823	0.402838	1.76222	35637.8	7.29E+20
533	128003	0.453981	1.60705	44067.4	9.41E+20
534	128184	0.502871	1.46985	51798.1	1.15E+21
535	128365	0.549452	1.34951	58921.6	1.37E+21
536	128545	0.593901	1.24439	65521.9	1.58E+21
537	128727	0.636351	1.1528	71675.3	1.79E+21
538	120784	0.676708	1.07339	77426.6	2.01E+21
539	1	1.63042	2.78E-04	682.604	9.85E+19
540	127283	0.282295	1.99915	6478.38	1.17E+20
541	127463	0.315452	1.88343	17298	3.27E+20
542	127643	0.365293	1.72796	27304.6	5.37E+20
543	127823	0.418182	1.57604	36452.8	7.48E+20
544	128003	0.469798	1.43867	44815	9.59E+20
545	128184	0.519068	1.31722	52486.4	1.17E+21
546	128365	0.565982	1.21066	59558.5	1.38E+21
547	128545	0.610722	1.11756	66114.2	1.60E+21
548	128727	0.653412	1.03643	72229.1	1.81E+21
549	120784	0.693937	0.966104	77946.9	2.03E+21
550	1	1.53904	2.71E-04	853.784	1.17E+20
551	127283	0.292012	1.73473	7379.97	1.34E+20
552	127463	0.327954	1.62956	18149.3	3.43E+20
553	127643	0.379006	1.49456	28088.9	5.54E+20
554	127823	0.432559	1.36381	37172	7.65E+20
555	128003	0.484651	1.24583	45475.8	9.76E+20
556	128184	0.534338	1.14156	53095.9	1.19E+21
557	128365	0.581646	1.05007	60123.4	1.40E+21
558	128545	0.626753	0.970125	66640.5	1.62E+21
559	128727	0.669774	0.900457	72722.1	1.83E+21

560	120784	0.710575	0.840068	78411.6	2.04E+21
561	1	1.47891	2.51E-04	1016.57	1.34E+20
562	127283	0.305385	1.50277	8162.14	1.48E+20
563	127463	0.343622	1.40607	18885.8	3.58E+20
564	127643	0.395639	1.28793	28767.4	5.69E+20
565	127823	0.449851	1.17481	37794.8	7.79E+20
566	128003	0.50262	1.07308	46048.7	9.91E+20
567	128184	0.553104	0.983284	53625.2	1.20E+21
568	128365	0.601328	0.904533	60614.7	1.42E+21
569	128545	0.647437	0.835748	67099.4	1.63E+21
570	128727	0.691507	0.775818	73152.2	1.85E+21
571	120784	0.733366	0.723885	78818.2	2.06E+21
572	1	1.4725	2.28E-04	1165.91	1.48E+20
573	127283	0.32097	1.29819	8839.29	1.62E+20
574	127463	0.361378	1.21135	19521.7	3.72E+20
575	127643	0.414678	1.10878	29353.1	5.82E+20
576	127823	0.469948	1.01133	38332.9	7.93E+20
577	128003	0.523768	0.923914	46544.3	1.00E+21
578	128184	0.575364	0.846797	54083.6	1.22E+21
579	128365	0.624755	0.779191	61041.1	1.43E+21
580	128545	0.672064	0.720154	67498.3	1.64E+21
581	128727	0.717333	0.668728	73526.4	1.86E+21
582	120784	0.760366	0.624169	79173.4	2.07E+21
583	1	1.48171	2.05E-04	1300.91	1.62E+20
584	127283	0.324743	1.18684	9440.52	1.74E+20
585	127463	0.366585	1.10508	20085.3	3.84E+20
586	127643	0.420253	1.01099	29872.4	5.95E+20
587	127823	0.475562	0.922165	38810.3	8.06E+20
588	128003	0.529348	0.84262	46984.6	1.02E+21
589	128184	0.580916	0.772494	54491.6	1.23E+21
590	128365	0.630302	0.711032	61421.1	1.44E+21
591	128545	0.677623	0.657369	67854.6	1.66E+21
592	128727	0.722904	0.610634	73861	1.87E+21
593	120784	0.765954	0.570134	79491.9	2.09E+21
594	1	1.44429	1.94E-04	1425.43	1.74E+20
595	127283	0.326278	1.08819	9991.29	1.86E+20
596	127463	0.369226	1.01152	20600.9	3.96E+20
597	127643	0.423035	0.925078	30347.5	6.06E+20
598	127823	0.478169	0.843889	39247.6	8.17E+20
599	128003	0.531694	0.771287	47388.3	1.03E+21
600	128184	0.582991	0.707308	54866.1	1.24E+21
601	128365	0.632112	0.651246	61770.6	1.45E+21
602	128545	0.679173	0.602303	68182.8	1.67E+21
603	128727	0.724187	0.559687	74169.3	1.88E+21
604	120784	0.766979	0.522747	79786.4	2.10E+21
605	1	1.40367	1.84E-04	1543.31	1.86E+20
606	127283	0.307189	1.08393	10517.4	1.96E+20
607	127463	0.350154	1.0062	21092.8	4.06E+20
608	127643	0.402556	0.920028	30800.9	6.17E+20
609	127823	0.455749	0.839416	39665.1	8.28E+20
610	128003	0.507122	0.76741	47774.1	1.04E+21

611	128184	0.556178	0.703973	55224.5	1.25E+21
612	128365	0.603021	0.64839	62105.2	1.47E+21
613	128545	0.647797	0.599867	68497.6	1.68E+21
614	128727	0.690534	0.557625	74464.9	1.89E+21
615	120784	0.731115	0.520994	80069.5	2.11E+21
616	1	1.28275	1.88E-04	1659.25	1.96E+20
617	127283	0.278129	1.10942	11048.8	2.06E+20
618	127463	0.320525	1.02876	21589	4.16E+20
619	127643	0.370781	0.940554	31258.2	6.26E+20
620	127823	0.421202	0.858321	40086.2	8.37E+20
621	128003	0.469531	0.784925	48163.4	1.05E+21
622	128184	0.515415	0.720273	55586.1	1.26E+21
623	128365	0.559025	0.663624	62443.1	1.48E+21
624	128545	0.600555	0.614168	68815.5	1.69E+21
625	128727	0.640063	0.571123	74763.5	1.90E+21
626	120784	0.677505	0.533773	80355.8	2.12E+21
627	1	1.12995	1.97E-04	1779.31	2.06E+20
628	4.90E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
629	5.15E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
630	990500	0.00E+00	0.00E+00	0.00E+00	0.00E+00
631	4.62E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
632	5.89E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
633	865720	0.00E+00	0.00E+00	0.00E+00	0.00E+00
634	565385	0.00E+00	0.00E+00	0.00E+00	0.00E+00
635	4.49E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
636	4.49E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
637	5.78E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
638	746102	0.00E+00	0.00E+00	0.00E+00	0.00E+00
639	1.61E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
640	1.61E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
641	1.61E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
642	1.68E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
643	5.43E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
644	3.06E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
645	937146	0.00E+00	0.00E+00	0.00E+00	0.00E+00
646	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
647	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
648	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
649	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
650	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
651	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
652	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
653	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
654	1.22E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
655	1.33E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
656	1.03E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
657	892397	0.00E+00	0.00E+00	0.00E+00	0.00E+00
658	8.21E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
659	9.77E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
660	9.77E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
661	9.77E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00

662	5.58E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
663	1.61E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
664	3.46E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
665	3.46E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
666	3.46E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
667	3.42E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
668	3.78E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
669	8.14E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
670	8.14E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
671	8.14E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
672	6.35E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
673	7.20E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
674	7.20E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
675	7.20E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
676	5.62E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
677	1.38E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
678	4.49E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
679	3.14E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
680	9.30E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
681	192334	0.00E+00	0.00E+00	0.00E+00	0.00E+00
682	1.08E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
683	8.05E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00

C-4 The general input file for MS MPBR1

```
$INPUT
    CORE_HEIGHT = 10.0D0, ! core height (m)
    CORE_RADIUS = 1.75D0, ! core radius(m)
    P_CORE = 250.0D0, ! core power (MWth)
    QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
    T_IRR = 1000.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 1000.0D0, ! irradiation time(Day)
    T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 118.D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 360000, ! number of pebbles in core
    NPARTICLE = 11000, ! number of particles per pebble
    DT = 5.534784D5, ! time step size (s)
    OUTTIME = 5.534784D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.1D0, ! EOL burnup (FIMA)
    EOLFLU = 2.0D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 10, ! number of fueling cycles
    FUELTYPE = 'UO2', ! fuel kernel type
    CURAT = 0.0D0, ! Carbon to Uranium ratio
    OURAT = 2.0D0, ! Oxygen to Uranium ratio
    U235ENR = 9.600D0, ! U235 enrichment (%)
    U235VAR = 0.1D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.81D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 10.95D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 497.0D0, ! kernel diameter (micron)
    KERNVAR = 14.1D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 1.00D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 94.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.3D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.90D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 41.0D0, ! IPyC thickness (micron)
    IPYCVAR = 4.0D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05788D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00543D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 1.5D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.90D0, ! OPyC density (g/cm^3)
    OPYCF = 24.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 40.0D0, ! OPyC thickness (micron)
    OPYCVAR = 2.2D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 36.0D0, ! SiC thickness (micron)
    SICVAR = 1.7D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Reference LEU TRISO fuel_MS MPBR1 ! particle description
    OSPEC = 'sMPBR1_MS', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .TRUE., ! flag determining whether ISEED from users is used
$END
```

C-5 The general input file for DS MPBR1

```
$INPUT
	CORE_HEIGHT = 10.0D0, ! core height (m)
	CORE_RADIUS = 1.75D0, ! core radius(m)
	P_CORE = 250.0D0, ! core power (MWth)
	QPPP_AVG = 3.65186D6, ! averaged power density (W/m^3)
	T_IRR = 1000.0D0, ! irradiation temperature (Celsius)
	IRRTIME = 1000.0D0, ! irradiation time(Day)
	T_GASIN = 450.0D0, ! coolant inlet temperature (Celsius)
	T_GASOUT = 850.0D0, ! coolant outlet temperature (Celsius)
	MF_HE = 118.D0, ! helium mass flow rate (kg/s)
	PEBRADIUS = 3.0D-2, ! pebble radius (m)
	PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
	NPEBBLE = 360000, ! number of pebbles in core
	NPARTICLE = 11000, ! number of particles per pebble
	DT = 5.534784D5, ! time step size (s)
	OUTTIME = 5.534784D5, ! time pebble is taken out of the core in each cycle (s)
	EOLBUP = 0.1D0, ! EOL burnup (FIMA)
	EOLFLU = 2.0D0, ! EOL fluence (10^21 n/cm^2)
	SHUFFLE = 10, ! number of fueling cycles
	FUELTYPE = 'UO2', ! fuel kernel type
	CURAT = 0.0D0, ! Carbon to Uranium ratio
	OURAT = 2.0D0, ! Oxygen to Uranium ratio
	U235ENR = 9.600D0, ! U235 enrichment (%)
	U235VAR = 0.1D0, ! standard deviation on U235 enrichment (%)
	KERND = 10.4D0, ! kernel density (g/cm^3)
	KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
	KERNT = 10.95D0, ! kernel theoretical density (g/cm^3)
	KERNDIA = 500.0D0, ! kernel diameter (micron)
	KERNVAR = 20.0D0, ! standard deviation on kernel diameter (micron)
	BUFFD = 1.05D0, ! buffer density (g/cm^3)
	BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
	BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
	BUFFTHK = 90.0D0, ! buffer thickness (micron)
	BUFFVAR = 18.0D0, ! standard deviation on buffer thickness (micron)
	IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
	IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
	IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
	IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
	IPYCD = 1.90D0, ! IPyC density (g/cm^3)
	IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
	IPYCM = 9.5D0, ! IPyC Weibull modulus
	IPYCTHK = 40.0D0, ! IPyC thickness (micron)
	IPYCVAR = 10.0D0, ! standard deviation on IPyC thickness (micron)
	OPYCBAF0I = 1.05788D0, ! OPyC as-fabricated BAF
	OPYCBAFVAR = 0.00543D0, ! standard deviation on OPyC as-fabricated BAF
	OPYCCRATE = 1.5D0, ! OPyC coating rate (micron/min)
	OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
	OPYCD = 1.90D0, ! OPyC density (g/cm^3)
	OPYCF = 24.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
	OPYCM = 9.5D0, ! OPyC Weibull modulus
	OPYCTHK = 40.0D0, ! OPyC thickness (micron)
	OPYCVAR = 10.0D0, ! standard deviation on OPyC thickness (micron)
	SICTHK = 35.0D0, ! SiC thickness (micron)
	SICVAR = 4.0D0, ! standard deviation on SiC thickness (micron)
	SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
	SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
	SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
	SICM = 6.0D0, ! SiC Weibull modulus
	PAMB = 0.10D0, ! ambient pressure (MPa)
	TITLE = 'Reference LEU TRISO fuel_DS MPBR1', ! particle description
	OSPEC = 'sMPBR1_DS', ! output file name
	DEBUG = .TRUE., ! flag for debugging
	ISEED = 30285171, ! initial seed for random number generator
	NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
	NCASES = 1000000, ! number of particles to be sampled
	NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
	DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
	HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
	RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
	USERSEED = .TRUE., ! flag determining whether ISEED from users is used
$END
```

Appendix D

Input files for MPBR2 simulations

D-1 The 'blocks.dat' file for MPBR2

Layers 1 to 93

z(cm)	FLUX 1	FLUX 2	FLUX 3	FLUX 4
354	1.39E+13	2.17E+13	5.18E+12	3.85E+13
414	2.87E+13	4.66E+13	1.11E+13	7.52E+13
474	4.28E+13	6.99E+13	1.68E+13	1.14E+14
534	5.43E+13	8.89E+13	2.14E+13	1.46E+14
594	6.05E+13	9.96E+13	2.40E+13	1.67E+14
654	6.24E+13	1.03E+14	2.48E+13	1.75E+14
714	6.01E+13	9.93E+13	2.39E+13	1.72E+14
764	5.54E+13	9.16E+13	2.21E+13	1.61E+14
824	4.91E+13	8.13E+13	1.96E+13	1.44E+14
884	4.26E+13	7.05E+13	1.70E+13	1.26E+14
944	3.63E+13	6.02E+13	1.45E+13	1.09E+14
1004	3.05E+13	5.07E+13	1.22E+13	9.21E+13
1064	2.55E+13	4.23E+13	1.02E+13	7.73E+13
1124	2.10E+13	3.48E+13	8.41E+12	6.40E+13
1184	1.71E+13	2.84E+13	6.85E+12	5.23E+13
1234	1.38E+13	2.29E+13	5.53E+12	4.24E+13
1284	1.12E+13	1.87E+13	4.50E+12	3.44E+13
1324	8.99E+12	1.50E+13	3.55E+12	2.67E+13
1364	6.35E+12	1.08E+13	2.74E+12	2.30E+13
1447.7	4.16E+12	6.85E+12	1.77E+12	1.72E+13
354	1.40E+13	2.29E+13	5.39E+12	3.07E+13
414	2.93E+13	4.98E+13	1.18E+13	6.05E+13
474	4.49E+13	7.62E+13	1.80E+13	9.45E+13
534	5.76E+13	9.78E+13	2.30E+13	1.23E+14
594	6.47E+13	1.10E+14	2.59E+13	1.40E+14
654	6.68E+13	1.14E+14	2.67E+13	1.47E+14
714	6.43E+13	1.10E+14	2.58E+13	1.44E+14
774	5.93E+13	1.01E+14	2.37E+13	1.34E+14
834	5.26E+13	8.97E+13	2.11E+13	1.20E+14
894	4.56E+13	7.78E+13	1.83E+13	1.05E+14
954	3.88E+13	6.63E+13	1.56E+13	9.01E+13
1014	3.27E+13	5.59E+13	1.31E+13	7.63E+13
1074	2.73E+13	4.66E+13	1.09E+13	6.40E+13
1134	2.25E+13	3.84E+13	9.01E+12	5.30E+13
1194	1.83E+13	3.13E+13	7.33E+12	4.31E+13
1254	1.46E+13	2.51E+13	5.86E+12	3.37E+13
1324	1.11E+13	1.91E+13	4.42E+12	2.51E+13
1447.7	6.19E+12	1.03E+13	2.40E+12	1.78E+13
354	1.34E+13	2.21E+13	5.22E+12	2.78E+13
414	2.82E+13	4.86E+13	1.15E+13	5.49E+13
474	4.40E+13	7.52E+13	1.77E+13	8.79E+13
534	5.70E+13	9.72E+13	2.28E+13	1.15E+14
594	6.43E+13	1.10E+14	2.57E+13	1.33E+14
654	6.65E+13	1.13E+14	2.66E+13	1.39E+14
714	6.41E+13	1.10E+14	2.57E+13	1.36E+14
764	5.91E+13	1.01E+14	2.36E+13	1.27E+14

824	5.25E+13	8.99E+13	2.10E+13	1.14E+14
884	4.56E+13	7.81E+13	1.82E+13	9.97E+13
944	3.89E+13	6.66E+13	1.56E+13	8.56E+13
1004	3.28E+13	5.62E+13	1.31E+13	7.26E+13
1064	2.74E+13	4.69E+13	1.09E+13	6.09E+13
1124	2.26E+13	3.87E+13	9.04E+12	5.05E+13
1184	1.84E+13	3.15E+13	7.35E+12	4.12E+13
1244	1.46E+13	2.50E+13	5.83E+12	3.28E+13
1314	1.10E+13	1.87E+13	4.33E+12	2.49E+13
1447.7	6.10E+12	9.95E+12	2.29E+12	1.69E+13
354	1.10E+13	1.82E+13	4.39E+12	2.43E+13
414	2.36E+13	4.03E+13	9.67E+12	4.93E+13
474	3.86E+13	6.44E+13	1.52E+13	8.53E+13
534	5.08E+13	8.41E+13	1.98E+13	1.14E+14
594	5.75E+13	9.52E+13	2.24E+13	1.33E+14
654	5.94E+13	9.83E+13	2.31E+13	1.39E+14
714	5.71E+13	9.47E+13	2.22E+13	1.36E+14
774	5.25E+13	8.71E+13	2.04E+13	1.26E+14
834	4.65E+13	7.72E+13	1.81E+13	1.13E+14
894	4.03E+13	6.69E+13	1.57E+13	9.92E+13
944	3.43E+13	5.70E+13	1.34E+13	8.51E+13
1004	2.89E+13	4.80E+13	1.13E+13	7.21E+13
1064	2.40E+13	4.00E+13	9.39E+12	6.03E+13
1124	1.98E+13	3.29E+13	7.73E+12	4.99E+13
1184	1.61E+13	2.67E+13	6.27E+12	4.07E+13
1254	1.27E+13	2.12E+13	4.97E+12	3.24E+13
1314	9.66E+12	1.61E+13	3.73E+12	2.47E+13
1447.7	5.53E+12	8.96E+12	2.11E+12	1.72E+13
354	8.22E+12	1.39E+13	3.63E+12	2.28E+13
414	1.78E+13	3.08E+13	7.95E+12	4.79E+13
474	3.03E+13	5.03E+13	1.27E+13	9.16E+13
534	4.02E+13	6.61E+13	1.66E+13	1.25E+14
594	4.57E+13	7.50E+13	1.88E+13	1.47E+14
654	4.71E+13	7.74E+13	1.94E+13	1.54E+14
714	4.52E+13	7.44E+13	1.86E+13	1.51E+14
774	4.15E+13	6.84E+13	1.71E+13	1.40E+14
834	3.67E+13	6.06E+13	1.52E+13	1.26E+14
894	3.17E+13	5.25E+13	1.31E+13	1.10E+14
944	2.70E+13	4.47E+13	1.12E+13	9.42E+13
1004	2.27E+13	3.76E+13	9.43E+12	7.98E+13
1064	1.89E+13	3.13E+13	7.85E+12	6.68E+13
1124	1.56E+13	2.58E+13	6.48E+12	5.53E+13
1184	1.27E+13	2.10E+13	5.27E+12	4.51E+13
1244	1.02E+13	1.69E+13	4.24E+12	3.62E+13
1294	8.17E+12	1.36E+13	3.37E+12	2.85E+13
1344	6.37E+12	1.06E+13	2.65E+12	2.28E+13
1447.7	3.74E+12	6.27E+12	1.66E+12	1.68E+13

D-2 The 'channels.dat' file for MPBR2

z-position (cm)		r-position (cm)				
	channel 0	channel 1	channel 2	channel 3	channel 4	channel 5
294	100	121.89	140.35	156.7	171.43	184.75
354	100	121.89	140.35	156.7	171.43	185
414	100	121.89	140.35	156.7	171.43	185
474	100	121.89	140.35	156.7	171.43	185
534	100	121.89	140.35	156.7	171.43	185
594	100	121.89	140.35	156.7	171.43	185
654	100	121.89	140.35	156.7	171.43	185
714	100	121.89	140.35	156.7	171.43	185
774	100	121.89	140.35	156.7	171.43	185
834	100	121.89	140.35	156.7	171.44	185
894	100	121.89	140.35	156.7	171.45	185
954	100	121.89	140.35	156.7	171.45	185
1014	100	121.82	140.31	156.7	171.43	185
1074	100	121.8	140.3	156.7	171.37	185
1134	100	121.97	140.4	156.7	171.37	185
1194	100	123.02	140.92	156.7	171.14	185
1254	100	126.03	142.41	156.7	170.26	185
1314	100	131.85	145.18	156.7	168.28	185
1374	119.21	140.73	148.46	156.37	164.23	174.85
1434	146.72	149.64	153.02	155.58	157.45	160.32
1447.7	153	152.04	153.77	155.3	156.5	157

D-3 The 'pdistr.dat' file for MPBR2

1	150038	0.151162	0.672659	239.58	4.35E+18		
2	150038	0.221972	0.619413	17546.3	3.85E+20		
3	150038	0.28553	0.541503	33263.5	7.66E+20		
4	150038	0.346953	0.471931	47140.6	1.15E+21		
5	150038	0.403075	0.413497	59406.7	1.53E+21		
6	150020	0.455331	0.36506	70330.5	1.91E+21		
7	1	1.9423	4.52E-05	20.576	4.35E+18	1	0.514013
8	150038	0.198445	1.31505	948.25	1.77E+19		
9	150038	0.237766	1.20622	18199.2	3.98E+20		
10	150038	0.30312	1.05352	33836.1	7.80E+20		
11	150038	0.366442	0.91778	47641.2	1.16E+21		
12	150038	0.424746	0.803866	59847.1	1.54E+21		
13	150020	0.479397	0.709493	70720.4	1.93E+21		
14	1	2.34851	9.40E-05	83.8685	1.77E+19	2	1.00099
15	150038	0.227188	1.90059	2094.74	4.01E+19		
16	150038	0.26628	1.75503	19257.3	4.21E+20		
17	150038	0.332928	1.54173	34765.3	8.02E+20		
18	150038	0.397275	1.34993	48454.7	1.18E+21		
19	150038	0.456473	1.188	60563.2	1.57E+21		
20	150020	0.511827	1.0534	71355.1	1.95E+21		
21	1	2.29009	1.53E-04	196.451	4.01E+19	3	1.46479
22	150038	0.239633	2.4208	3635.84	7.04E+19		
23	150038	0.284463	2.21651	20675.5	4.51E+20		
24	150038	0.35303	1.94449	36011.7	8.32E+20		
25	150038	0.418931	1.70229	49547.2	1.21E+21		
26	150038	0.479918	1.49817	61526	1.60E+21		
27	150020	0.537255	1.32868	72209.7	1.98E+21		
28	1	2.02092	2.25E-04	369.688	7.04E+19	4	1.85183
29	150038	0.259572	2.64021	5440.19	1.06E+20		
30	150038	0.308606	2.41909	22329.7	4.87E+20		
31	150038	0.377998	2.13087	37467.2	8.68E+20		
32	150038	0.444034	1.87341	50825.4	1.25E+21		
33	150038	0.50499	1.65567	62654.6	1.63E+21		
34	150020	0.5621	1.47454	73213.6	2.01E+21		
35	1	1.78591	2.92E-04	606.861	1.06E+20	5	2.03231
36	150038	0.268631	2.74052	7358.92	1.45E+20		
37	150038	0.323689	2.4881	24080.3	5.26E+20		
38	150038	0.394242	2.18874	39008.7	9.07E+20		
39	150038	0.460908	1.92439	52181.7	1.29E+21		
40	150038	0.522682	1.7014	63854.7	1.67E+21		
41	150020	0.580746	1.51621	74283.7	2.05E+21		
42	1	1.58769	3.46E-04	900.137	1.45E+20	6	2.09323
43	150038	0.283841	2.60364	9264.12	1.83E+20		
44	150038	0.343198	2.35872	25808.6	5.64E+20		
45	150038	0.414366	2.0797	40531.3	9.45E+20		

46	150038	0.480987	1.83384	53523.2	1.33E+21		
47	150038	0.542586	1.62627	65043.8	1.71E+21		
48	150020	0.600318	1.45383	75346.2	2.09E+21		
49	1	1.44649	3.76E-04	1232.22	1.83E+20	7	1.99267
50	150038	0.291744	2.41089	11052	2.19E+20		
51	150038	0.35511	2.16991	27423.3	6.00E+20		
52	150038	0.426691	1.9117	41954.8	9.81E+20		
53	150038	0.493382	1.68617	54779.3	1.36E+21		
54	150038	0.555208	1.49621	66159.4	1.75E+21		
55	150020	0.613254	1.33865	76345.7	2.13E+21		
56	1	1.3493	3.81E-04	1580.36	2.19E+20	8	1.83559
57	150038	0.304895	2.10939	12663.5	2.52E+20		
58	150038	0.371354	1.89558	28872.8	6.33E+20		
59	150038	0.443449	1.67276	43233	1.01E+21		
60	150038	0.510186	1.47859	55908.6	1.40E+21		
61	150038	0.571942	1.31503	67164	1.78E+21		
62	150020	0.629771	1.1794	77247.8	2.16E+21		
63	1	1.28359	3.64E-04	1922.94	2.52E+20	9	1.60847
64	150038	0.31124	1.8332	14069.2	2.81E+20		
65	150038	0.379829	1.64102	30134	6.62E+20		
66	150038	0.451868	1.44764	44346	1.04E+21		
67	150038	0.5184	1.28006	56893.3	1.42E+21		
68	150038	0.580081	1.13914	68041.8	1.81E+21		
69	150020	0.637889	1.02241	78038.3	2.19E+21		
70	1	1.23624	3.35E-04	2244.15	2.81E+20	10	1.39392
71	150038	0.319345	1.55101	15276	3.06E+20		
72	150038	0.389565	1.38637	31213.7	6.86E+20		
73	150038	0.461629	1.22387	45299.3	1.07E+21		
74	150038	0.52798	1.08342	57737.5	1.45E+21		
75	150038	0.589474	0.965371	68795.7	1.83E+21		
76	150020	0.647039	0.867644	78718.7	2.21E+21		
77	1	1.20216	2.98E-04	2534.99	3.06E+20	11	1.17962
78	150038	0.323626	1.308	16295.7	3.26E+20		
79	150038	0.394854	1.16662	32124.7	7.07E+20		
80	150038	0.466679	1.02976	46104	1.09E+21		
81	150038	0.532746	0.911862	58451.1	1.47E+21		
82	150038	0.594051	0.812879	69434.5	1.85E+21		
83	150020	0.651459	0.731005	79296.7	2.24E+21		
84	1	1.17624	2.60E-04	2791.63	3.26E+20	12	0.993359
85	150038	0.328965	1.08548	17149.5	3.44E+20		
86	150038	0.400991	0.967323	32886.4	7.25E+20		
87	150038	0.472685	0.854238	46777.5	1.11E+21		
88	150038	0.538533	0.756978	59049.2	1.49E+21		
89	150038	0.599634	0.675357	69971.3	1.87E+21		
90	150020	0.656804	0.60788	79783.4	2.25E+21		
91	1	1.15725	2.23E-04	3013.73	3.44E+20	13	0.824546
92	150038	0.332349	0.895345	17856.4	3.59E+20		
93	150038	0.404897	0.796888	33516.8	7.39E+20		

94	150038	0.476418	0.703696	47335.6	1.12E+21		
95	150038	0.542095	0.623708	59545.8	1.50E+21		
96	150038	0.603096	0.55663	70418.2	1.88E+21		
97	150020	0.66018	0.501212	80189.4	2.27E+21		
98	1	1.14412	1.88E-04	3202.62	3.59E+20	14	0.679583
99	150038	0.336342	0.727662	18435.9	3.70E+20		
100	150038	0.409279	0.647297	34033.4	7.51E+20		
101	150038	0.480682	0.571747	47793.6	1.13E+21		
102	150038	0.546225	0.506973	59954.4	1.51E+21		
103	150038	0.607121	0.452672	70786.8	1.90E+21		
104	150020	0.664082	0.407832	80525	2.28E+21		
105	1	1.13499	1.56E-04	3360.65	3.70E+20	15	0.552366
106	150038	0.338527	0.588365	18906	3.80E+20		
107	150038	0.411729	0.523	34453	7.61E+20		
108	150038	0.482997	0.461946	48166.1	1.14E+21		
109	150038	0.548417	0.409665	60287.4	1.52E+21		
110	150038	0.609235	0.365858	71088	1.91E+21		
111	150020	0.666119	0.329703	80799.8	2.29E+21		
112	1	1.12707	1.28E-04	3491.02	3.80E+20	16	0.446425
113	150038	0.34056	0.476367	19286.5	3.88E+20		
114	150038	0.413792	0.423208	34793.3	7.69E+20		
115	150038	0.484838	0.373799	48468.5	1.15E+21		
116	150038	0.550095	0.331528	60558.4	1.53E+21		
117	150038	0.610811	0.296124	71333.6	1.91E+21		
118	150020	0.667608	0.266918	81023.9	2.30E+21		
119	1	1.12185	1.05E-04	3597.84	3.88E+20	17	0.361326
120	150038	0.350425	0.369952	19589.5	3.94E+20		
121	150038	0.424574	0.328495	35064.7	7.75E+20		
122	150038	0.496514	0.29012	48710.2	1.16E+21		
123	150038	0.562771	0.257318	60775.3	1.54E+21		
124	150038	0.624553	0.229858	71530.5	1.92E+21		
125	150020	0.682411	0.207214	81203.6	2.30E+21		
126	1	1.14545	8.19E-05	3683.66	3.94E+20	18	0.280494
127	150038	0.320142	0.317191	19835.9	3.99E+20		
128	150038	0.391075	0.28155	35285.9	7.80E+20		
129	150038	0.458972	0.248656	48907.5	1.16E+21		
130	150038	0.52097	0.220553	60952.7	1.54E+21		
131	150038	0.578444	0.197031	71691.4	1.93E+21		
132	150020	0.632061	0.177639	81350.6	2.31E+21		
133	1	1.0383	7.06E-05	3753.95	3.99E+20	19	0.240438
134	150038	0.306948	0.234834	20034.5	4.02E+20		
135	150038	0.376707	0.208457	35464.5	7.84E+20		
136	150038	0.442912	0.18414	49067.1	1.16E+21		
137	150038	0.503031	0.163365	61096.4	1.55E+21		
138	150038	0.558538	0.145976	71821.8	1.93E+21		
139	150020	0.610174	0.131642	81469.7	2.31E+21		
140	1	0.987247	5.26E-05	3810.87	4.02E+20	20	0.17807
141	150038	0.186475	0.549858	195.788	4.38E+18		

142	150038	0.266915	0.504942	17505.4	3.85E+20		
143	150038	0.335539	0.440811	33227.5	7.66E+20		
144	150038	0.403293	0.383773	47109.1	1.15E+21		
145	150038	0.466475	0.335942	59379	1.53E+21		
146	150038	0.526252	0.29633	70305.9	1.91E+21		
147	6.0625	2.3965	3.72E-05	16.908	4.38E+18	21	0.418607
148	150038	0.245504	1.08616	778.924	1.79E+19		
149	150038	0.286824	0.994255	18041.7	3.99E+20		
150	150038	0.357659	0.867379	33697.7	7.80E+20		
151	150038	0.427853	0.754976	47520	1.16E+21		
152	150038	0.493797	0.660789	59740.5	1.54E+21		
153	150038	0.556561	0.582824	70626	1.93E+21		
154	6.0625	2.90713	7.80E-05	69.2753	1.79E+19	22	0.824391
155	150038	0.275247	1.6248	1745.31	4.11E+19		
156	150038	0.315265	1.49733	18932	4.22E+20		
157	150038	0.387295	1.3136	34478.8	8.03E+20		
158	150038	0.458416	1.14907	48203.5	1.18E+21		
159	150038	0.525048	1.01044	60341.9	1.57E+21		
160	150038	0.588192	0.895334	71158.9	1.95E+21		
161	6.0625	2.77629	1.32E-04	164.721	4.11E+19	23	1.24842
162	150038	0.288259	2.10163	3074.05	7.32E+19		
163	150038	0.333433	1.92398	20153.8	4.54E+20		
164	150038	0.407124	1.68699	35551.8	8.35E+20		
165	150038	0.479506	1.47639	49143.7	1.22E+21		
166	150038	0.547538	1.29917	61170.3	1.60E+21		
167	150038	0.612176	1.15213	71894	1.98E+21		
168	6.0625	2.42239	1.97E-04	315.155	7.32E+19	24	1.60671
169	150038	0.309924	2.31454	4648.48	1.11E+20		
170	150038	0.358516	2.12344	21598.3	4.92E+20		
171	150038	0.432764	1.87071	36822.7	8.74E+20		
172	150038	0.504953	1.64507	50259.8	1.26E+21		
173	150038	0.572467	1.45447	62156.2	1.64E+21		
174	150038	0.636233	1.29599	72771.2	2.02E+21		
175	6.0625	2.11529	2.59E-04	524.324	1.11E+20	25	1.78402
176	150038	0.318941	2.41089	6333.63	1.53E+20		
177	150038	0.373216	2.19544	23139.3	5.33E+20		
178	150038	0.448271	1.9333	38180.7	9.15E+20		
179	150038	0.520632	1.70149	51455.5	1.30E+21		
180	150038	0.588379	1.50605	63215.2	1.68E+21		
181	150038	0.652409	1.34375	73716.4	2.06E+21		
182	6.0625	1.85949	3.10E-04	785.791	1.53E+20	26	1.84847
183	150038	0.334953	2.29356	8011.04	1.94E+20		
184	150038	0.393054	2.08727	24666.9	5.75E+20		
185	150038	0.468378	1.84388	39528.5	9.56E+20		
186	150038	0.540222	1.62872	52644.8	1.34E+21		
187	150038	0.607169	1.44702	64271.2	1.72E+21		
188	150038	0.670108	1.29602	74661.6	2.10E+21		
189	6.0625	1.67582	3.38E-04	1083.98	1.94E+20	27	1.76607

190	150038	0.341897	2.1281	9587.87	2.32E+20		
191	150038	0.403959	1.92609	26098.4	6.13E+20		
192	150038	0.479386	1.70128	40793.4	9.94E+20		
193	150038	0.550846	1.50408	53763.4	1.38E+21		
194	150038	0.617456	1.33785	65266.9	1.76E+21		
195	150038	0.680066	1.19985	75555.8	2.14E+21		
196	6.0625	1.54687	3.45E-04	1398.35	2.32E+20	28	1.63286
197	150038	0.354916	1.86655	11012.3	2.67E+20		
198	150038	0.419839	1.68845	27387.6	6.48E+20		
199	150038	0.495452	1.49486	41933.7	1.03E+21		
200	150038	0.566495	1.32521	54773.5	1.41E+21		
201	150038	0.632457	1.18211	66168.2	1.79E+21		
202	150038	0.694185	1.06327	76367.6	2.18E+21		
203	6.0625	1.45686	3.31E-04	1709.43	2.67E+20	29	1.43673
204	150038	0.360132	1.62638	12258.1	2.98E+20		
205	150038	0.427304	1.46622	28513	6.79E+20		
206	150038	0.502663	1.29821	42930.4	1.06E+21		
207	150038	0.573173	1.15173	55658.3	1.44E+21		
208	150038	0.638655	1.02833	66959.4	1.82E+21		
209	150038	0.699912	0.92595	77082.5	2.21E+21		
210	6.0625	1.39207	3.06E-04	2002.6	2.98E+20	30	1.24946
211	150038	0.367993	1.37778	13329.6	3.25E+20		
212	150038	0.436875	1.24098	29479	7.05E+20		
213	150038	0.512134	1.10007	43786.5	1.09E+21		
214	150038	0.582213	0.977451	56419.2	1.47E+21		
215	150038	0.647171	0.874156	67641.7	1.85E+21		
216	150038	0.707796	0.78847	77700.8	2.23E+21		
217	6.0625	1.3451	2.74E-04	2269.09	3.25E+20	31	1.05981
218	150038	0.371387	1.16378	14236.3	3.47E+20		
219	150038	0.441427	1.04616	30295.3	7.28E+20		
220	150038	0.516333	0.927491	44510.9	1.11E+21		
221	150038	0.585915	0.824554	57064.2	1.49E+21		
222	150038	0.650424	0.737912	68221.6	1.87E+21		
223	150038	0.710608	0.666087	78227.7	2.26E+21		
224	6.0625	1.30939	2.39E-04	2504.97	3.47E+20	32	0.894324
225	150038	0.376305	0.967327	14996.8	3.66E+20		
226	150038	0.447263	0.869128	30979.3	7.47E+20		
227	150038	0.521962	0.771142	45118.6	1.13E+21		
228	150038	0.591146	0.686248	57606.2	1.51E+21		
229	150038	0.655208	0.614801	68710.2	1.89E+21		
230	150038	0.714876	0.555586	78673	2.27E+21		
231	6.0625	1.28198	2.06E-04	2709.67	3.66E+20	33	0.744034
232	150038	0.379327	0.79883	15627.2	3.81E+20		
233	150038	0.450948	0.7169	31546.2	7.62E+20		
234	150038	0.525432	0.636138	45623	1.14E+21		
235	150038	0.594338	0.566307	58057.3	1.52E+21		
236	150038	0.658166	0.50757	69118.3	1.91E+21		
237	150038	0.717601	0.458913	79045.7	2.29E+21		

238	6.0625	1.26403	1.74E-04	2884.2	3.81E+20	34	0.614106
239	150038	0.385238	0.645991	16143.1	3.94E+20		
240	150038	0.45753	0.579542	32010.3	7.75E+20		
241	150038	0.532096	0.514491	46036.7	1.16E+21		
242	150038	0.601018	0.458294	58428.2	1.54E+21		
243	150038	0.664859	0.411029	69454.8	1.92E+21		
244	150038	0.724265	0.371889	79353.7	2.30E+21		
245	6.0625	1.25714	1.44E-04	3030.09	3.94E+20	35	0.496869
246	150038	0.396402	0.505226	16554.5	4.04E+20		
247	150038	0.469784	0.452897	32380.8	7.85E+20		
248	150038	0.545189	0.402061	46367.6	1.17E+21		
249	150038	0.615027	0.358203	58725.7	1.55E+21		
250	150038	0.679853	0.321334	69725.5	1.93E+21		
251	150038	0.740233	0.290818	79601.9	2.31E+21		
252	6.0625	1.27709	1.14E-04	3148.4	4.04E+20	36	0.388421
253	150038	0.410706	0.377051	16870	4.13E+20		
254	150038	0.485255	0.337885	32665.7	7.93E+20		
255	150038	0.561793	0.300012	46622.5	1.17E+21		
256	150038	0.632861	0.267362	58955.6	1.56E+21		
257	150038	0.698968	0.239922	69935.4	1.94E+21		
258	150038	0.760596	0.217217	79794.7	2.32E+21		
259	6.0625	1.30767	8.60E-05	3240.3	4.13E+20	37	0.289906
260	150038	0.38289	0.262505	17099.2	4.18E+20		
261	150038	0.45487	0.235421	32873.6	7.99E+20		
262	150038	0.527696	0.209211	46809.2	1.18E+21		
263	150038	0.594622	0.186595	59124.7	1.56E+21		
264	150038	0.656395	0.167578	70090.3	1.94E+21		
265	150038	0.713655	0.151839	79937.4	2.33E+21		
266	6.0625	1.19703	6.07E-05	3307.87	4.18E+20	38	0.20219
267	150038	0.196765	0.498957	177.648	4.18E+18		
268	150038	0.282163	0.458037	17488.7	3.85E+20		
269	150038	0.352465	0.399791	33212.9	7.66E+20		
270	150038	0.422306	0.348017	47096.4	1.15E+21		
271	150038	0.4878	0.30461	59367.8	1.53E+21		
272	150038	0.550028	0.268666	70296.1	1.91E+21		
273	6.3125	2.53053	3.38E-05	15.3653	4.18E+18	39	0.379677
274	150038	0.258753	0.99231	709.151	1.72E+19		
275	150038	0.300637	0.90825	17977.5	3.98E+20		
276	150038	0.372985	0.792251	33641.6	7.79E+20		
277	150038	0.445085	0.68952	47471.1	1.16E+21		
278	150038	0.51314	0.603454	59697.6	1.54E+21		
279	150038	0.578141	0.53222	70588.2	1.93E+21		
280	6.3125	3.07621	7.12E-05	63.0977	1.72E+19	40	0.752996
281	150038	0.286328	1.52145	1605.2	3.98E+19		
282	150038	0.326179	1.40262	18803.4	4.21E+20		
283	150038	0.399288	1.23053	34366.3	8.02E+20		
284	150038	0.471829	1.0764	48105.3	1.18E+21		
285	150038	0.540023	0.946542	60255.8	1.57E+21		

286	150038	0.604798	0.838722	71082.8	1.95E+21		
287	6.3125	2.91153	1.23E-04	151.341	3.98E+19	41	1.16937
288	150038	0.298853	1.9897	2857.13	7.14E+19		
289	150038	0.343634	1.82302	19955.3	4.52E+20		
290	150038	0.418302	1.59871	35378.1	8.33E+20		
291	150038	0.491993	1.39925	48992	1.21E+21		
292	150038	0.561444	1.23139	61037.2	1.60E+21		
293	150038	0.627544	1.09212	71776.3	1.98E+21		
294	6.3125	2.53607	1.86E-04	292.268	7.14E+19	42	1.52235
295	150038	0.32075	2.20379	4352.16	1.09E+20		
296	150038	0.368639	2.02437	21328.5	4.90E+20		
297	150038	0.443756	1.78395	36586.6	8.71E+20		
298	150038	0.517151	1.56904	50053.6	1.25E+21		
299	150038	0.585955	1.38748	61975.1	1.63E+21		
300	150038	0.651025	1.23651	72610.9	2.02E+21		
301	6.3125	2.21123	2.45E-04	489.503	1.09E+20	43	1.70085
302	150038	0.329749	2.30155	5958.84	1.50E+20		
303	150038	0.383265	2.09907	22799.9	5.31E+20		
304	150038	0.459168	1.84919	37883.7	9.12E+20		
305	150038	0.532699	1.62789	51196	1.29E+21		
306	150038	0.601674	1.44127	62987.2	1.68E+21		
307	150038	0.666924	1.28626	73514.5	2.06E+21		
308	6.3125	1.93991	2.93E-04	737.034	1.50E+20	44	1.76752
309	150038	0.345975	2.19259	7561.31	1.91E+20		
310	150038	0.403188	1.99895	24261.7	5.72E+20		
311	150038	0.479312	1.76677	39174.2	9.53E+20		
312	150038	0.552266	1.56115	52335	1.33E+21		
313	150038	0.620356	1.38744	63998.8	1.72E+21		
314	150038	0.684411	1.24303	74420.4	2.10E+21		
315	6.3125	1.74482	3.21E-04	1020.05	1.91E+20	45	1.69164
316	150038	0.35265	2.03763	9069.94	2.30E+20		
317	150038	0.413867	1.84773	25633.9	6.11E+20		
318	150038	0.490078	1.63304	40387.3	9.92E+20		
319	150038	0.5626	1.44434	53408.3	1.37E+21		
320	150038	0.630282	1.28521	64954.7	1.76E+21		
321	150038	0.693922	1.15306	75279.1	2.14E+21		
322	6.3125	1.60646	3.28E-04	1319.1	2.30E+20	46	1.56683
323	150038	0.365458	1.79087	10435.2	2.65E+20		
324	150038	0.429495	1.62329	26872	6.46E+20		
325	150038	0.505839	1.43813	41483.1	1.03E+21		
326	150038	0.577869	1.27553	54379.5	1.41E+21		
327	150038	0.644806	1.13829	65821.6	1.79E+21		
328	150038	0.707454	1.02428	76060.4	2.17E+21		
329	6.3125	1.50906	3.16E-04	1615.77	2.65E+20	47	1.38172
330	150038	0.370307	1.56332	11631.6	2.95E+20		
331	150038	0.436667	1.41227	27955	6.76E+20		
332	150038	0.512747	1.25133	42443	1.06E+21		
333	150038	0.5842	1.11072	55232	1.44E+21		

334	150038	0.650594	0.992196	66584.5	1.82E+21		
335	150038	0.712699	0.893808	76750.1	2.20E+21		
336	6.3125	1.43875	2.93E-04	1896.08	2.95E+20	48	1.20393
337	150038	0.377896	1.32676	12662.5	3.22E+20		
338	150038	0.445993	1.19752	28886.3	7.03E+20		
339	150038	0.521947	1.06235	43269	1.08E+21		
340	150038	0.592918	0.944461	55966.6	1.47E+21		
341	150038	0.658724	0.845088	67243.6	1.85E+21		
342	150038	0.720126	0.76261	77347.7	2.23E+21		
343	6.3125	1.38751	2.63E-04	2151.5	3.22E+20	49	1.02312
344	150038	0.381033	1.12229	13536.2	3.44E+20		
345	150038	0.450361	1.01097	29674.6	7.25E+20		
346	150038	0.525961	0.896988	43969.1	1.11E+21		
347	150038	0.596408	0.797905	56590.4	1.49E+21		
348	150038	0.661727	0.71445	67804.7	1.87E+21		
349	150038	0.722645	0.645225	77858.1	2.25E+21		
350	6.3125	1.34874	2.30E-04	2378.04	3.44E+20	50	0.864632
351	150038	0.38615	0.933342	14269.8	3.63E+20		
352	150038	0.456458	0.840335	30335.9	7.44E+20		
353	150038	0.531881	0.746193	44557	1.13E+21		
354	150038	0.601946	0.664451	57115.2	1.51E+21		
355	150038	0.666828	0.595605	68278.3	1.89E+21		
356	150038	0.727237	0.53851	78289.9	2.27E+21		
357	6.3125	1.32028	1.98E-04	2574.93	3.63E+20	51	0.719734
358	150038	0.388698	0.772606	14878.7	3.79E+20		
359	150038	0.459699	0.694798	30884.6	7.60E+20		
360	150038	0.534873	0.617032	45045.8	1.14E+21		
361	150038	0.604604	0.549647	57552.6	1.52E+21		
362	150038	0.669187	0.492922	68674.3	1.90E+21		
363	150038	0.729294	0.445902	78652	2.29E+21		
364	6.3125	1.29941	1.68E-04	2743.07	3.79E+20	52	0.59548
365	150038	0.393126	0.627838	15378.8	3.92E+20		
366	150038	0.464719	0.56443	31335.5	7.73E+20		
367	150038	0.539816	0.501503	45448.1	1.15E+21		
368	150038	0.609375	0.44702	57913.6	1.54E+21		
369	150038	0.67377	0.40116	69002.1	1.92E+21		
370	150038	0.733643	0.363157	78952.1	2.30E+21		
371	6.3125	1.28638	1.39E-04	2884.16	3.92E+20	53	0.484181
372	150038	0.397359	0.49937	15781.6	4.02E+20		
373	150038	0.469522	0.448625	31699.1	7.83E+20		
374	150038	0.5447	0.398642	45773.1	1.16E+21		
375	150038	0.614321	0.35542	58206.1	1.55E+21		
376	150038	0.678806	0.319051	69268.7	1.93E+21		
377	150038	0.738759	0.288926	79196.9	2.31E+21		
378	6.3125	1.28211	1.12E-04	2999.8	4.02E+20	54	0.385003
379	150038	0.404013	0.377389	16095.2	4.10E+20		
380	150038	0.47674	0.33896	31982.8	7.91E+20		
381	150038	0.55221	0.301274	46027.3	1.17E+21		

382	150038	0.622122	0.268703	58435.5	1.55E+21		
383	150038	0.686909	0.241301	69478.3	1.94E+21		
384	150038	0.747134	0.218609	79389.4	2.32E+21		
385	6.3125	1.28692	8.60E-05	3091.01	4.10E+20	55	0.291037
386	150038	0.384378	0.252651	16320.9	4.15E+20		
387	150038	0.455292	0.227078	32188.1	7.96E+20		
388	150038	0.528003	0.201989	46211.8	1.18E+21		
389	150038	0.594812	0.180287	58602.9	1.56E+21		
390	150038	0.656343	0.162021	69631.7	1.94E+21		
391	150038	0.713275	0.146891	79530.8	2.33E+21		
392	6.3125	1.2035	5.83E-05	3157.48	4.15E+20	56	0.195151
393	150038	0.189799	0.434784	154.789	3.44E+18		
394	150038	0.282322	0.399305	17467.7	3.84E+20		
395	150038	0.352637	0.34859	33194.6	7.65E+20		
396	150038	0.422471	0.303483	47080.5	1.15E+21		
397	150038	0.487918	0.265658	59353.9	1.53E+21		
398	150038	0.550067	0.234332	70283.8	1.91E+21		
399	5.875	2.44667	2.93E-05	13.3537	3.44E+18	57	0.331023
400	150038	0.245142	0.886266	625.621	1.43E+19		
401	150038	0.286501	0.811895	17901.3	3.95E+20		
402	150038	0.35727	0.708382	33575.1	7.76E+20		
403	150038	0.427464	0.616606	47413.4	1.16E+21		
404	150038	0.493394	0.539695	59647.1	1.54E+21		
405	150038	0.556129	0.476027	70543.7	1.92E+21		
406	5.875	2.95458	6.28E-05	55.295	1.43E+19	58	0.673141
407	150038	0.259264	1.46161	1462.6	3.37E+19		
408	150038	0.297754	1.34944	18673.9	4.15E+20		
409	150038	0.36797	1.18427	34253.6	7.96E+20		
410	150038	0.436995	1.03602	48007.3	1.18E+21		
411	150038	0.501302	0.911059	60170	1.56E+21		
412	150038	0.561981	0.807267	71007.2	1.94E+21		
413	5.875	2.72028	1.15E-04	136.096	3.37E+19	59	1.12494
414	150038	0.269278	1.95205	2679.82	6.17E+19		
415	150038	0.312428	1.79098	19795.6	4.43E+20		
416	150038	0.384068	1.57075	35239	8.24E+20		
417	150038	0.454128	1.37451	48870.8	1.21E+21		
418	150038	0.519594	1.20927	60931	1.59E+21		
419	150038	0.581531	1.07213	71682.4	1.97E+21		
420	5.875	2.38942	1.75E-04	268.553	6.17E+19	60	1.49494
421	150038	0.289105	2.17458	4151.03	9.56E+19		
422	150038	0.33551	1.99997	21148.7	4.76E+20		
423	150038	0.407821	1.7621	36429.8	8.58E+20		
424	150038	0.477851	1.549	49916.5	1.24E+21		
425	150038	0.542989	1.36884	61854.4	1.62E+21		
426	150038	0.604287	1.21899	72503.7	2.00E+21		
427	5.875	2.1054	2.30E-04	454.096	9.56E+19	61	1.6789
428	150038	0.2979	2.26793	5735.22	1.32E+20		
429	150038	0.349905	2.06997	22600.9	5.13E+20		

430	150038	0.423221	1.82246	37709.5	8.94E+20		
431	150038	0.493694	1.60284	51042.7	1.28E+21		
432	150038	0.559381	1.41753	62851.3	1.66E+21		
433	150038	0.621301	1.26357	73392.8	2.04E+21		
434	5.875	1.86087	2.74E-04	685.537	1.32E+20	62	1.74071
435	150038	0.313597	2.14957	7310.25	1.69E+20		
436	150038	0.369506	1.96057	24038.6	5.50E+20		
437	150038	0.443412	1.7312	38977.6	9.31E+20		
438	150038	0.513749	1.52769	52160.8	1.31E+21		
439	150038	0.579056	1.35567	63843	1.69E+21		
440	150038	0.640351	1.21264	74279.7	2.08E+21		
441	5.875	1.6855	2.96E-04	947.886	1.69E+20	63	1.65621
442	150038	0.32015	1.99013	8786.46	2.03E+20		
443	150038	0.380103	1.80465	25381.6	5.84E+20		
444	150038	0.454315	1.59288	40163.7	9.65E+20		
445	150038	0.524512	1.40646	53208.5	1.35E+21		
446	150038	0.589761	1.24917	64774.5	1.73E+21		
447	150038	0.651039	1.11853	75115.1	2.11E+21		
448	5.875	1.55725	3.01E-04	1222.85	2.03E+20	64	1.52696
449	150038	0.332406	1.74263	10117.5	2.34E+20		
450	150038	0.395365	1.57911	26588.4	6.15E+20		
451	150038	0.470006	1.39677	41230.2	9.96E+20		
452	150038	0.540052	1.23639	54152.2	1.38E+21		
453	150038	0.604938	1.10097	65615.3	1.76E+21		
454	150038	0.665644	0.988455	75871.2	2.14E+21		
455	5.875	1.46751	2.88E-04	1493.93	2.34E+20	65	1.34071
456	150038	0.337087	1.51779	11280.3	2.61E+20		
457	150038	0.402426	1.37031	27640.6	6.42E+20		
458	150038	0.476965	1.2119	42161.2	1.02E+21		
459	150038	0.546642	1.07332	54977.2	1.40E+21		
460	150038	0.611232	0.956458	66352	1.79E+21		
461	150038	0.671673	0.859437	76535.8	2.17E+21		
462	5.875	1.40129	2.66E-04	1748.83	2.61E+20	66	1.16486
463	150038	0.344399	1.28505	12280	2.85E+20		
464	150038	0.411601	1.1589	28543	6.65E+20		
465	150038	0.48621	1.02598	42960.1	1.05E+21		
466	150038	0.555632	0.909895	55686.1	1.43E+21		
467	150038	0.619887	0.812009	66986.5	1.81E+21		
468	150038	0.6799	0.730756	77109.8	2.19E+21		
469	5.875	1.35354	2.38E-04	1980.29	2.85E+20	67	0.987091
470	150038	0.347476	1.08506	13125.5	3.04E+20		
471	150038	0.415965	0.976392	29305.2	6.85E+20		
472	150038	0.490339	0.864376	43635.5	1.07E+21		
473	150038	0.559383	0.766882	56286.4	1.45E+21		
474	150038	0.623323	0.684737	67525.1	1.83E+21		
475	150038	0.683041	0.616593	77598.5	2.21E+21		
476	5.875	1.31693	2.08E-04	2184.97	3.04E+20	68	0.832335
477	150038	0.352521	0.899933	13833.8	3.21E+20		

478	150038	0.42209	0.809268	29943	7.02E+20		
479	150038	0.49643	0.716899	44201.3	1.08E+21		
480	150038	0.565255	0.636604	56790.2	1.46E+21		
481	150038	0.628938	0.568956	67978.5	1.85E+21		
482	150038	0.688339	0.512851	78011	2.23E+21		
483	5.875	1.29071	1.78E-04	2362.36	3.21E+20	69	0.690748
484	150038	0.355151	0.742482	14420	3.35E+20		
485	150038	0.425465	0.666794	30470.6	7.16E+20		
486	150038	0.499648	0.590686	44670.2	1.10E+21		
487	150038	0.568253	0.524665	57208.7	1.48E+21		
488	150038	0.631765	0.469072	68356.5	1.86E+21		
489	150038	0.691006	0.422989	78355.6	2.24E+21		
490	5.875	1.2716	1.50E-04	2513.32	3.35E+20	70	0.569444
491	150038	0.359398	0.601534	14900	3.46E+20		
492	150038	0.430358	0.539987	30902.7	7.27E+20		
493	150038	0.504546	0.478544	45054.9	1.11E+21		
494	150038	0.573071	0.425289	57553	1.49E+21		
495	150038	0.6365	0.38045	68668.5	1.87E+21		
496	150038	0.695619	0.343292	78640.5	2.26E+21		
497	5.875	1.25967	1.24E-04	2639.55	3.46E+20	71	0.461513
498	150038	0.363295	0.478181	15285.8	3.55E+20		
499	150038	0.434836	0.428914	31250.5	7.36E+20		
500	150038	0.509135	0.380109	45365.1	1.12E+21		
501	150038	0.577765	0.337863	57831.5	1.50E+21		
502	150038	0.641338	0.302306	68921.5	1.88E+21		
503	150038	0.700602	0.272852	78872.4	2.26E+21		
504	5.875	1.25582	1.00E-04	2742.78	3.55E+20	72	0.366702
505	150038	0.369405	0.363334	15586.7	3.62E+20		
506	150038	0.441519	0.325792	31522.5	7.43E+20		
507	150038	0.516129	0.288774	45608.2	1.12E+21		
508	150038	0.585084	0.256749	58050.4	1.51E+21		
509	150038	0.649006	0.229801	69121.1	1.89E+21		
510	150038	0.708599	0.207485	79055.3	2.27E+21		
511	5.875	1.26097	7.71E-05	2824.34	3.62E+20	73	0.278654
512	150038	0.352361	0.250385	15806.5	3.67E+20		
513	150038	0.422975	0.224598	31722.1	7.48E+20		
514	150038	0.495198	0.199188	45787.2	1.13E+21		
515	150038	0.561465	0.177197	58212.3	1.51E+21		
516	150038	0.622565	0.158685	69269.2	1.89E+21		
517	150038	0.679298	0.143354	79191.5	2.28E+21		
518	5.875	1.18478	5.37E-05	2884.61	3.67E+20	74	0.192233
519	150038	0.166315	0.403572	143.679	2.57E+18		
520	150038	0.262632	0.370849	17457.6	3.83E+20		
521	150038	0.330789	0.323817	33185.8	7.64E+20		
522	150038	0.397928	0.281953	47072.8	1.15E+21		
523	150038	0.460369	0.246836	59347.2	1.53E+21		
524	150030	0.519316	0.217748	70277.9	1.91E+21		
525	1	2.14891	2.70E-05	12.3141	2.57E+18	75	0.307463

526	150038	0.208313	0.849995	590.486	1.07E+19		
527	150038	0.248337	0.779376	17869.4	3.91E+20		
528	150038	0.314931	0.680197	33547.5	7.73E+20		
529	150038	0.379988	0.592149	47389.3	1.15E+21		
530	150038	0.440238	0.518326	59626.1	1.54E+21		
531	150030	0.496963	0.457198	70525.2	1.92E+21		
532	1	2.54586	5.93E-05	51.6226	1.07E+19	76	0.646207
533	150038	0.205057	1.53683	1441.54	2.58E+19		
534	150038	0.241874	1.42107	18656.3	4.07E+20		
535	150038	0.306279	1.24768	34238.8	7.88E+20		
536	150038	0.368154	1.09167	47994.7	1.17E+21		
537	150038	0.424636	0.960031	60159.2	1.55E+21		
538	150030	0.477133	0.850635	70997.7	1.93E+21		
539	1	2.22538	1.17E-04	131.739	2.58E+19	77	1.18466
540	150038	0.212399	2.08585	2733.48	4.78E+19		
541	150038	0.253855	1.91488	19848	4.29E+20		
542	150038	0.319665	1.67911	35285.8	8.10E+20		
543	150038	0.38259	1.46867	48911.9	1.19E+21		
544	150038	0.440298	1.29134	60967.1	1.57E+21		
545	150030	0.494186	1.1441	71714.3	1.96E+21		
546	1	1.98666	1.78E-04	266.53	4.78E+19	78	1.59733
547	150038	0.228081	2.33756	4310.56	7.47E+19		
548	150038	0.272995	2.149	21298.5	4.56E+20		
549	150038	0.339318	1.89174	36561.5	8.37E+20		
550	150038	0.402168	1.66105	50031.2	1.22E+21		
551	150038	0.459694	1.46592	61954.5	1.60E+21		
552	150030	0.513276	1.30358	72591.6	1.98E+21		
553	1	1.78054	2.31E-04	454.227	7.47E+19	79	1.80148
554	150038	0.23652	2.4301	6010.55	1.04E+20		
555	150038	0.287127	2.21408	22855	4.85E+20		
556	150038	0.354852	1.94585	37931.2	8.66E+20		
557	150038	0.418674	1.70793	51234.7	1.25E+21		
558	150038	0.47739	1.50715	63017.7	1.63E+21		
559	150030	0.532345	1.34034	73538	2.01E+21		
560	1	1.60072	2.72E-04	685.528	1.04E+20	80	1.85758
561	150038	0.249914	2.29707	7695.71	1.33E+20		
562	150038	0.304388	2.08848	24389.3	5.14E+20		
563	150038	0.372695	1.83905	39281.4	8.95E+20		
564	150038	0.436588	1.61812	52422.1	1.28E+21		
565	150038	0.495354	1.43147	64068.1	1.66E+21		
566	150030	0.550298	1.27632	74474.6	2.04E+21		
567	1	1.46863	2.91E-04	944.289	1.33E+20	81	1.75842
568	150038	0.256707	2.1162	9269.12	1.60E+20		
569	150038	0.3153	1.91091	25815.4	5.41E+20		
570	150038	0.384368	1.68069	40536.8	9.22E+20		
571	150038	0.448711	1.47854	53527.3	1.30E+21		
572	150038	0.508107	1.30812	65047.2	1.69E+21		
573	150030	0.563809	1.16667	75349.5	2.07E+21		

574	1	1.37203	2.92E-04	1212.35	1.60E+20	82	1.61019
575	150038	0.267291	1.84974	10682.9	1.84E+20		
576	150038	0.328732	1.66735	27091.2	5.65E+20		
577	150038	0.398244	1.46839	41659.8	9.46E+20		
578	150038	0.462653	1.29403	54516.8	1.33E+21		
579	150038	0.522076	1.147	65925	1.71E+21		
580	150030	0.577733	1.02497	76135.3	2.09E+21		
581	1	1.30287	2.77E-04	1474.24	1.84E+20	83	1.40858
582	150038	0.272358	1.60511	11914.8	2.06E+20		
583	150038	0.336242	1.44056	28199.6	5.87E+20		
584	150038	0.406035	1.26776	42635.9	9.68E+20		
585	150038	0.47056	1.1172	55377.7	1.35E+21		
586	150038	0.530238	0.990443	66690	1.73E+21		
587	150030	0.586232	0.885354	76822	2.11E+21		
588	1	1.25287	2.54E-04	1718.77	2.06E+20	84	1.21774
589	150038	0.278855	1.35686	12971	2.24E+20		
590	150038	0.344397	1.21563	29147	6.05E+20		
591	150038	0.414277	1.07032	43470.3	9.86E+20		
592	150038	0.47871	0.944017	56114.2	1.37E+21		
593	150038	0.538328	0.83772	67345.4	1.75E+21		
594	150030	0.594247	0.749632	77411.5	2.13E+21		
595	1	1.21542	2.26E-04	1939.57	2.24E+20	85	1.02903
596	150038	0.28236	1.14239	13862.4	2.40E+20		
597	150038	0.349249	1.02081	29945	6.20E+20		
598	150038	0.419183	0.898424	44173.4	1.00E+21		
599	150038	0.483599	0.792423	56735.5	1.38E+21		
600	150038	0.5433	0.703307	67899.6	1.77E+21		
601	150030	0.599352	0.629517	77911.4	2.15E+21		
602	1	1.18811	1.97E-04	2133.97	2.40E+20	86	0.86448
603	150038	0.286917	0.946704	14607.6	2.53E+20		
604	150038	0.354742	0.845046	30611.2	6.33E+20		
605	150038	0.424667	0.743961	44760.8	1.01E+21		
606	150038	0.48899	0.656544	57255.3	1.40E+21		
607	150038	0.54863	0.583077	68364.5	1.78E+21		
608	150030	0.604609	0.522268	78331.6	2.16E+21		
609	1	1.16768	1.68E-04	2301.85	2.53E+20	87	0.716268
610	150038	0.289866	0.780496	15224	2.63E+20		
611	150038	0.358486	0.695584	31161.7	6.44E+20		
612	150038	0.428458	0.612223	45246.9	1.03E+21		
613	150038	0.492811	0.540294	57686.4	1.41E+21		
614	150038	0.552557	0.479885	68751.2	1.79E+21		
615	150030	0.608669	0.429917	78681.9	2.17E+21		
616	1	1.15426	1.42E-04	2444.44	2.63E+20	88	0.589734
617	150038	0.293776	0.633027	15728.6	2.72E+20		
618	150038	0.362959	0.563789	31612.4	6.53E+20		
619	150038	0.432966	0.496314	45645.4	1.03E+21		
620	150038	0.497332	0.438152	58040.7	1.42E+21		
621	150038	0.557126	0.389317	69070	1.80E+21		

622	150030	0.613279	0.348938	78971.2	2.18E+21		
623	1	1.14568	1.17E-04	2563.57	2.72E+20	89	0.478257
624	150038	0.297887	0.506152	16135.5	2.79E+20		
625	150038	0.367709	0.450349	31976.3	6.60E+20		
626	150038	0.437982	0.396382	45967.7	1.04E+21		
627	150038	0.502645	0.349928	58327.9	1.42E+21		
628	150038	0.562799	0.310943	69329.2	1.81E+21		
629	150030	0.619326	0.278725	79206.8	2.19E+21		
630	1	1.1462	9.51E-05	2661.26	2.79E+20	90	0.38208
631	150038	0.303321	0.397711	16458.6	2.85E+20		
632	150038	0.373652	0.353697	32265.8	6.66E+20		
633	150038	0.444231	0.311331	46224.5	1.05E+21		
634	150038	0.509254	0.274889	58557.5	1.43E+21		
635	150038	0.569824	0.244313	69536.9	1.81E+21		
636	150030	0.626771	0.219055	79395.9	2.20E+21		
637	1	1.15269	7.57E-05	2739.8	2.85E+20	91	0.300166
638	150038	0.301637	0.317399	16714.5	2.90E+20		
639	150038	0.371985	0.282125	32495.8	6.71E+20		
640	150038	0.442224	0.248315	46428.9	1.05E+21		
641	150038	0.506865	0.219253	58740.7	1.43E+21		
642	150038	0.567056	0.194878	69702.9	1.82E+21		
643	150030	0.623619	0.174749	79547.2	2.20E+21		
644	1	1.13608	6.09E-05	2802.67	2.90E+20	92	0.239453
645	150038	0.28868	0.231794	16911.5	2.93E+20		
646	150038	0.357862	0.2061	32673.3	6.74E+20		
647	150038	0.426258	0.181479	46587.2	1.06E+21		
648	150038	0.488797	0.160309	58883.1	1.44E+21		
649	150038	0.54675	0.142549	69831.9	1.82E+21		
650	150030	0.601017	0.127881	79664.9	2.20E+21		
651	1	1.07337	4.49E-05	2851.47	2.93E+20	93	0.175019
652	2.26E+06	0	0	0	0		
653	1.79E+06	0	0	0	0		
654	1.15E+06	0	0	0	0		
655	5.29E+06	0	0	0	0		
656	9.89E+06	0	0	0	0		
657	7.18E+06	0	0	0	0		
658	1.15E+06	0	0	0	0		
659	3.19E+06	0	0	0	0		
660	2.22E+06	0	0	0	0		
661	6.99E+06	0	0	0	0		
662	4.86E+06	0	0	0	0		
663	1.32E+06	0	0	0	0		
664	1.73E+06	0	0	0	0		
665	2.66E+06	0	0	0	0		
666	2.66E+06	0	0	0	0		
667	2.66E+06	0	0	0	0		
668	2.80E+06	0	0	0	0		
669	3.23E+06	0	0	0	0		

670	1.53E+06	0	0	0	0
671	1.86E+06	0	0	0	0
672	1.86E+06	0	0	0	0
673	1.86E+06	0	0	0	0
674	1.86E+06	0	0	0	0
675	1.86E+06	0	0	0	0
676	1.86E+06	0	0	0	0
677	1.86E+06	0	0	0	0
678	1.86E+06	0	0	0	0
679	1.86E+06	0	0	0	0
680	1.87E+06	0	0	0	0
681	6.21E+06	0	0	0	0
682	9.57E+06	0	0	0	0
683	9.57E+06	0	0	0	0
684	9.57E+06	0	0	0	0
685	5.41E+06	0	0	0	0
686	1.16E+07	0	0	0	0
687	1.80E+07	0	0	0	0
688	1.80E+07	0	0	0	0
689	1.80E+07	0	0	0	0
690	1.02E+07	0	0	0	0
691	5.98E+06	0	0	0	0
692	9.22E+06	0	0	0	0
693	9.22E+06	0	0	0	0
694	9.22E+06	0	0	0	0
695	5.21E+06	0	0	0	0
696	5.84E+06	0	0	0	0
697	7.64E+06	0	0	0	0
698	7.64E+06	0	0	0	0
699	7.64E+06	0	0	0	0
700	1.33E+07	0	0	0	0
701	9.02E+06	0	0	0	0
702	1.17E+07	0	0	0	0
703	2.52E+07	0	0	0	0
704	6.85E+06	0	0	0	0
705	2.00E+06	0	0	0	0
706	7.87E+06	0	0	0	0
707	2.12E+06	0	0	0	0
708	1.68E+06	0	0	0	0
709	1.51E+06	0	0	0	0
710	1.51E+06	0	0	0	0
711	1.58E+07	0	0	0	0
712	6.92E+06	0	0	0	0
713	6.92E+06	0	0	0	0
714	9.23E+06	0	0	0	0
715	3.46E+06	0	0	0	0
716	3.85E+06	0	0	0	0
717	1.58E+08	0	0	0	0

718	2.14E+07	0	0	0	0
719	1.68E+06	0	0	0	0
720	2.12E+06	0	0	0	0
721	798623	0	0	0	0
722	555968	0	0	0	0
723	2.07E+06	0	0	0	0
724	532895	0	0	0	0
725	798623	0	0	0	0
726	555968	0	0	0	0
727	1.03E+06	0	0	0	0
728	1.57E+06	0	0	0	0
729	1.51E+06	0	0	0	0
730	1.20E+06	0	0	0	0
731	665364	0	0	0	0
732	812761	0	0	0	0
733	812761	0	0	0	0
734	812761	0	0	0	0
735	812761	0	0	0	0
736	812761	0	0	0	0
737	812761	0	0	0	0
738	812761	0	0	0	0
739	812761	0	0	0	0
740	812761	0	0	0	0
741	814876	0	0	0	0

D-4 The general input file for MS MPBR2

```
$INPUT
    CORE_HEIGHT = 11.0D0, ! core height (m)
    CORE_RADIUS = 1.85D0, ! core radius(m)
    P_CORE = 400.0D0, ! core power (MWth)
    QPPP_AVG = 4.77689D6, ! averaged power density (W/m3)
    T_IRR = 1000.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 936.0D0, ! irradiation time(Day)
    T_GASIN = 500.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 900.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 154.6D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 451600, ! number of pebbles in core
    NPARTICLE = 15000, ! number of particles per pebble
    DT = 7.2576D5, ! time step size (s)
    OUTTIME = 7.2576D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.1D0, ! EOL burnup (FIMA)
    EOLFLU = 2.8D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 6, ! number of fueling cycles
    FUELTYPE = 'UO2', ! fuel kernel type
    CURAT = 0.0D0, ! Carbon to Uranium ratio
    OURAT = 2.0D0, ! Oxygen to Uranium ratio
    U235ENR = 9.600D0, ! U235 enrichment (%)
    U235VAR = 0.1D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.81D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 10.95D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 497.0D0, ! kernel diameter (micron)
    KERNVAR = 14.1D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 1.00D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 94.0D0, ! buffer thickness (micron)
    BUFFVAR = 10.3D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.90D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 41.0D0, ! IPyC thickness (micron)
    IPYCVAR = 4.0D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05788D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00543D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 1.5D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.90D0, ! OPyC density (g/cm^3)
    OPYCF = 24.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 40.0D0, ! OPyC thickness (micron)
    OPYCVAR = 2.2D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 36.0D0, ! SiC thickness (micron)
    SICVAR = 1.7D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 3500.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Reference LEU TRISO fuel_MS MPBR2', ! particle description
    OSPEC = 'sMPBR2_MS', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .TRUE., ! flag determining whether ISEED from users is used
$END
```

D-5 The general input file for DS MPBR2

```
$INPUT
    CORE_HEIGHT = 11.0D0, ! core height (m)
    CORE_RADIUS = 1.85D0, ! core radius(m)
    P_CORE = 400.0D0, ! core power (MWth)
    QPPP_AVG = 4.77689D6, ! averaged power density (W/m3)
    T_IRR = 1000.0D0, ! irradiation temperature (Celsius)
    IRRTIME = 936.0D0, ! irradiation time(Day)
    T_GASIN = 500.0D0, ! coolant inlet temperature (Celsius)
    T_GASOUT = 900.0D0, ! coolant outlet temperature (Celsius)
    MF_HE = 154.6D0, ! helium mass flow rate (kg/s)
    PEBRADIUS = 3.0D-2, ! pebble radius (m)
    PFZRADIUS = 2.5D-2, ! pebble fuel zone radius (m)
    NPEBBLE = 451600, ! number of pebbles in core
    NPARTICLE = 15000, ! number of particles per pebble
    DT = 7.2576D5, ! time step size (s)
    OUTTIME = 7.2576D5, ! time pebble is taken out of the core in each cycle (s)
    EOLBUP = 0.1D0, ! EOL burnup (FIMA)
    EOLFLU = 2.8D0, ! EOL fluence (10^21 n/cm^2)
    SHUFFLE = 6, ! number of fueling cycles
    FUELTYPE = 'UO2', ! fuel kernel type
    CURAT = 0.0D0, ! Carbon to Uranium ratio
    OURAT = 2.0D0, ! Oxygen to Uranium ratio
    U235ENR = 9.600D0, ! U235 enrichment (%)
    U235VAR = 0.1D0, ! standard deviation on U235 enrichment (%)
    KERND = 10.4D0, ! kernel density (g/cm^3)
    KERNDVAR = 0.01D0, ! standard deviation on kernel density (g/cm^3)
    KERNT = 10.95D0, ! kernel theoretical density (g/cm^3)
    KERNDIA = 500.0D0, ! kernel diameter (micron)
    KERNVAR = 20.0D0, ! standard deviation on kernel diameter (micron)
    BUFFD = 1.05D0, ! buffer density (g/cm^3)
    BUFFDVAR = 0.05D0, ! standard deviation on buffer density (g/cm^3)
    BUFFT = 2.25D0, ! buffer theoretical density (g/cm^3)
    BUFFTHK = 90.0D0, ! buffer thickness (micron)
    BUFFVAR = 18.0D0, ! standard deviation on buffer thickness (micron)
    IPYCBAF0I = 1.05788D0, ! IPyC as-fabricated BAF
    IPYCBAFVAR = 0.00543D0, ! standard deviation on IPyC as-fabricated BAF
    IPYCCRATE = 1.5D0, ! IPyC coating rate (micron/min)
    IPYCLC = 29.98D0, ! IPyC crystallite length (micron)
    IPYCD = 1.90D0, ! IPyC density (g/cm^3)
    IPYCF = 24.0D0, ! IPyC characteristic strength (MPa.m^3/modulus)
    IPYCM = 9.5D0, ! IPyC Weibull modulus
    IPYCTHK = 40.0D0, ! IPyC thickness (micron)
    IPYCVAR = 10.0D0, ! standard deviation on IPyC thickness (micron)
    OPYCBAF0I = 1.05788D0, ! OPyC as-fabricated BAF
    OPYCBAFVAR = 0.00543D0, ! standard deviation on OPyC as-fabricated BAF
    OPYCCRATE = 1.5D0, ! OPyC coating rate (micron/min)
    OPYCLC = 29.98D0, ! OPyC crystallite length (micron)
    OPYCD = 1.90D0, ! OPyC density (g/cm^3)
    OPYCF = 24.0D0, ! OPyC characteristic strength (MPa.m^3/modulus)
    OPYCM = 9.5D0, ! OPyC Weibull modulus
    OPYCTHK = 40.0D0, ! OPyC thickness (micron)
    OPYCVAR = 10.0D0, ! standard deviation on OPyC thickness (micron)
    SICTHK = 35.0D0, ! SiC thickness (micron)
    SICVAR = 4.0D0, ! standard deviation on SiC thickness (micron)
    SICF = 9.0D0, ! SiC characteristic strength (MPa.m^3/modulus)
    SICKIC0 = 4000.0D0, ! SiC fracture toughness (MPa.micron^1/2)
    SICKVAR = 530.72D0, ! standard deviation on SiC fracture toughness
    SICM = 6.0D0, ! SiC Weibull modulus
    PAMB = 0.10D0, ! ambient pressure (MPa)
    TITLE = 'Reference LEU TRISO fuel_DS MPBR2', ! particle description
    OSPEC = 'sMPBR2_DS', ! output file name
    DEBUG = .TRUE., ! flag for debugging
    ISEED = 30285171, ! initial seed for random number generator
    NBURP = 10000, ! send intermediate outputs for every NBURP sampled particles
    NCASES = 1000000, ! number of particles to be sampled
    NOMINAL = .FALSE., ! flag turning on/off Monte Carlo sampling
    DIFFUSION = .FALSE., ! flag turning on/off diffusion model for gas release
    HISTOGRAM = .TRUE., ! flag turning on/off histogram outputs
    RUNIRR = 'FAILURE', ! flag turning on/off fuel failure evaluation
    USERSEED = .TRUE., ! flag determining whether ISEED from users is used
$END
```

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