A behavioural study of fission products released into the helium coolant of the PBMR with special emphasis on Fresco-II and Spatra codes.

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Abstract

The fission products release rates into the helium coolant for the PBMR reactor, and their plate-out (sedimentation) were numerically calculated. These were done using the well known FRESCO-II and SPATRA codes respectively for both normal and upset operational conditions.

It was found that for the Ag-110m, under normal operating conditions, the release rate is higher than, for example, for Cs-134, Sr-90, I-131. The release of Ag-110m is comparably high due to its fast diffusion in the fuel element components and bad retention on graphite.

On the other hand the plate-out calculation show that Cs-137 has a higher plate-out. This is expected since it has strong chemisorption by the fuel element graphite. Moreover, it was found that more activity is obtained in the recuperator of reactor than in any other secondary part of the reactor. Finally, the two codes were linked for the purpose of producing a single consolidation code. The results show to be reliably reproduced and to be in agreement with the previously calculated ones.

Acknowledgement

I wish to express my gratitude to Moreosele 's family for their encouragement of study. I also appreciate my supervisors and the members of PBMR for useful comments on this study. A great deal of thanks is heartily given to Mr Lekala and his family for their hours of time, valued information, and advice. To all my friends, I gratefully acknowledge the help and advice you have given me.

A bopelotlhomogi jwa Morena wa rona Jesu Keresete bo nne le rona! Amen. Baroma 16:24

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Definition of terms

UNIT, ABBREVIATION OR ACRONYM	DESCRIPTION
AVR	Arbeitsgemeinschaft Versuchsreaktor (German for Jointly-operated Prototype Reactor)
CP	Coated Particle
CS	Core Structures
d	Day
DLOFC	Depressurized Loss of Forced Cooling
FS	Fuel Sphere
FZJ	Forschungszentrum Jülich GmbH (Jülich Research Centre)
G	Giga
Gen	Generator
GS	Graphite Sphere
GSC	Graphite Sphere Container
GenS	Generator System
GT	Gas Turbine
GT-MHR	Gas Turbine-Modular High Temperature Reactor
GW	Giga Watt
GWd/t	Giga Watt Days per Tonne
h	hour
H	Henry
He	Helium
HICS	Helium Inventory Control System
HP	High Pressure
HPC	High Pressure Compressor
HPS	Helium Purification System
HPT	High Pressure Turbine
HTR	High Temperature Reactor
HTR Modul	High Temperature Modular Reactor
ICS	Inter Cooling System
k	kilo

kg	Kilogramme
kg/s	Kilogram/Second
kJ	Kilojoule
Km	Kilometre
kV	Kilovolt
LOCA	Loss-of-coolant accident
LOFC	Loss of Forced Cooling
LP	Low Pressure
LPC	Low Pressure Compressor
LPT	Low-pressure Turbine
LPTC	Low Pressure Turbo-unit Compressor
LPTU	Low Pressure Turbo Unit
LPTV	Low Pressure Turbo Vessel
m	Metre
M	Mega
MCLR	Metallic Core Lateral Restraint
MCSS	Metallic Core Support Structure
MHTGR	Modular High Temperature Gas Cooled Reactor
min	Minute
mm	millimetre
MPS	Main Power System
NPP	Nuclear Power Plant
PB	Pressure Boundary
PBMR	Pebble Bed Modular Reactor
PCRV	Prestressed Concrete Reactor Vessel
PCS	Pressure Control System
PCU	Power Conversion Unit
PCUPS	Power Conversion Unit Pipe System
PCUPV	Power Conversion Unit Pressure Vessel
PLOFC	Pressurised Loss of Forced Cooling
PP	Power Plant
PT	Power Turbine
PTG	Power Turbine Generator
PTGS	Power Turbine Generator System
PyC	Pyrolytic Carbon

Ref	Reference
ROT	Average helium Reactor Outlet Temperature
RPV	Reactor Pressure Vessel
RV	Reactor Vessel
s	second
SF	Spent Fuel
SFT	Spent Fuel Tank
SiC	Silicon Carbide
Sv	Sievert
THTR	Thorium High Temperature Reactor
u	Atomic Mass Unit
U	Uranium
UF	Used Fuel
UFT	Used Fuel Tank
2D	Two-dimensional
3D	Three-dimensional

CHAPTER 1

INTRODUCTION

The Pebble Bed Modular Reactor (PBMR) is a graphite-moderated, helium-cooled reactor that uses the Brayton direct gas cycle to convert the heat into electrical energy by means of a gas turbo-generator [George 2001]. PBMR has unique features that make it ideal for use as a power source for economic development around the world. These include the small size, low cost and high efficiency, robust and inherent safe design, simplicity of operation, and potential application as a heat source as well as cheap generation of electricity.

1.1 Core structure

PBMR core is based on German high-temperature gas cooled technology, developed from 1969 to 1988. The core is the region which contains the nuclear fuel along with structural materials, moderator, and coolant [Holmes & Meghreblian 1960] The reactor core structure consists of the Ceramic core Reflector as shown in Figure 1-1. This core reflector structure consists of an inner cylinder of high-quality graphite blocks surrounded at the bottom and on the sides by carbon blocks. Its design philosophy is to ensure that individual columns can expand thermally and accommodate irradiation-induced dimensional changes, independent of adjacent columns, under all normal operating conditions and upset conditions. The ceramic core structure is divided into 3 sections [Mulder 2000]:

I. The bottom reflector structure, which supports the pebble bed. It provides direction, containment and separation of the inlet and outlet gas flow, and it also provides essential function of fuel discharge.

II. The side reflector structure, supports the pebble bed, and provides the flow passage for the inlet gas.

III. The top reflector structure, provides essential function for helium inlet control and distribution, and provides access for refueling points.

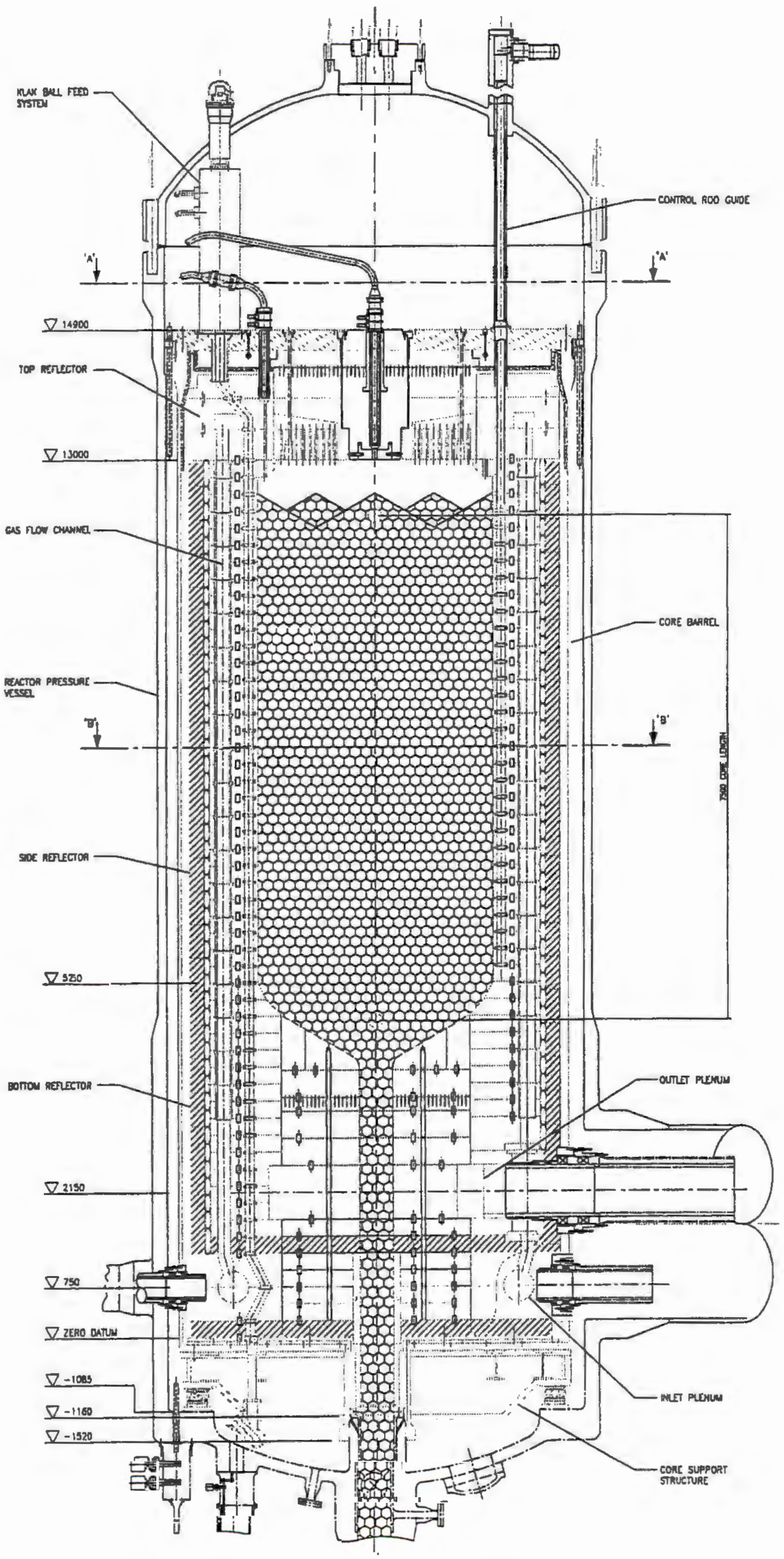

Figure 1-1:Reactor core structure

In the pebble bed version, the fuel uranium dioxide enriched in ^{238}U to 8% consists of particles coated with two layers of carbon and silicon carbide embedded in a carbon matrix, which act as the principal barrier against radioactive release as explained in details in chapter 2. The fission process is essential to the operation of nuclear reactors.

Fission product release behaviour under normal operating conditions is of significant interest to the design and safety analysis. Fission product activity is available as plate-out activity on surfaces of the helium circuit, dust-borne activity or coolant activity, providing potential significant exposure levels with a severe impact on maintenance procedure.

Plate-out is the natural process by which bits of fission products are gathered, moved around, and then left in a place by helium coolant. The condensable fission products may plate-out depending on the temperature, pressure and the helium gas mass flow. Plate-out rate is determined by mass transfer rates from coolant to exposed surfaces by the sorptivities of fission products on various materials of construction and by the temperature of operation [IAEA 1997].

PURPOSE OF STUDY

The inherent safe design of PBMR is made efficient by the two codes that have been extensively studied, namely FRESCO-II and SPATRA. The FRESCO-II code is used to calculate the release of fission products from single fuel sphere during irradiation (normal operation) and upset condition. On the other hand SPATRA code is used to determine the plate-out distribution of condensable fission products on various helium-wetted surfaces in the Power Conversion Unit (PCU).

The studies have lead to a great interest in research for further improvement in these codes. In addition, linking together of these codes in order to calculate plate-out distribution in PBMR is studied. However, linking these two codes has not yet been done, so this constitute a major part of this project in order to determine the theoretical and physical background of these codes and also to improve on them

CHAPTER 2

LITERATURE REVIEW

2.1 Pebbles

The first pebble bed fuel elements of German design produced on a large scale were loaded into the AVR in 1968. Development continued and culminated in proof tests performed in 1989 on fuel elements using LEU-TRISO coated particles. The fuel elements for the PBMR are equivalent to German fuel elements based on LEU-TRISO coated particles [Mannheim 1989].

In case of PBMR, the reactor core contains a load of 444 000 spheres, of which 334 000 are fuel spheres and the rest are graphite spheres. The latter serve as the additional nuclear moderator to the graphite blocks [Mulder 2000]. Graphite spheres are loaded into the centre of the reactor core to form a central graphite reflector. Fuel spheres are loaded around the periphery of the reactor core to form an annular fuel region around the central graphite reflector [Venter 2000].

The fuel sphere, shown in Figure 2-1 consists of 15 000 coated uranium dioxide particles. The fuel specifications are summerized in Table 2.1. Four coatings surround each uranium dioxide particle, and these coatings are discussed in subsections that follow below. The major advantage of these coated particles, is that nearly all the radioactive fission products which are created by fission of uranium in the particle, remain trapped inside the particle, even at high temperatures[Tennenbaum 2000].

2.1.1 Buffer layer

The buffer layer provides void volume for gaseous fission products, in order to limit the pressure build-up within the coated particle [George 2001]. It also accommodates any mechanical deformation that the uranium dioxide particle may undergo during the lifetime of the fuel.

2.1.2 Inner pyrolytic carbon layer (IPyC)

The inner high-density, layer of pyrolytic carbon forms the first pressure barrier against fission products pressure within the uranium dioxide particle, thereby reducing the pressure on the next layer (SiC) [George 2001].

2.1.3 Silicon carbide layer (SiC)

The SiC layer retains gaseous and other fission products. It also acts as the 'primary pressure vessel boundary' (such as the reactor pressure vessel encloses all main components of the primary system in an integrated design) within a coated particle [Bindon 1988, George 2001].

2.1.4 Outer pyrolytic carbon layer (OPyC)

The OPyC protects the SiC layer against damage in the fuel manufacturing process following the coating process. It also provides prestress on the outside of the SiC layer, due to shrinkage of OPyC under fast neutron irradiation during the fuel lifetime in the reactor core, thereby reducing the tensile stress in the SiC.

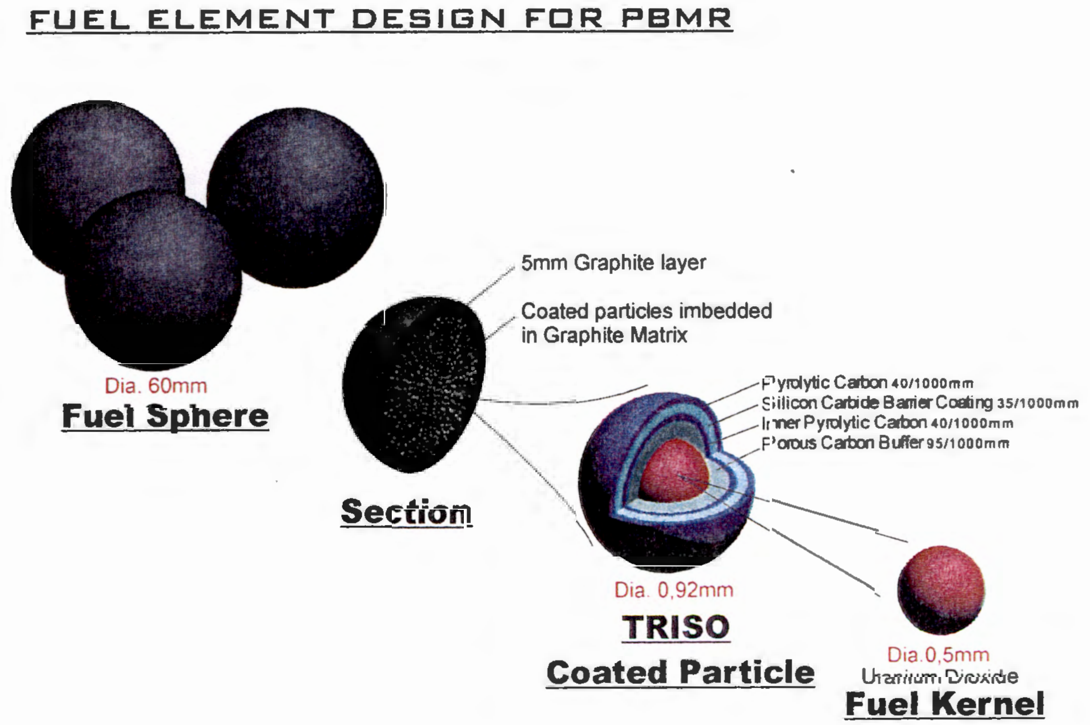

Figure 2-1:Fuel sphere

Description	**PBMR**	**Units**
Coated particle		
Particle diameter	500	μm
CP density	10.4	g/cm^3
Coating material	C/C/SiC/C	
Layer thickness	95/40/35/40	μm
Layer densities	1.05/1.90/3.18/1.90	g/cm^3

Table 2.1: Overview of PBMR coated particles

A single sphere circulates through the core on average ten cycles, that is, on average 874 days before the decision of whether to recirculate or discard is taken (1 cycle is equivalent to 8.74 days). When it had reached its maximum designed burn-up, which is mostly after the tenth cycle it, is discarded. For each nuclide the fractional release is determined for 10 cycles.

2.2 Nuclear Fission

Fission is caused by the absorption of a neutron, occurs with certain nuclei of high atomic number and mass number and hence the repulsive force within the nucleus is an important contributory factor. When fission takes place, the excited compound nucleus formed after absorption of a neutron breaks up into two lighter nuclei, called fission fragments, accompanied by the release of over 200 MeV of energy [Glasstone & Sesonke 1980].

The fission fragments undergo, on average, about four stages of radioactive decay before stable nuclei are formed. The general term fission product is applied to the complex, highly radioactive, mixture of nuclides consisting of the fission fragments and their various decay products [Glasstone 1956].

At the present, uranium is the most important element for the release of nuclear energy by fission. Only three nuclides, having sufficient stability to permit storage for a long time, namely, uranium-233, uranium-235, plutonium-239, are fissionable by neutrons of all energies. These nuclides are referred to as fissile nuclides. Of these nuclides, U-235 occurs in nature, the other two are produced artificially from thorium-232 and uranium-238 respectively. Naturally occurring Th-232 and U-238 undergo fission when bombarded with fast neutrons of energies greater than 0.7 and 1.7 MeV, respectively. At lower neutron energies, (n,γ) reaction followed by β-decays results in Pu-239 and U-233, both fissionable when bombarded with slow or fast neutrons [Wang 1974]. Figure 2-2 shows how the fission products formed.

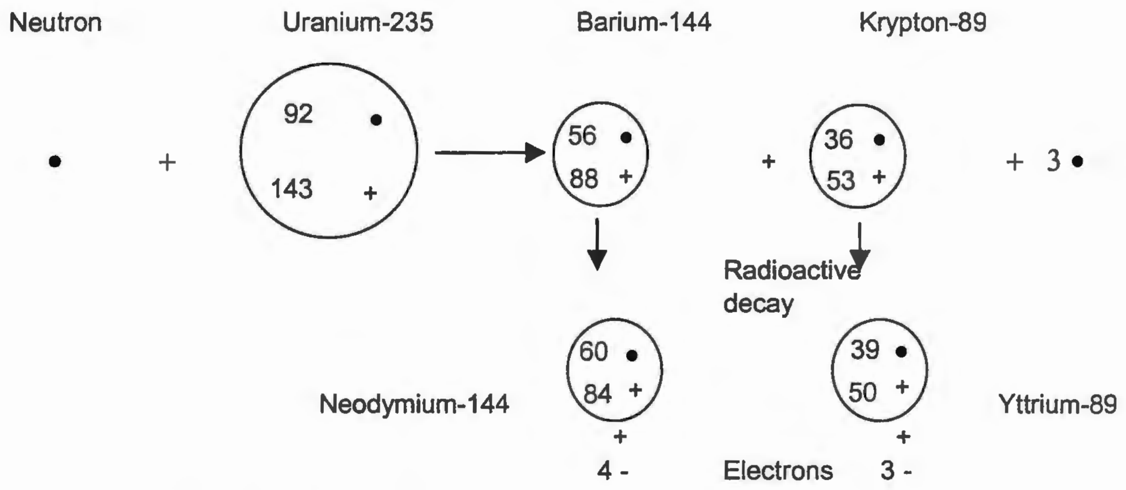

Figure 2-2: Fission of U^{235}

Moreover, since Th-232 and U-238 can be converted into the fissile species, U-233 and Pu-239, respectively, they are also called fertile nuclides.

$$U^{238}_{92} + \mathrm{n} \rightarrow U^{239}_{92} \qquad Th^{232}_{90} + \mathrm{n} \rightarrow Th^{233}_{90}$$

$$U^{239}_{92} \rightarrow Np^{239}_{93} + \mathrm{e} \qquad Th^{233}_{90} \rightarrow Pa^{233}_{91} + \mathrm{e}$$

$$Np^{239}_{93} \rightarrow Pu^{239}_{94} + \mathrm{e} \qquad Pa^{233}_{91} \rightarrow U^{233}_{92} + \mathrm{e}$$

In PBMR, the nuclear fission takes place in the coated particle. The PBMR core design is such that the controlled fission of atomic nuclei produces a self-sustaining or nuclear chain reaction. Pebbles containing uranium enriched to approximately 8% in U-235 prove this.

$n+U^{235} \rightarrow (U^{236}) \rightarrow Ba^{141}+Kr^{92}+3n, \ Q=200MeV$

$n+U^{235} \rightarrow (U^{236}) \rightarrow Sr^{94}+Xe^{140}+2n$

$n+U^{235} \rightarrow (U^{236}) \rightarrow Ba^{139}+Kr^{94}+3n$

Moreover, the reactor is continuously replenished with reusable fuel from the top of the reactor, while the used fuel is removed from the bottom. The pebbles are measured to determine the amount of fissionable material that is left after each cycle through the reactor core.

2.3 How the PBMR works

PBMR has been chosen helium as a coolant because of its advantages. The helium turbine is much more efficient than a steam-cycle turbine; helium has an exellent heat transfer capacity, which leads to high thermal efficiencies. Second, the speed of sound in helium is five times higher than it is in air, which translates into the possibility of higher rotational speeds, permitting the turbine units to be made much smaller and more compact. A third advantage is that helium is chemically and radiologically inert [Tennenbaum 2000].

Helium gas enters the reactor core at the top at 540°C and moves down ward between the hot fuel spheres. It carries along fission products and heat released from the fuel spheres (which have been produced by nuclear fission) into the Power Conversion Unit (PCU). The helium then leaves the reactor at a temperature of about 900°C [Bindon 1988], Figure 2-3 shows the flow of helium.

The helium then expands in the High Pressure Turbine (HPT). This turbine forms part of the High Pressure Turbo, which drives the High Pressure Compressor. The helium will flow through the Low Pressure Turbo Unit. The Low Pressure Turbine drives the Low Pressure Compressor.

The helium then expands in the Power Turbine, and this turbine drives the generator. At this point the helium is still at high temperature. It then flows through the primary side of the recuperator where it transfers heat to the low temperature gas returning to the reactor. The helium that passed through the primary side of the recuperator is then cooled by means of a pre-cooler. This increases the density of the helium and improves the efficiency of the compressor. The helium is then compressed by the Low Pressure Compressor.

The helium is then cooled in the inter-cooler. This process increases the density and improves the efficiency of the compressor. The High Pressure Compressor then compresses the helium. The cold, high-pressure helium steam then flows through the recuperator where it is pre-heated after which it returns to the reactor [Eskom webside].

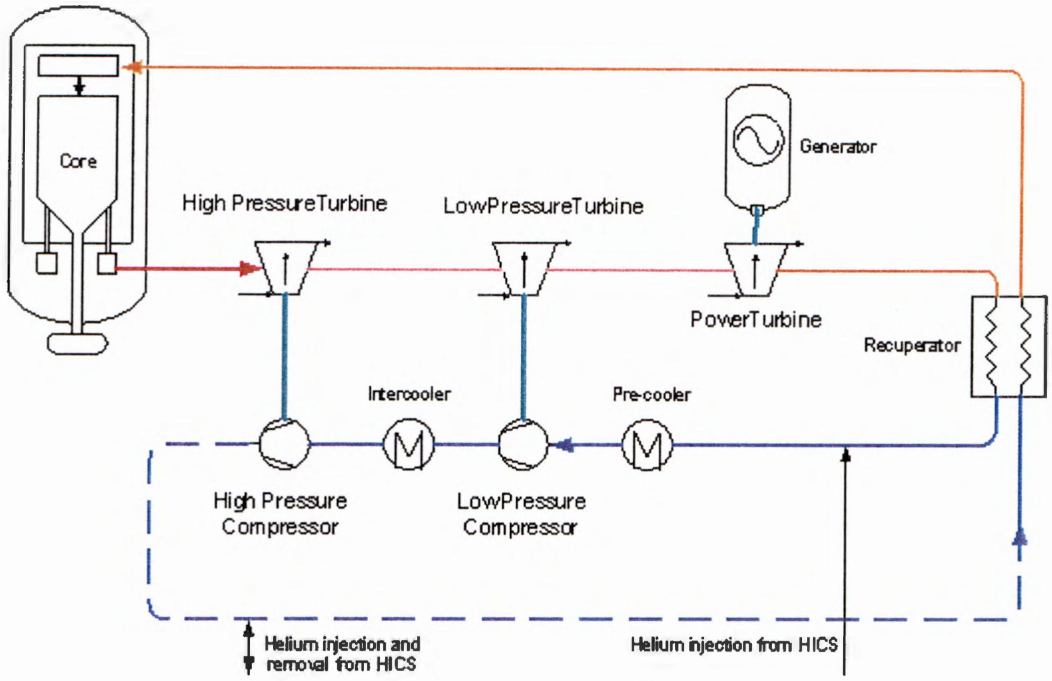

Figure 2-3: Brayton cycle (helium flow)

The PBMR as an example for future nuclear power stations, is completely different from conventional light water reactors. The only common feature of both systems is merely the nuclear fission by thermal neutrons. Apart from that they differ in [Baumer,Barnert…1990]:

- Fuel element, their construction, power density and resistance and fueling.
- Coolant, their state of aggregation and chemical reactivity

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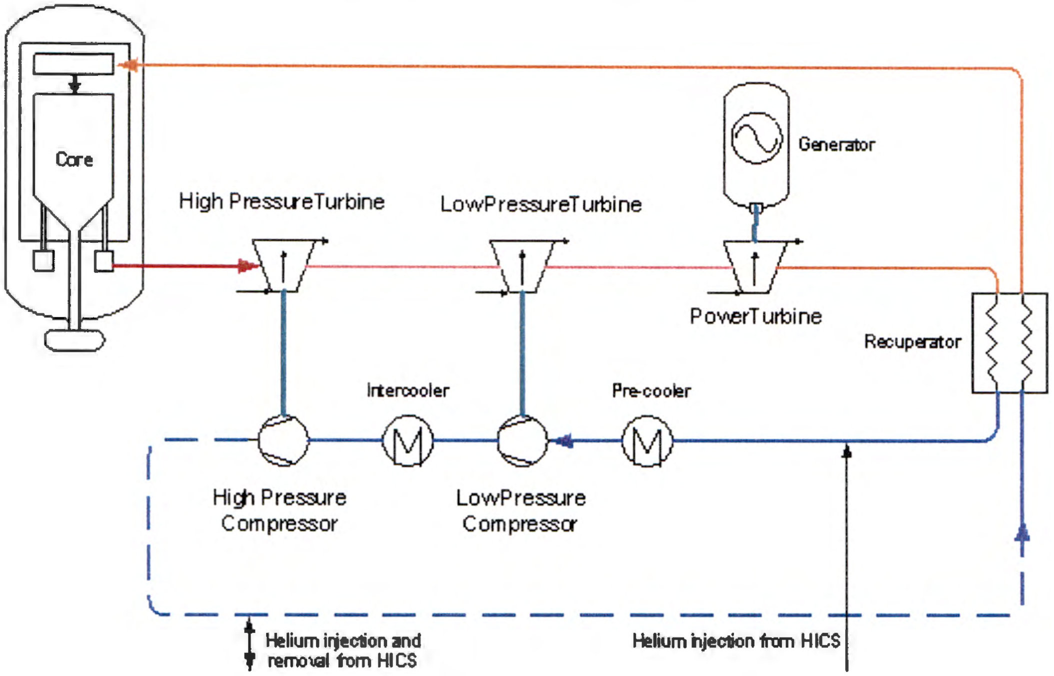

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- Fuel element, their construction, power density and resistance and fueling.
- Coolant, their state of aggregation and chemical reactivity

- Moderator, their construction and the available heat capacity,
- Power station process, their states of steaming and turbines.

The type of fuel particle failures which release fission products are generally placed into three categories: (1) cracked coatings which expose the kernel, (2) uranium contamination (including all uranium outside the kernel) and (3) particle with defective Sic layers [Wichner 1991]. [Moorman 1913]Studies reveal that the following nuclides have been identified as most important for HTR safety analysis: Sr-90, I-131, Cs-134, and Cs-137. In general, I-131 is most important for design and emergency planning (maximum individual doses are limiting factors), whereas Cs-137 dominates the consequences in realistic models (which are based on collective doses). By heating of irradiated HTR fuel elements, it was shown that a significant release of radiological important fission products might not happen at temperature <1600°C-1650°C [Moormann 1913].

Release of Kr-85 (which shows similar release behaviour as I-131) may be taken as an indicator for defective particle coatings, because its diffusion in intact coating is negligible but fast at 1600°C in particle kernels and no retention occurs in graphite [Schenk & Nabielek 1913]. The low release of Kr-85 indicates that all coatings remain intact during heating and that no defective particles by production or irradiation exist in that particular fuel element.

Cs and Sr diffuse slowly via intact coatings, and release is caused by interaction of fission products with the SiC layer and its eventual degradation. Beyond 200°C, thermal decomposition makes the fission product retaining SiC layer increasingly permeable, reaching complete SiC destruction at 2500°-2600°C. A large amount fraction of released Cs is, however, still retained within the graphite structure [Schenk & Nabielek 1913]. However, the strong chemisorptions of these elements by the fuel element graphite prevent a significant release, in particular for strontium. Release of Ag-110m is comparably high due to its fast diffusion in the fuel element components and bad retention on graphite and its amount in the fuel is small [Moormann 1913].

FRESCO-II CODE

The following are the assumptions embodied in the Fresco-II code:

- gases behaves as ideal gases,
- reactions between fission products are not important,
- reactions between fission products and coolant impurities are not important,
- diffusion rates of all isotopes of a given nuclide are the same,
- desorption and absorption of metallic fission products at the coolant-graphite surfaces can vary with fission product concentration, in accordance with empirical adsorption isotherms, and
- adsorption on graphite applies to fission-product metals,
- temperature difference between fuel particle and matrix graphite at a given location are very small relative to their influence on value of diffusion coefficients,
- the graphite matrix consists of graphite grains and graphite binder material

- a part of the uranium contamination in the graphite matrix is in the grains, with the remainder in the binder connecting the grains,
- fission products that escape the coated particles remain only in the binder, and do not enter the grains,
- fission product transport from the grains to the binder follow the relatively slow volume diffusion process, and
- fission product transport through the binder follows the relatively fast pore diffusion process [Mulder 1998].

2.1 Metallic fission product transport in graphite matrix

The metallic fission products from uranium contamination in the graphite are small compared with those arising from defective fuel particles. As a result, the release of metallic fission products during accident conditions because of fuel coating failures is much greater than that released from contamination.

For gaseous fission products, slow diffusion from the graphite grains to the binder material takes place due to high porosity existing in the binder, and gaseous fission products diffuse rapidly through the binder to the fuel element surface. After release from a given fuel element, the metallic fission products can be deposited on colder graphite surfaces and be re-adsorbed. In graphite, diffusion transport and adsorption is given by the following equation [Mulder 1998]:

$$\frac{\partial c}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Dr^2\frac{\partial c}{\partial r}\right) - \lambda c + Q \qquad (1)$$

Where

$c=c(r,t)$=fission product concentration in graphite, atoms/cc

r= radial co-ordinate, cm(r=zero at centre of fuel compact)

$D= D_{eff}$ diffusion coefficient, cm^2/s

t=time, s

λ=decay constant,1/s

Q=source term, atoms/cc-s

D_{eff} implies an effective value based on one-phase diffusion, which is equivalent to use of more basic diffusion coefficients in a complex mathematical system. D_{eff} comes from experimental measurements [Mulder 1998].

The boundary condition is given by:

$$-D_{eff} = \left(r^2 \frac{\partial c}{\partial r}\right)_{r=rp} = \beta\left(c_w - c_{00}\right) \qquad (2)$$

Where

β=empirical mass transfer coefficient, cm/s

c_w=fission product concentration in coolant at graphite surface,atom/cc

c_{00}=fission product concentration in main coolant.

The fission product concentration in the coolant next to the graphite(c_w) depends on the fission product concentration at the graphite surface(c_{gr}) and also on the temperature. C_{gr} is related to the adsorption isotherm as given by:

$$C_w=f(c_{gr}.T) \qquad (3)$$

Where

c_{gr}=fission product concentration in graphite surface,atom/cc

T=temperature,°K

The above diffusion model is generally used in calculations of the Cs and Sr release from fuel spheres during normal reactor operations.

2.2 Calculations within coated particles

The equation used to calculate fission product diffusion in coated fuel particle is:

$$\frac{\partial c}{\partial t} = div(D \bullet \nabla c) - \lambda c + Q \qquad (4)$$

Where

c=fission product concentration in the coated-fuel particle, atoms/cc

λ=decay constant,1/s

Q=production rate of fission products, atoms/cc-s

t=time, s

D=effective diffusion coefficient, cm^2/s

If c and D are dependent (only the radial position r) equation 4 can be written as:

$$\frac{\partial c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Dr^2\frac{\partial c}{\partial r}\right) - \lambda c + Q \qquad (5)$$

D is assumed to be independent of position within a given region for a given temperature. Under transient temperature conditions, d is considered to be constant within a given region for a given temperature, then equation 5 becomes equation 6:

$$\frac{\partial c}{\partial t} = D(T)\left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}\right) - \lambda c + Q \qquad (6)$$

The diffusion coefficient varies with temperature in accordance with the following Arrhenius relation:

$$D(T) = D_0 e(-{}^{A}\!/_{RT}) \qquad (7)$$

Where

D=diffusion coefficient at temperature T, cm^2/s

D_0=based diffusion coefficient at temperature $T=T_0$

A=Arrhenius activation energy, J/mol

R=gas constant, 8.3143J/°K-mol

T=temperature, °K

At coating layer boundaries, the rate of fission product transport from one layer to the adjacent one is equal to the amount transported into the adjacent layer is given by:

$$D_i\left(\frac{\partial c}{\partial r}\right)_{r_i} = D_{i+1}\left(\frac{\partial c}{\partial t}\right)_{r_i+1} \qquad (8)$$

Where

i refers to a given region boundary, and $i+1$ refers to the adjacent region boundary.

At the centre of the fuel kernel, the concentration is considered to be zero, therefore

$$\left(\frac{\partial c}{\partial r}\right)_{r=0}=0$$

The fission product release from the fuel kernel by diffusion is given by:

$$F_k=-4\pi D\left(r^2\frac{\partial c}{\partial r}\right)_{r=r_k} \tag{9}$$

Where

F_k=fission product release from kernel by diffusion, atom/s

r_k=outer radius of kernel

In general the fission product release from the coated-fuel particle by diffusion is given by:

$$F_p=-4\pi D\left(r^2\frac{\partial c}{\partial r}\right)_{r=A} \tag{10}$$

Where

r_p=outer radius of coated-fuel particle

The fission product concentration in the binder surrounding the coated particle is essentially equal to the concentration at the outer diameter of the fuel particle. As a result, the fission product concentration in the binder graphite surrounding the coated particle is:

$$c_b=c(r=r_p) \tag{11}$$

- they are formed in the outer fuel coating layer due to uranium contamination, and also escape the coating layer without diffusion,
- and they are formed in the outer fuel-free zone of the spherical fuel elements, and escape the fuel element without diffusion.

Recoil reactions are independent of temperature and decay constants. The relation for recoil release of fission products from the outer regions of a spherical region is given by:

$$\text{Release of fission products} = \frac{1}{2} - \frac{{R_0}^2 - R^2 - r^2}{4Rr} \qquad (12)$$

Where

R=recoil distance

R_0=outer diameter of spherical region

r=distance from centre to point in question

The recoil release rate, f_{rec}(atoms/s)is given by:

$$f_{rec} = Q\pi\left(R{R_0}^2 \frac{R^3}{12}\right) \qquad (13)$$

For intact particles, recoil release from the kernel is assumed to give a homogeneous source of fission products in the buffer region. For defective particles, the recoil fission product release from the kernel provides a source to the fuel element graphite binder.

The source term for recoil fission products from a given zone is given by:

$$Q_{Re2}=Q-f_{rec}/v_{Re2} \qquad (14)$$

Where

Q_{Re2}=source term for recoil fission products from a given outer spherical zone

V_{Re2}=volume of the recoil zone

Q=total source term

2.4 Volume diffusion in graphite grains

The following equation is used to calculate the transport of fission products from the graphite grains to the graphite binder material. Fission product transport is by diffusion in the grains calculated using equation (6).

At the surface of the graphite grains, the diffusion of fission products into the binder is given by:

$$F_c=-4\pi D\left(r^2\frac{\partial c}{\partial r}\right)_{r=r_c} \qquad (15)$$

Where

F_c=fission product release from a graphite grains by diffusion, atoms/s

r_c=outer radius of graphite grains

The diffusion of metallic fission products in the binder is controlled and calculated using the equation (6)

In the particle-containing region of the fuel element, the fission product release to the binder from the coated fuel particles and from the graphite grains is considered to provide a homogeneous source in the graphite binder. The source term Q is

$$Q=(1/v_{Be-CP})R_{particle} \qquad (16)$$

Where

Q=source term

v_{BE-CP}=volume of the particle containing zone of the fuel element

$R_{particle}$=release rate from coated particles plus that from graphite grains

At the boundary of the fuel element surface($r=r_{BE}$), the vapour pressure of the specific fission product is calculated from an adsorption isotherm and it gives the relation between the concentration of the specific fission product on the surface (c_w) and in the coolant boundary layer(c_g):

$$\ln p=(A+B/T)+(E+F/T).\ln c_w \qquad (17)$$

Where

p=partial pressure of the specific fission product in the coolant

c_w=concentration of the fission product on the surface

A,B,E,F=empirical constants

Since it is assumed that the fission product behaves as an ideal gas, then

$$P=10k.Tc_g \qquad (18)$$

Where

k=Boltzmann constant

T=temperature in °K

c_g=concentration of fission product in the coolant boundary layer.

The fission product from the boundary layer into the coolant is calculated from the relation:

$$j=\beta(ac_w-c_\infty) \qquad (19)$$

Where

j=fission product flux across surface boundary, cm^{-2}/s

a=fission product concentration in the centre of the coolant stream, cm^{-3}

β=mass transfer coefficient at surface boundary, cm/s

The previous equations can be used in the relation for transport of metallic fission products into the coolant from the surface of the fuel element given by:

$$D(\partial c/\partial r)r=r_{BE}=\beta(ac_w-c_\infty) \tag{20}$$

2.5 Sorption effects

The FRESCO-II code takes the sorption of metallic fission products on graphite as an important effect. At the gas/fuel element interface the transfer of the fission product is governed by a mass transfer equation of the form given above,

$$-D\frac{\partial c}{\partial t}=\beta(c_w-c_{00}) \tag{21}$$

Where, $\beta=\mu\alpha$

μ=mass transfer coefficient

α=sorption factor

c_w=concentration at the fuel element surface

To model sorption, α is a function of the concentration, when no sorption occurs, α is set equal to 1. if the concentration is low, the Henry regime is used to find α:

$$\alpha_{Henry} = \frac{1}{T}\exp\left(A_H + \frac{B_H}{T}\right) \qquad (22)$$

Where, A_H and B_H are coefficients

T=temperature

At high concentrations, the sorption enters the Freundlich regime:

$$\alpha_F = \frac{1}{T}\exp\left(A_F + \frac{B_F}{T} + D_F + \frac{E_F}{T}\right) In(c) \qquad (23)$$

where the subscript F refer to the Freundlich values

A_F,B_F,D_F,E_F are the sorption coefficients

c=concentration at the surface of the fuel element

Adsorption in the Freundlich regime has the effect of decreasing the mass transfer coefficient at the boundary layer and decreasing the release of fission products from the fuel elements at low temperatures.

SPATRA CODE

2.1 Adsorption on surfaces

Adsorption is the attachment of species (absorbate) to a surface (substrate or adsorbent). If the substrate-adsorbate interaction does not involve the formation of chemical bond, the process is called physiorption. If chemical bonds are formed, then the process is called chemisorption. The reverse of adsorption is called desorption.

The overall plate-out consist mainly of two different processes, ad/desorption and mass transfer to/from the gas bulk. The nuclides that are transported in a steam gas does not react chemically with other nuclides or wall materials, the mass transport equation is given by:

$$\frac{\partial C}{\partial t} + \frac{\partial (\nu C)}{\partial z} = \frac{U}{A}\left(j_{DES} - j_{ADS}\right) - \lambda C \qquad (1)$$

Where

j_{DES}=desorption mass flow density from the wall into the stream of gas

j_{ADS}=adsortion mass flow density which describe plate-out of the nuclides on the wall

U=circumference of gas channel

A=free flow cross-section

v=flow velocity

λ=constant for radioactive decay of the nuclide

C=atomic volume concentration, atoms/m^3

The following equation describe the mass equilibrium for surface concentration of the nuclide on the wall:

$$\frac{dC_w}{dt} = j_{ADS} - j_{DES} - j_w - \lambda C_w \qquad (2)$$

where

j_w=mass flow density of nuclide transport into the wall

C_w=atomic surface concentration, atoms/m^2

The mass flow rate into the wall is always nearly small in the metal surfaces compared to the desorption and adsorption mass flow rate. Transport into the wall is described by Fickian's diffusion using experimentally determined effective diffusion constants. The absorption mass flow rate is proportional to the nuclide concentration in the gas C_0 in area immediately above the wall surface, and the desorption mass flow rate is proportional to the surface concentration in area where the wall concentration is small (the so-called Henry area). A relationship between the wall concentrations of C_0 in the gas above the wall is given by:

$$j_{ADS}=j_{DES} \quad (3)$$

The above equation represents one form of the adsorption isotherm relationship between the wall and the gas concentrations. The adsorption rate is proportional to the number of molecules that occur on the surface per unit time. In terms of kinetic gas theory, this rate can be expressed as:

$$N=\frac{p}{\sqrt{2\pi mkT}} \quad (4)$$

where, p =partial pressure on the surface

m=molecular mass

The atomic adsorption mass flow density is applied as:

$$j_{ADS}=\alpha nN \quad (5)$$

where $\propto$ is proportionality factor which is designated as the condesation coefficient. If the partial pressure is replaced with the concentration on the surface, the following equation is obtained:

$$j_{ADS}=C_0 v_A \quad (5)$$

where v_A represent the following equation, which is the adsorption velocity:

$$v_A = \alpha\sqrt{\frac{kT}{2\pi m}} \qquad (6)$$

The desorption mass flow density in areas where the wall concentration is low is given by:

$$j_{DES} = f_D \exp\left\{-\frac{Q_D}{RT}\right\} C_w \qquad (7)$$

where

Q_D=activation energy for desorption

f_D=frequency factor

The relationship for adsorption isotherm in areas where the concentrations are small is given by:

$$\alpha\sqrt{\frac{kT}{2\pi m}} C_0 = f_D \exp\left\{-\frac{Q_D}{RT}\right\} C_w \qquad (8)$$

In case where the wall concentrations are high the desorption mass flow rate can be expressed as follows:

$$j_{DES} = f_D \exp\left\{-\frac{Q_D}{RT}\right\} \Phi(C_w) C_w \qquad (9)$$

When the adsorption and desorption process occurs in a system that is under pressure, the process can be hamperd by diffusion resistance in the gas as long as equilibrium is not reached. A boundary layer is formed on the wall, in which the nuclide concentration at the wall changes over to the concentration in the nuclear flow. This difference in concentration can be introduced to the relationship with the net mass flow density $j_{net}=j_{DES}-j_{ADS}$ by transfer coefficient h_M if the following formula is used:

$$h_M(C_0-C)=j_{net} \qquad (10)$$

where

C_0=nuclide concentration at the wall

C=concentration in the nuclear flow

2.2 Absorption

Absorption is the penetration of species into substrate. SPATRA is a simplified model for consideration of absorption process. A partition coefficient α is assumed between adsorption and absorption state. Another option for handling absorption is the penetration coefficient π_p. Absorption effects are experimentally confirmed to some extent to Cs. Diffusion profiles of Cs have been found within the oxide/metal layers of metals for some µm at temperature of 600-800°C for diffusion times in order of some 100-1000 h.

However, the absolute amount of fission products deeper than the first step of sectioning is very small, indicating that the absorbed fraction is probably much smaller than the adsorbed fraction.

2.3 Chemical reactions

The equilibrium equations for nuclides, which react chemically with each other, are represented by a system of differential equations, which are coupled chemical reaction rates. The compounds, which are formed on the walls, can have a low saturation pressure so that condensation effects occur where the thickness of the condensation films is not limited to a single or monolayer. When saturation pressure is exceeded, evaporation instead of desorption of the condensate film occurs.

Atomic iodine reacts with cesium to form cesium iodide and also react with iron to form iron iodide compounds. It also reacts with many metal wall materials to form metal iodide.

2.4 Nuclide transport in the wall

The nuclide transport in the wall is also described as Fick diffusion with effective diffusion constants. If nuclide concentration in the wall is C_w, then the transport is described by a differential equation:

$$\frac{\partial C_w}{\partial t}=\frac{\partial}{\partial r}\left(D_w\frac{\partial C_w}{\partial r}\right)-\lambda C_w \qquad (1)$$

Where r is a coordinate, which is at right angle to the channel axis. The diffusion mass flow rate on the outer surface of the wall which faces away from the channel, is made equal to zero, and on the inner wall surface the mass flow rate density is described by:

$$j_{w0}=h_E(C-C_{w1}) \tag{2}$$

Where

C=gas concentration

C_{w1}=wall concentration

r=δ, if δ represent the thickness of the boundary layer

C_{w1} is calculated from the constancy condition for the mass flow density at the boundary layer:

$$h_E(C-C_{w1})=-D_w\left(\frac{\partial C_w}{\partial r}\right)_{r=\delta} \tag{3}$$

h_E is an affective mass transfer coefficient, which is defined by the following:

$$\frac{1}{h_E}=\frac{1}{h_M}+\frac{1}{h_{0x}} \tag{4}$$

h_{0x} is mass transfer coefficient of the oxide layer, which may be present on the wall surface. h_M is the mass transfer coefficient, $h_M=\frac{D}{d_H}Sh$, where D is a binary diffusion coefficient of a given nuclide in helium, d_H is the hydraulic diameter, Sh represents a Sherwood number. The oxide coefficient is defined by:

$$h_{ox} = \frac{D_{ox}}{\delta_{0x}} \tag{5}$$

Where

D_{0x}=diffusion coefficient

δ_{0x}=thickness of oxide layer

The correlations for effective diffusion constants for graphite are more temperature dependent that the binary diffusion coefficient. This temperature dependence is represented in the form of:

$$D_w = D_{w0} \exp\left(-\frac{Q_w}{RT}\right) \tag{6}$$

Where

D_{w0}=constant parameter

Q_w=activation energy

A similar equation is usually used for the oxide layer [6].

CHAPTER 3

METHODOLOGY

As mentioned in previous chapter, Fresco-II code was used to calculate the fractional release of fission products from the fuel sphere. Since the release of fission products is from the fuel kernel, then this computer program calculates the release from fuel kernel→coated particle→graphite grains→fuel sphere as explained in details in Appendix A.

For calculational purposes the fuel region (in the reactor core) is further divided into four fuel channels. Proceeding outward from the fuel sphere surrounding the graphite spheres, these channels are known, as are fuel channel 1, fuel channel 2, fuel channel 3 and fuel channel

4. It takes 780 days for fission products to be released from channel 1 to channel 2, 780 days from channel 2 to channel 3 and 780 days from channel 3 to channel 4. The release rates were calculated by dividing the fractional release with time taken by the fission product to be released out of the fuel sphere. This was done for each fuel channel for all nuclides of interests as shown in chapter 4. For each nuclide the core inventory was calculated using the Origin code and the following equation was used to calculate the release rates (Bq/s):

Release rates(Bq/s)=Release rate × Core inventory(GBq)

CHAPTER 4

RESULTS

In this chapter, the results will be presented, and discussion of results is in chapter 5. **Table 4.1** show the release rates(atoms/s) of each nuclide in different channels.

		Cs-134	Cs-137	Sr-90	Ag-110m	I-131	I-134
Irradiation time	Channel	Release rate	Release rate	Release rate	Release rate	Release rate	Release rate
67392000	1	1.58E-15	1.58E-15	9.34E-18	3.45E-04	2.88E-17	2.88E-17
74131200	2	1.27E-14	1.27E-14	2.40E-17	2.60E-12	2.40E-17	2.40E-17
80870400	3	1.89E-14	1.89E-14	2.72E-17	5.78E-12	6.57E-17	6.57E-17
87609600	4	2.78E-14	2.78E-14	3.03E-17	1.21E-11	9.80E-17	9.80E-17
	Average	1.52E-14	1.52E-14	2.27E-17	5.12E-12	5.41E-17	5.41E-17
	Core inventory	1.18E+07	1.59E+07	1.49E+07	8.51E+04	2.64E+08	5.69E+08

Table 4.1: Release rates and core inventory

By using the equation in chapter 3, the release rates(Bq/s) were obtained as shown in Table 4.2

Nuclides	Release rates (Bq/s)
Cs-134	1.80E+02
Cs-137	2.42E+02
Sr-90	3.39E-01
Ag-110m	4.36E+02
I-131	1.43E+01
I-133	3.08E+01

Table 4.2: Release rates

The lifetime of PBMR is ~36 years, because of the continuous fuel loading and unloading, the plant would have to shutdown only 30-50 days once every six years for maintenance outages, according to the preliminary design plans. To keep the reactor safe, the plate-out is calculated after each 3 years. The following are the results obtained from Spatra code for 3 years to 36 years. The results of selected nuclides, due to their importance in the safety analysis and maintenance procedures are presented in Table 1-12.

Table 4.3: Expected plate-out in the PCU at 3 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	2.88E-03	5.94E-03	3.89E-04	3.23E-07	7.45E-08	2.38E-06
B	HPT Inlet Volute	3.53E-03	7.30E-03	4.78E-04	3.98E-07	9.16E-08	2.93E-06
150	HPT Intake	7.95E-04	1.64E-03	1.08E-04	8.95E-08	2.06E-08	6.60E-07
9	High Pressure Turbine	1.11E-03	2.29E-03	1.58E-04	1.24E-07	2.88E-08	9.21E-07
11	HPT Diffuser	6.75E-04	1.39E-03	1.01E-04	7.58E-08	1.77E-08	5.64E-07
D1	HPT Dump	1.62E-03	3.34E-03	2.48E-04	1.85E-07	4.31E-08	1.37E-06
13	* HPT Outlet Pipe	2.01E-03	4.15E-03	3.06E-04	2.28E-07	5.32E-08	1.70E-06
F	LPT Inlet Volute	1.02E-03	2.11E-03	1.55E-04	1.16E-07	2.70E-08	8.61E-07
152	LPT Intake	8.03E-04	1.66E-03	1.21E-04	9.02E-08	2.10E-08	6.71E-07
17	Low Pressure Turbine	9.51E-04	1.95E-03	2.22E-04	1.05E-07	2.52E-08	8.24E-07
19	LPT Diffuser	1.12E-03	2.26E-03	5.66E-04	1.19E-07	3.06E-08	1.09E-06
I1	LPT Dump	1.59E-03	3.18E-03	9.59E-04	1.69E-07	4.44E-08	1.63E-06
21	* LPT Outlet Pipe	2.05E-03	4.10E-03	1.23E-03	2.17E-07	5.70E-08	2.09E-06
L	PT Volute	7.19E-03	1.44E-02	4.32E-03	7.59E-07	2.00E-07	7.34E-06
27	PT Intake	1.51E-03	3.02E-03	9.08E-04	1.59E-07	4.19E-08	1.54E-06
29	Power Turbine	1.32E-02	2.32E-02	3.08E-02	9.04E-07	3.27E-07	2.22E-05
31	PT Diffuser	6.26E-02	1.09E-01	1.43E-01	6.97E-07	7.95E-07	2.01E-04
35	PT Outlet Contraction	2.07E-02	3.89E-02	3.46E-02	2.12E-07	2.97E-07	6.99E-05
P	Rec Inlet	1.52E-01	3.13E-01	1.79E-01	8.50E-05	3.08E-05	5.09E-04
39	Recuperator LP	9.57E+00	1.98E+01	1.13E+01	1.05E-02	2.43E-03	3.21E-02
R	Rec Outlet	3.77E-02	7.80E-02	4.46E-02	4.53E-05	9.68E-06	1.27E-04
158	RX(LP) to PC Connection	1.11E-02	2.29E-02	1.31E-02	1.33E-05	2.84E-06	3.71E-05
340	PC Inlet ducting	1.05E-02	2.17E-02	1.24E-02	1.26E-05	2.69E-06	3.52E-05
41	Pre-cooler bundle	1.29E+00	2.67E+00	1.52E+00	1.55E-03	3.31E-04	4.33E-03
47	PC Outlet ducting	1.01E-02	2.09E-02	1.19E-02	1.21E-05	2.59E-06	3.39E-05
51	LPC Intake	9.73E-04	2.01E-03	1.15E-03	1.17E-06	2.50E-07	3.27E-06
53	Low Pressure Compressor	4.71E-02	9.75E-02	5.57E-02	5.66E-05	1.21E-05	1.58E-04

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
55	LPC Diffuser	4.63E-03	9.59E-03	5.48E-03	5.56E-06	1.19E-06	1.56E-05
Y	LPC Dump	7.22E-03	1.49E-02	8.53E-03	8.67E-06	1.85E-06	2.42E-05
57	LPC Outlet Pipe	1.39E-02	2.87E-02	1.64E-02	1.67E-05	3.57E-06	4.67E-05
162	IC Inlet	1.62E-02	3.36E-02	1.92E-02	1.95E-05	4.17E-06	5.45E-05
61	Intercooler bundle	4.89E-01	1.01E+00	5.78E-01	5.88E-04	1.26E-04	1.64E-03
67	IC Outlet ducting	3.47E-03	7.17E-03	4.10E-03	4.16E-06	8.90E-07	1.16E-05
71	HPC Intake	1.22E-03	2.52E-03	1.44E-03	1.47E-06	3.13E-07	4.10E-06
73	High Pressure Compressor	2.27E-02	4.69E-02	2.68E-02	2.72E-05	5.82E-06	7.62E-05
75	HPC Diffuser	3.96E-04	8.20E-04	4.68E-04	4.76E-07	1.02E-07	1.33E-06
GG	HPC Dump	1.90E-03	3.94E-03	2.25E-03	2.29E-06	4.89E-07	6.39E-06
83	RX(HP) Inlet Pipes	8.57E-03	1.77E-02	1.01E-02	1.03E-05	2.20E-06	2.88E-05
338	RX Inlet header pipe	7.64E-03	1.58E-02	9.03E-03	9.18E-06	1.96E-06	2.57E-05
85	Recuperator HP	1.44E-01	2.97E-01	1.70E-01	1.72E-04	3.69E-05	4.82E-04
87	RX(HP) Outlet Pipes(a)	5.51E-04	1.12E-03	7.06E-04	3.92E-08	4.36E-08	1.86E-06
89	Core Inlet Pipes(e)	8.90E-04	1.71E-03	1.39E-03	8.77E-09	1.25E-08	3.01E-06
Total plate-out in the PCU		**1.20E+01**	**2.47E+01**	**1.42E+01**	**1.31E-02**	**3.01E-03**	**4.01E-02**

Table 4.4: Expected plate-out in the PCU at 6 years of PBMR normal operation

Elem	Description				GBQ		
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	3.94E-03	1.15E-02	4.07E-04	3.23E-07	7.45E-08	4.60E-06
B	HPT Inlet Volute	4.84E-03	1.41E-02	5.01E-04	3.98E-07	9.16E-08	5.66E-06
150	HPT Intake	1.09E-03	3.18E-03	1.13E-04	8.95E-08	2.06E-08	1.27E-06
9	High Pressure Turbine	1.52E-03	4.42E-03	1.65E-04	1.24E-07	2.88E-08	1.77E-06
11	HPT Diffuser	9.24E-04	2.69E-03	1.06E-04	7.58E-08	1.77E-08	1.08E-06
D1	HPT Dump	2.22E-03	6.46E-03	2.59E-04	1.85E-07	4.31E-08	2.64E-06
13	* HPT Outlet Pipe	2.76E-03	8.03E-03	3.19E-04	2.28E-07	5.32E-08	3.26E-06
F	LPT Inlet Volute	1.40E-03	4.07E-03	1.62E-04	1.16E-07	2.70E-08	1.65E-06
152	LPT Intake	1.10E-03	3.20E-03	1.26E-04	9.02E-08	2.10E-08	1.29E-06
17	Low Pressure Turbine	1.30E-03	3.75E-03	2.28E-04	1.05E-07	2.52E-08	1.54E-06
19	LPT Diffuser	1.51E-03	4.26E-03	5.73E-04	1.19E-07	3.06E-08	1.90E-06
I1	LPT Dump	2.13E-03	5.97E-03	9.69E-04	1.69E-07	4.44E-08	2.76E-06
21	* LPT Outlet Pipe	2.74E-03	7.69E-03	1.24E-03	2.17E-07	5.70E-08	3.55E-06
L	PT Volute	9.61E-03	2.70E-02	4.36E-03	7.59E-07	2.00E-07	1.24E-05
27	PT Intake	2.02E-03	5.67E-03	9.17E-04	1.59E-07	4.19E-08	2.61E-06
29	Power Turbine	1.60E-02	3.76E-02	3.09E-02	9.04E-07	3.27E-07	2.80E-05
31	PT Diffuser	6.56E-02	1.23E-01	1.45E-01	6.97E-07	7.95E-07	2.28E-04
35	PT Outlet Contraction	2.28E-02	4.92E-02	3.56E-02	2.12E-07	2.97E-07	9.23E-05
P	Rec Inlet	2.08E-01	6.06E-01	1.88E-01	8.50E-05	3.08E-05	9.83E-04
39	Recuperator LP	1.31E+01	3.84E+01	1.19E+01	1.05E-02	2.43E-03	6.22E-02
R	Rec Outlet	5.18E-02	1.51E-01	4.67E-02	4.53E-05	9.68E-06	2.45E-04
158	RX(LP) to PC Connection	1.52E-02	4.44E-02	1.37E-02	1.33E-05	2.84E-06	7.19E-05
340	PC Inlet ducting	1.44E-02	4.20E-02	1.30E-02	1.26E-05	2.69E-06	6.81E-05
41	Pre-cooler bundle	1.77E+00	5.18E+00	1.60E+00	1.55E-03	3.31E-04	8.39E-03
47	PC Outlet ducting	1.39E-02	4.05E-02	1.25E-02	1.21E-05	2.59E-06	6.56E-05
51	LPC Intake	1.34E-03	3.90E-03	1.21E-03	1.17E-06	2.50E-07	6.33E-06
53	Low Pressure Compressor	6.47E-02	1.89E-01	5.85E-02	5.66E-05	1.21E-05	3.07E-04

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
55	LPC Diffuser	6.36E-03	1.86E-02	5.75E-03	5.56E-06	1.19E-06	3.01E-05
Y	LPC Dump	9.91E-03	2.90E-02	8.95E-03	8.67E-06	1.85E-06	4.69E-05
57	LPC Outlet Pipe	1.91E-02	5.57E-02	1.72E-02	1.67E-05	3.57E-06	9.04E-05
162	IC Inlet	2.23E-02	6.51E-02	2.01E-02	1.95E-05	4.17E-06	1.06E-04
61	Intercooler bundle	6.72E-01	1.96E+00	6.07E-01	5.88E-04	1.26E-04	3.18E-03
67	IC Outlet ducting	4.76E-03	1.39E-02	4.30E-03	4.16E-06	8.90E-07	2.25E-05
71	HPC Intake	1.68E-03	4.89E-03	1.51E-03	1.47E-06	3.13E-07	7.94E-06
73	High Pressure Compressor	3.11E-02	9.10E-02	2.81E-02	2.72E-05	5.82E-06	1.48E-04
75	HPC Diffuser	5.44E-04	1.59E-03	4.91E-04	4.76E-07	1.02E-07	2.58E-06
GG	HPC Dump	2.61E-03	7.64E-03	2.36E-03	2.29E-06	4.89E-07	1.24E-05
83	RX(HP) Inlet Pipes	1.18E-02	3.44E-02	1.06E-02	1.03E-05	2.20E-06	5.57E-05
338	RX Inlet header pipe	1.05E-02	3.06E-02	9.47E-03	9.18E-06	1.96E-06	4.97E-05
85	Recuperator HP	1.97E-01	5.76E-01	1.78E-01	1.72E-04	3.69E-05	9.33E-04
87	RX(HP) Outlet Pipes(a)	7.15E-04	1.96E-03	7.37E-04	3.92E-08	4.36E-08	3.29E-06
89	Core Inlet Pipes(e)	1.01E-03	2.29E-03	1.44E-03	8.77E-09	1.25E-08	4.22E-06
Total plate-out in the PCU		**1.64E+01**	**4.78E+01**	**1.49E+01**	**1.31E-02**	**3.01E-03**	**7.74E-02**

Table 4.5: Expected plate-out in the PCU at 9 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.34E-03	1.67E-02	4.08E-04	3.23E-07	7.45E-08	6.66E-06
B	HPT Inlet Volute	5.33E-03	2.05E-02	5.02E-04	3.98E-07	9.16E-08	8.19E-06
150	HPT Intake	1.20E-03	4.61E-03	1.13E-04	8.95E-08	2.06E-08	1.84E-06
9	High Pressure Turbine	1.67E-03	6.42E-03	1.65E-04	1.24E-07	2.88E-08	2.56E-06
11	HPT Diffuser	1.02E-03	3.90E-03	1.06E-04	7.58E-08	1.77E-08	1.57E-06
D1	HPT Dump	2.44E-03	9.37E-03	2.59E-04	1.85E-07	4.31E-08	3.81E-06
13	* HPT Outlet Pipe	3.03E-03	1.16E-02	3.20E-04	2.28E-07	5.32E-08	4.71E-06
F	LPT Inlet Volute	1.54E-03	5.91E-03	1.62E-04	1.16E-07	2.70E-08	2.39E-06
152	LPT Intake	1.21E-03	4.64E-03	1.27E-04	9.02E-08	2.10E-08	1.86E-06
17	Low Pressure Turbine	1.42E-03	5.42E-03	2.28E-04	1.05E-07	2.52E-08	2.21E-06
19	LPT Diffuser	1.65E-03	6.13E-03	5.73E-04	1.19E-07	3.06E-08	2.64E-06
I1	LPT Dump	2.33E-03	8.57E-03	9.69E-04	1.69E-07	4.44E-08	3.81E-06
21	* LPT Outlet Pipe	3.00E-03	1.10E-02	1.24E-03	2.17E-07	5.70E-08	4.90E-06
L	PT Volute	1.05E-02	3.87E-02	4.37E-03	7.59E-07	2.00E-07	1.72E-05
27	PT Intake	2.21E-03	8.14E-03	9.17E-04	1.59E-07	4.19E-08	3.61E-06
29	Power Turbine	1.70E-02	5.09E-02	3.09E-02	9.04E-07	3.27E-07	3.33E-05
31	PT Diffuser	6.61E-02	1.30E-01	1.45E-01	6.97E-07	7.95E-07	2.34E-04
35	PT Outlet Contraction	2.31E-02	5.25E-02	3.56E-02	2.12E-07	2.97E-07	9.96E-05
P	Rec Inlet	2.28E-01	8.78E-01	1.89E-01	8.50E-05	3.08E-05	1.42E-03
39	Recuperator LP	1.45E+01	5.57E+01	1.19E+01	1.05E-02	2.43E-03	9.03E-02
R	Rec Outlet	5.70E-02	2.20E-01	4.69E-02	4.53E-05	9.68E-06	3.56E-04
158	RX(LP) to PC Connection	1.67E-02	6.44E-02	1.37E-02	1.33E-05	2.84E-06	1.04E-04
340	PC Inlet ducting	1.58E-02	6.10E-02	1.30E-02	1.26E-05	2.69E-06	9.88E-05
41	Pre-cooler bundle	1.95E+00	7.52E+00	1.60E+00	1.55E-03	3.31E-04	1.22E-02
47	PC Outlet ducting	1.53E-02	5.88E-02	1.25E-02	1.21E-05	2.59E-06	9.52E-05
51	LPC Intake	1.47E-03	5.67E-03	1.21E-03	1.17E-06	2.50E-07	9.18E-06
53	Low Pressure Compressor	7.12E-02	2.75E-01	5.86E-02	5.66E-05	1.21E-05	4.45E-04

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.00E-03	2.70E-02	5.76E-03	5.56E-06	1.19E-06	4.37E-05
Y	LPC Dump	1.09E-02	4.21E-02	8.97E-03	8.67E-06	1.85E-06	6.81E-05
57	LPC Outlet Pipe	2.10E-02	8.09E-02	1.73E-02	1.67E-05	3.57E-06	1.31E-04
162	IC Inlet	2.45E-02	9.46E-02	2.02E-02	1.95E-05	4.17E-06	1.53E-04
61	Intercooler bundle	7.40E-01	2.85E+00	6.08E-01	5.88E-04	1.26E-04	4.62E-03
67	IC Outlet ducting	5.24E-03	2.02E-02	4.31E-03	4.16E-06	8.90E-07	3.27E-05
71	HPC Intake	1.84E-03	7.11E-03	1.52E-03	1.47E-06	3.13E-07	1.15E-05
73	High Pressure Compressor	3.43E-02	1.32E-01	2.82E-02	2.72E-05	5.82E-06	2.14E-04
75	HPC Diffuser	5.99E-04	2.31E-03	4.92E-04	4.76E-07	1.02E-07	3.74E-06
GG	HPC Dump	2.88E-03	1.11E-02	2.37E-03	2.29E-06	4.89E-07	1.80E-05
83	RX(HP) Inlet Pipes	1.29E-02	4.99E-02	1.06E-02	1.03E-05	2.20E-06	8.08E-05
338	RX Inlet header pipe	1.15E-02	4.45E-02	9.50E-03	9.18E-06	1.96E-06	7.21E-05
85	Recuperator HP	2.17E-01	8.36E-01	1.78E-01	1.72E-04	3.69E-05	1.35E-03
87	RX(HP) Outlet Pipes(a)	7.67E-04	2.64E-03	7.39E-04	3.92E-08	4.36E-08	4.45E-06
89	Core Inlet Pipes(e)	1.03E-03	2.50E-03	1.44E-03	8.77E-09	1.25E-08	4.71E-06
Total plate-out in the PCU		**1.81E+01**	**6.94E+01**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**1.12E-01**

Table 4.6: Expected plate-out in the PCU at 12 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
7	* Core Outlet Pipe	4.49E-03	2.15E-02	4.08E-04	3.23E-07	7.45E-08	8.58E-06
B	HPT Inlet Volute	5.51E-03	2.64E-02	5.02E-04	3.98E-07	9.16E-08	1.06E-05
150	HPT Intake	1.24E-03	5.95E-03	1.13E-04	8.95E-08	2.06E-08	2.38E-06
9	High Pressure Turbine	1.73E-03	8.28E-03	1.65E-04	1.24E-07	2.88E-08	3.30E-06
11	HPT Diffuser	1.05E-03	5.03E-03	1.06E-04	7.58E-08	1.77E-08	2.02E-06
D1	HPT Dump	2.52E-03	1.21E-02	2.59E-04	1.85E-07	4.31E-08	4.91E-06
13	* HPT Outlet Pipe	3.14E-03	1.50E-02	3.20E-04	2.28E-07	5.32E-08	6.06E-06
F	LPT Inlet Volute	1.59E-03	7.62E-03	1.62E-04	1.16E-07	2.70E-08	3.07E-06
152	LPT Intake	1.25E-03	5.98E-03	1.27E-04	9.02E-08	2.10E-08	2.40E-06
17	Low Pressure Turbine	1.47E-03	6.99E-03	2.28E-04	1.05E-07	2.52E-08	2.83E-06
19	LPT Diffuser	1.70E-03	7.88E-03	5.73E-04	1.19E-07	3.06E-08	3.34E-06
I1	LPT Dump	2.40E-03	1.10E-02	9.69E-04	1.69E-07	4.44E-08	4.79E-06
21	* LPT Outlet Pipe	3.09E-03	1.42E-02	1.24E-03	2.17E-07	5.70E-08	6.16E-06
L	PT Volute	1.08E-02	4.97E-02	4.37E-03	7.59E-07	2.00E-07	2.16E-05
27	PT Intake	2.28E-03	1.04E-02	9.17E-04	1.59E-07	4.19E-08	4.53E-06
29	Power Turbine	1.74E-02	6.34E-02	3.09E-02	9.04E-07	3.27E-07	3.83E-05
31	PT Diffuser	6.63E-02	1.35E-01	1.45E-01	6.97E-07	7.95E-07	2.37E-04
35	PT Outlet Contraction	2.32E-02	5.41E-02	3.56E-02	2.12E-07	2.97E-07	1.02E-04
P	Rec Inlet	2.36E-01	1.13E+00	1.89E-01	8.50E-05	3.08E-05	1.83E-03
39	Recuperator LP	1.50E+01	7.19E+01	1.19E+01	1.05E-02	2.43E-03	1.16E-01
R	Rec Outlet	5.89E-02	2.83E-01	4.69E-02	4.53E-05	9.68E-06	4.58E-04
158	RX(LP) to PC Connection	1.73E-02	8.32E-02	1.37E-02	1.33E-05	2.84E-06	1.34E-04
340	PC Inlet ducting	1.64E-02	7.87E-02	1.30E-02	1.26E-05	2.69E-06	1.27E-04
41	Pre-cooler bundle	2.02E+00	9.70E+00	1.60E+00	1.55E-03	3.31E-04	1.57E-02
47	PC Outlet ducting	1.58E-02	7.59E-02	1.25E-02	1.21E-05	2.59E-06	1.23E-04
51	LPC Intake	1.52E-03	7.32E-03	1.21E-03	1.17E-06	2.50E-07	1.18E-05
53	Low Pressure Compressor	7.37E-02	3.54E-01	5.86E-02	5.66E-05	1.21E-05	5.73E-04

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.24E-03	3.48E-02	5.76E-03	5.56E-06	1.19E-06	5.64E-05
Y	LPC Dump	1.13E-02	5.43E-02	8.97E-03	8.67E-06	1.85E-06	8.78E-05
57	LPC Outlet Pipe	2.17E-02	1.04E-01	1.73E-02	1.67E-05	3.57E-06	1.69E-04
162	IC Inlet	2.54E-02	1.22E-01	2.02E-02	1.95E-05	4.17E-06	1.97E-04
61	Intercooler bundle	7.65E-01	3.68E+00	6.08E-01	5.88E-04	1.26E-04	5.95E-03
67	IC Outlet ducting	5.42E-03	2.61E-02	4.31E-03	4.16E-06	8.90E-07	4.21E-05
71	HPC Intake	1.91E-03	9.17E-03	1.52E-03	1.47E-06	3.13E-07	1.48E-05
73	High Pressure Compressor	3.54E-02	1.71E-01	2.82E-02	2.72E-05	5.82E-06	2.76E-04
75	HPC Diffuser	6.19E-04	2.98E-03	4.92E-04	4.76E-07	1.02E-07	4.82E-06
GG	HPC Dump	2.98E-03	1.43E-02	2.37E-03	2.29E-06	4.89E-07	2.31E-05
83	RX(HP) Inlet Pipes	1.34E-02	6.44E-02	1.06E-02	1.03E-05	2.20E-06	1.04E-04
338	RX Inlet header pipe	1.19E-02	5.75E-02	9.50E-03	9.18E-06	1.96E-06	9.29E-05
85	Recuperator HP	2.24E-01	1.08E+00	1.78E-01	1.72E-04	3.69E-05	1.74E-03
87	RX(HP) Outlet Pipes(a)	7.85E-04	3.21E-03	7.39E-04	3.92E-08	4.36E-08	5.43E-06
89	Core Inlet Pipes(e)	1.03E-03	2.59E-03	1.44E-03	8.77E-09	1.25E-08	4.92E-06
Total plate-out in the PCU		**1.87E+01**	**8.95E+01**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**1.45E-01**

Table 4.7: Expected plate-out in the PCU at 15 years of PBMR normal operation

Elem	Description			GBQ			
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.54E-03	2.60E-02	4.08E-04	3.23E-07	7.45E-08	1.04E-05
B	HPT Inlet Volute	5.58E-03	3.20E-02	5.02E-04	3.98E-07	9.16E-08	1.28E-05
150	HPT Intake	1.25E-03	7.19E-03	1.13E-04	8.95E-08	2.06E-08	2.87E-06
9	High Pressure Turbine	1.75E-03	1.00E-02	1.65E-04	1.24E-07	2.88E-08	3.99E-06
11	HPT Diffuser	1.06E-03	6.08E-03	1.06E-04	7.58E-08	1.77E-08	2.43E-06
D1	HPT Dump	2.56E-03	1.46E-02	2.59E-04	1.85E-07	4.31E-08	5.92E-06
13	* HPT Outlet Pipe	3.17E-03	1.82E-02	3.20E-04	2.28E-07	5.32E-08	7.32E-06
F	LPT Inlet Volute	1.61E-03	9.22E-03	1.62E-04	1.16E-07	2.70E-08	3.71E-06
152	LPT Intake	1.26E-03	7.24E-03	1.27E-04	9.02E-08	2.10E-08	2.90E-06
17	Low Pressure Turbine	1.49E-03	8.45E-03	2.28E-04	1.05E-07	2.52E-08	3.40E-06
19	LPT Diffuser	1.72E-03	9.51E-03	5.73E-04	1.19E-07	3.06E-08	3.98E-06
I1	LPT Dump	2.43E-03	1.33E-02	9.69E-04	1.69E-07	4.44E-08	5.71E-06
21	* LPT Outlet Pipe	3.13E-03	1.71E-02	1.24E-03	2.17E-07	5.70E-08	7.33E-06
L	PT Volute	1.10E-02	5.99E-02	4.37E-03	7.59E-07	2.00E-07	2.57E-05
27	PT Intake	2.31E-03	1.26E-02	9.17E-04	1.59E-07	4.19E-08	5.39E-06
29	Power Turbine	1.75E-02	7.51E-02	3.09E-02	9.04E-07	3.27E-07	4.30E-05
31	PT Diffuser	6.63E-02	1.40E-01	1.45E-01	6.97E-07	7.95E-07	2.39E-04
35	PT Outlet Contraction	2.32E-02	5.53E-02	3.56E-02	2.12E-07	2.97E-07	1.03E-04
P	Rec Inlet	2.39E-01	1.37E+00	1.89E-01	8.50E-05	3.08E-05	2.21E-03
39	Recuperator LP	1.51E+01	8.71E+01	1.19E+01	1.05E-02	2.43E-03	1.41E-01
R	Rec Outlet	5.96E-02	3.43E-01	4.69E-02	4.53E-05	9.68E-06	5.54E-04
158	RX(LP) to PC Connection	1.75E-02	1.01E-01	1.37E-02	1.33E-05	2.84E-06	1.63E-04
340	PC Inlet ducting	1.66E-02	9.53E-02	1.30E-02	1.26E-05	2.69E-06	1.54E-04
41	Pre-cooler bundle	2.04E+00	1.17E+01	1.60E+00	1.55E-03	3.31E-04	1.90E-02
47	PC Outlet ducting	1.60E-02	9.19E-02	1.25E-02	1.21E-05	2.59E-06	1.48E-04
51	LPC Intake	1.54E-03	8.86E-03	1.21E-03	1.17E-06	2.50E-07	1.43E-05
53	Low Pressure Compressor	7.45E-02	4.29E-01	5.86E-02	5.66E-05	1.21E-05	6.93E-04

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
55	LPC Diffuser	7.33E-03	4.22E-02	5.76E-03	5.56E-06	1.19E-06	6.81E-05
Y	LPC Dump	1.14E-02	6.57E-02	8.97E-03	8.67E-06	1.85E-06	1.06E-04
57	LPC Outlet Pipe	2.20E-02	1.26E-01	1.73E-02	1.67E-05	3.57E-06	2.04E-04
162	IC Inlet	2.57E-02	1.48E-01	2.02E-02	1.95E-05	4.17E-06	2.39E-04
61	Intercooler bundle	7.74E-01	4.45E+00	6.08E-01	5.88E-04	1.26E-04	7.19E-03
67	IC Outlet ducting	5.48E-03	3.15E-02	4.31E-03	4.16E-06	8.90E-07	5.09E-05
71	HPC Intake	1.93E-03	1.11E-02	1.52E-03	1.47E-06	3.13E-07	1.79E-05
73	High Pressure Compressor	3.59E-02	2.06E-01	2.82E-02	2.72E-05	5.82E-06	3.33E-04
75	HPC Diffuser	6.27E-04	3.61E-03	4.92E-04	4.76E-07	1.02E-07	5.82E-06
GG	HPC Dump	3.01E-03	1.73E-02	2.37E-03	2.29E-06	4.89E-07	2.80E-05
83	RX(HP) Inlet Pipes	1.35E-02	7.80E-02	1.06E-02	1.03E-05	2.20E-06	1.26E-04
338	RX Inlet header pipe	1.21E-02	6.95E-02	9.50E-03	9.18E-06	1.96E-06	1.12E-04
85	Recuperator HP	2.27E-01	1.31E+00	1.78E-01	1.72E-04	3.69E-05	2.11E-03
87	RX(HP) Outlet Pipes(a)	7.91E-04	3.72E-03	7.39E-04	3.92E-08	4.36E-08	6.27E-06
89	Core Inlet Pipes(e)	1.03E-03	2.63E-03	1.44E-03	8.77E-09	1.25E-08	5.01E-06
Total plate-out in the PCU		**1.89E+01**	**1.08E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**1.75E-01**

Table 4.9: Expected plate-out in the PCU at 21 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	3.42E-02	4.08E-04	3.23E-07	7.45E-08	1.36E-05
B	HPT Inlet Volute	5.61E-03	4.20E-02	5.02E-04	3.98E-07	9.16E-08	1.67E-05
150	HPT Intake	1.26E-03	9.45E-03	1.13E-04	8.95E-08	2.06E-08	3.76E-06
9	High Pressure Turbine	1.76E-03	1.32E-02	1.65E-04	1.24E-07	2.88E-08	5.22E-06
11	HPT Diffuser	1.07E-03	7.99E-03	1.06E-04	7.58E-08	1.77E-08	3.19E-06
D1	HPT Dump	2.57E-03	1.92E-02	2.59E-04	1.85E-07	4.31E-08	7.75E-06
13	* HPT Outlet Pipe	3.19E-03	2.39E-02	3.20E-04	2.28E-07	5.32E-08	9.58E-06
F	LPT Inlet Volute	1.62E-03	1.21E-02	1.62E-04	1.16E-07	2.70E-08	4.86E-06
152	LPT Intake	1.27E-03	9.50E-03	1.27E-04	9.02E-08	2.10E-08	3.79E-06
17	Low Pressure Turbine	1.50E-03	1.11E-02	2.28E-04	1.05E-07	2.52E-08	4.44E-06
19	LPT Diffuser	1.73E-03	1.24E-02	5.73E-04	1.19E-07	3.06E-08	5.15E-06
I1	LPT Dump	2.44E-03	1.74E-02	9.69E-04	1.69E-07	4.44E-08	7.35E-06
21	* LPT Outlet Pipe	3.14E-03	2.24E-02	1.24E-03	2.17E-07	5.70E-08	9.44E-06
L	PT Volute	1.10E-02	7.84E-02	4.37E-03	7.59E-07	2.00E-07	3.31E-05
27	PT Intake	2.32E-03	1.65E-02	9.17E-04	1.59E-07	4.19E-08	6.94E-06
29	Power Turbine	1.76E-02	9.61E-02	3.09E-02	9.04E-07	3.27E-07	5.13E-05
31	PT Diffuser	6.64E-02	1.49E-01	1.45E-01	6.97E-07	7.95E-07	2.43E-04
35	PT Outlet Contraction	2.32E-02	5.73E-02	3.56E-02	2.12E-07	2.97E-07	1.04E-04
P	Rec Inlet	2.40E-01	1.79E+00	1.89E-01	8.50E-05	3.08E-05	2.89E-03
39	Recuperator LP	1.52E+01	1.14E+02	1.19E+01	1.05E-02	2.43E-03	1.84E-01
R	Rec Outlet	6.00E-02	4.51E-01	4.69E-02	4.53E-05	9.68E-06	7.26E-04
158	RX(LP) to PC Connection	1.76E-02	1.32E-01	1.37E-02	1.33E-05	2.84E-06	2.13E-04
340	PC Inlet ducting	1.67E-02	1.25E-01	1.30E-02	1.26E-05	2.69E-06	2.02E-04
41	Pre-cooler bundle	2.05E+00	1.54E+01	1.60E+00	1.55E-03	3.31E-04	2.48E-02
47	PC Outlet ducting	1.61E-02	1.21E-01	1.25E-02	1.21E-05	2.59E-06	1.94E-04
51	LPC Intake	1.55E-03	1.16E-02	1.21E-03	1.17E-06	2.50E-07	1.87E-05
53	Low Pressure Compressor	7.50E-02	5.64E-01	5.86E-02	5.66E-05	1.21E-05	9.08E-04

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.37E-03	5.54E-02	5.76E-03	5.56E-06	1.19E-06	8.93E-05
Y	LPC Dump	1.15E-02	8.63E-02	8.97E-03	8.67E-06	1.85E-06	1.39E-04
57	LPC Outlet Pipe	2.21E-02	1.66E-01	1.73E-02	1.67E-05	3.57E-06	2.68E-04
162	IC Inlet	2.58E-02	1.94E-01	2.02E-02	1.95E-05	4.17E-06	3.13E-04
61	Intercooler bundle	7.79E-01	5.85E+00	6.08E-01	5.88E-04	1.26E-04	9.42E-03
67	IC Outlet ducting	5.51E-03	4.14E-02	4.31E-03	4.16E-06	8.90E-07	6.67E-05
71	HPC Intake	1.94E-03	1.46E-02	1.52E-03	1.47E-06	3.13E-07	2.35E-05
73	High Pressure Compressor	3.61E-02	2.71E-01	2.82E-02	2.72E-05	5.82E-06	4.37E-04
75	HPC Diffuser	6.30E-04	4.74E-03	4.92E-04	4.76E-07	1.02E-07	7.63E-06
GG	HPC Dump	3.03E-03	2.28E-02	2.37E-03	2.29E-06	4.89E-07	3.67E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.02E-01	1.06E-02	1.03E-05	2.20E-06	1.65E-04
338	RX Inlet header pipe	1.22E-02	9.14E-02	9.50E-03	9.18E-06	1.96E-06	1.47E-04
85	Recuperator HP	2.28E-01	1.72E+00	1.78E-01	1.72E-04	3.69E-05	2.76E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	4.58E-03	7.39E-04	3.92E-08	4.36E-08	7.70E-06
89	Core Inlet Pipes(e)	1.03E-03	2.70E-03	1.44E-03	8.77E-09	1.25E-08	5.08E-06
Total plate-out in the PCU		**1.90E+01**	**1.42E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**2.29E-01**

Table 4.9: Expected plate-out in the PCU at 21 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	3.42E-02	4.08E-04	3.23E-07	7.45E-08	1.36E-05
B	HPT Inlet Volute	5.61E-03	4.20E-02	5.02E-04	3.98E-07	9.16E-08	1.67E-05
150	HPT Intake	1.26E-03	9.45E-03	1.13E-04	8.95E-08	2.06E-08	3.76E-06
9	High Pressure Turbine	1.76E-03	1.32E-02	1.65E-04	1.24E-07	2.88E-08	5.22E-06
11	HPT Diffuser	1.07E-03	7.99E-03	1.06E-04	7.58E-08	1.77E-08	3.19E-06
D1	HPT Dump	2.57E-03	1.92E-02	2.59E-04	1.85E-07	4.31E-08	7.75E-06
13	* HPT Outlet Pipe	3.19E-03	2.39E-02	3.20E-04	2.28E-07	5.32E-08	9.58E-06
F	LPT Inlet Volute	1.62E-03	1.21E-02	1.62E-04	1.16E-07	2.70E-08	4.86E-06
152	LPT Intake	1.27E-03	9.50E-03	1.27E-04	9.02E-08	2.10E-08	3.79E-06
17	Low Pressure Turbine	1.50E-03	1.11E-02	2.28E-04	1.05E-07	2.52E-08	4.44E-06
19	LPT Diffuser	1.73E-03	1.24E-02	5.73E-04	1.19E-07	3.06E-08	5.15E-06
I1	LPT Dump	2.44E-03	1.74E-02	9.69E-04	1.69E-07	4.44E-08	7.35E-06
21	* LPT Outlet Pipe	3.14E-03	2.24E-02	1.24E-03	2.17E-07	5.70E-08	9.44E-06
L	PT Volute	1.10E-02	7.84E-02	4.37E-03	7.59E-07	2.00E-07	3.31E-05
27	PT Intake	2.32E-03	1.65E-02	9.17E-04	1.59E-07	4.19E-08	6.94E-06
29	Power Turbine	1.76E-02	9.61E-02	3.09E-02	9.04E-07	3.27E-07	5.13E-05
31	PT Diffuser	6.64E-02	1.49E-01	1.45E-01	6.97E-07	7.95E-07	2.43E-04
35	PT Outlet Contraction	2.32E-02	5.73E-02	3.56E-02	2.12E-07	2.97E-07	1.04E-04
P	Rec Inlet	2.40E-01	1.79E+00	1.89E-01	8.50E-05	3.08E-05	2.89E-03
39	Recuperator LP	1.52E+01	1.14E+02	1.19E+01	1.05E-02	2.43E-03	1.84E-01
R	Rec Outlet	6.00E-02	4.51E-01	4.69E-02	4.53E-05	9.68E-06	7.26E-04
158	RX(LP) to PC Connection	1.76E-02	1.32E-01	1.37E-02	1.33E-05	2.84E-06	2.13E-04
340	PC Inlet ducting	1.67E-02	1.25E-01	1.30E-02	1.26E-05	2.69E-06	2.02E-04
41	Pre-cooler bundle	2.05E+00	1.54E+01	1.60E+00	1.55E-03	3.31E-04	2.48E-02
47	PC Outlet ducting	1.61E-02	1.21E-01	1.25E-02	1.21E-05	2.59E-06	1.94E-04
51	LPC Intake	1.55E-03	1.16E-02	1.21E-03	1.17E-06	2.50E-07	1.87E-05
53	Low Pressure Compressor	7.50E-02	5.64E-01	5.86E-02	5.66E-05	1.21E-05	9.08E-04

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.37E-03	5.54E-02	5.76E-03	5.56E-06	1.19E-06	8.93E-05
Y	LPC Dump	1.15E-02	8.63E-02	8.97E-03	8.67E-06	1.85E-06	1.39E-04
57	LPC Outlet Pipe	2.21E-02	1.66E-01	1.73E-02	1.67E-05	3.57E-06	2.68E-04
162	IC Inlet	2.58E-02	1.94E-01	2.02E-02	1.95E-05	4.17E-06	3.13E-04
61	Intercooler bundle	7.79E-01	5.85E+00	6.08E-01	5.88E-04	1.26E-04	9.42E-03
67	IC Outlet ducting	5.51E-03	4.14E-02	4.31E-03	4.16E-06	8.90E-07	6.67E-05
71	HPC Intake	1.94E-03	1.46E-02	1.52E-03	1.47E-06	3.13E-07	2.35E-05
73	High Pressure Compressor	3.61E-02	2.71E-01	2.82E-02	2.72E-05	5.82E-06	4.37E-04
75	HPC Diffuser	6.30E-04	4.74E-03	4.92E-04	4.76E-07	1.02E-07	7.63E-06
GG	HPC Dump	3.03E-03	2.28E-02	2.37E-03	2.29E-06	4.89E-07	3.67E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.02E-01	1.06E-02	1.03E-05	2.20E-06	1.65E-04
338	RX Inlet header pipe	1.22E-02	9.14E-02	9.50E-03	9.18E-06	1.96E-06	1.47E-04
85	Recuperator HP	2.28E-01	1.72E+00	1.78E-01	1.72E-04	3.69E-05	2.76E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	4.58E-03	7.39E-04	3.92E-08	4.36E-08	7.70E-06
89	Core Inlet Pipes(e)	1.03E-03	2.70E-03	1.44E-03	8.77E-09	1.25E-08	5.08E-06
Total plate-out in the PCU		**1.90E+01**	**1.42E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**2.29E-01**

Table 4.10: Expected plate-out in the PCU at 24 years of PBMR normal operation

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	3.79E-02	4.08E-04	3.23E-07	7.45E-08	1.50E-05
B	HPT Inlet Volute	5.61E-03	4.65E-02	5.02E-04	3.98E-07	9.16E-08	1.85E-05
150	HPT Intake	1.26E-03	1.05E-02	1.13E-04	8.95E-08	2.06E-08	4.16E-06
9	High Pressure Turbine	1.76E-03	1.46E-02	1.65E-04	1.24E-07	2.88E-08	5.77E-06
11	HPT Diffuser	1.07E-03	8.85E-03	1.06E-04	7.58E-08	1.77E-08	3.52E-06
D1	HPT Dump	2.57E-03	2.13E-02	2.59E-04	1.85E-07	4.31E-08	8.57E-06
13	* HPT Outlet Pipe	3.19E-03	2.64E-02	3.20E-04	2.28E-07	5.32E-08	1.06E-05
F	LPT Inlet Volute	1.62E-03	1.34E-02	1.62E-04	1.16E-07	2.70E-08	5.37E-06
152	LPT Intake	1.27E-03	1.05E-02	1.27E-04	9.02E-08	2.10E-08	4.19E-06
17	Low Pressure Turbine	1.50E-03	1.23E-02	2.28E-04	1.05E-07	2.52E-08	4.91E-06
19	LPT Diffuser	1.73E-03	1.38E-02	5.73E-04	1.19E-07	3.06E-08	5.67E-06
I1	LPT Dump	2.44E-03	1.92E-02	9.69E-04	1.69E-07	4.44E-08	8.08E-06
21	* LPT Outlet Pipe	3.14E-03	2.47E-02	1.24E-03	2.17E-07	5.70E-08	1.04E-05
L	PT Volute	1.10E-02	8.67E-02	4.37E-03	7.59E-07	2.00E-07	3.64E-05
27	PT Intake	2.32E-03	1.82E-02	9.17E-04	1.59E-07	4.19E-08	7.64E-06
29	Power Turbine	1.76E-02	1.06E-01	3.09E-02	9.04E-07	3.27E-07	5.51E-05
31	PT Diffuser	6.64E-02	1.53E-01	1.45E-01	6.97E-07	7.95E-07	2.44E-04
35	PT Outlet Contraction	2.32E-02	5.81E-02	3.56E-02	2.12E-07	2.97E-07	1.05E-04
P	Rec Inlet	2.40E-01	1.97E+00	1.89E-01	8.50E-05	3.08E-05	3.19E-03
39	Recuperator LP	1.52E+01	1.27E+02	1.19E+01	1.05E-02	2.43E-03	2.04E-01
R	Rec Outlet	6.00E-02	4.99E-01	4.69E-02	4.53E-05	9.68E-06	8.03E-04
158	RX(LP) to PC Connection	1.76E-02	1.46E-01	1.37E-02	1.33E-05	2.84E-06	2.36E-04
340	PC Inlet ducting	1.67E-02	1.39E-01	1.30E-02	1.26E-05	2.69E-06	2.23E-04
41	Pre-cooler bundle	2.05E+00	1.71E+01	1.60E+00	1.55E-03	3.31E-04	2.75E-02
47	PC Outlet ducting	1.61E-02	1.34E-01	1.25E-02	1.21E-05	2.59E-06	2.15E-04
51	LPC Intake	1.55E-03	1.29E-02	1.21E-03	1.17E-06	2.50E-07	2.07E-05
53	Low Pressure Compressor	7.50E-02	6.24E-01	5.86E-02	5.66E-05	1.21E-05	1.00E-03

Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.38E-03	6.14E-02	5.76E-03	5.56E-06	1.19E-06	9.87E-05
Y	LPC Dump	1.15E-02	9.56E-02	8.97E-03	8.67E-06	1.85E-06	1.54E-04
57	LPC Outlet Pipe	2.21E-02	1.84E-01	1.73E-02	1.67E-05	3.57E-06	2.96E-04
162	IC Inlet	2.59E-02	2.15E-01	2.02E-02	1.95E-05	4.17E-06	3.46E-04
61	Intercooler bundle	7.79E-01	6.48E+00	6.08E-01	5.88E-04	1.26E-04	1.04E-02
67	IC Outlet ducting	5.52E-03	4.59E-02	4.31E-03	4.16E-06	8.90E-07	7.38E-05
71	HPC Intake	1.94E-03	1.62E-02	1.52E-03	1.47E-06	3.13E-07	2.60E-05
73	High Pressure Compressor	3.61E-02	3.00E-01	2.82E-02	2.72E-05	5.82E-06	4.83E-04
75	HPC Diffuser	6.31E-04	5.25E-03	4.92E-04	4.76E-07	1.02E-07	8.44E-06
GG	HPC Dump	3.03E-03	2.52E-02	2.37E-03	2.29E-06	4.89E-07	4.06E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.13E-01	1.06E-02	1.03E-05	2.20E-06	1.82E-04
338	RX Inlet header pipe	1.22E-02	1.01E-01	9.50E-03	9.18E-06	1.96E-06	1.63E-04
85	Recuperator HP	2.29E-01	1.90E+00	1.78E-01	1.72E-04	3.69E-05	3.06E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	4.96E-03	7.39E-04	3.92E-08	4.36E-08	8.31E-06
89	Core Inlet Pipes(e)	1.03E-03	2.72E-03	1.44E-03	8.77E-09	1.25E-08	5.09E-06
Total plate-out in the PCU		**1.90E+01**	**1.58E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**2.53E-01**

Table 4.11: Expected plate-out in the PCU at 27 years of PBMR normal operation:

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	4.13E-02	4.08E-04	3.23E-07	7.45E-08	1.64E-05
B	HPT Inlet Volute	5.61E-03	5.07E-02	5.02E-04	3.98E-07	9.16E-08	2.01E-05
150	HPT Intake	1.26E-03	1.14E-02	1.13E-04	8.95E-08	2.06E-08	4.53E-06
9	High Pressure Turbine	1.76E-03	1.59E-02	1.65E-04	1.24E-07	2.88E-08	6.29E-06
11	HPT Diffuser	1.07E-03	9.65E-03	1.06E-04	7.58E-08	1.77E-08	3.84E-06
D1	HPT Dump	2.57E-03	2.32E-02	2.59E-04	1.85E-07	4.31E-08	9.34E-06
13	* HPT Outlet Pipe	3.20E-03	2.88E-02	3.20E-04	2.28E-07	5.32E-08	1.15E-05
F	LPT Inlet Volute	1.62E-03	1.46E-02	1.62E-04	1.16E-07	2.70E-08	5.85E-06
152	LPT Intake	1.27E-03	1.15E-02	1.27E-04	9.02E-08	2.10E-08	4.56E-06
17	Low Pressure Turbine	1.50E-03	1.34E-02	2.28E-04	1.05E-07	2.52E-08	5.34E-06
19	LPT Diffuser	1.73E-03	1.50E-02	5.73E-04	1.19E-07	3.06E-08	6.15E-06
I1	LPT Dump	2.44E-03	2.09E-02	9.69E-04	1.69E-07	4.44E-08	8.76E-06
21	* LPT Outlet Pipe	3.15E-03	2.70E-02	1.24E-03	2.17E-07	5.70E-08	1.13E-05
L	PT Volute	1.10E-02	9.45E-02	4.37E-03	7.59E-07	2.00E-07	3.95E-05
27	PT Intake	2.32E-03	1.99E-02	9.17E-04	1.59E-07	4.19E-08	8.29E-06
29	Power Turbine	1.76E-02	1.14E-01	3.09E-02	9.04E-07	3.27E-07	5.86E-05
31	PT Diffuser	6.64E-02	1.57E-01	1.45E-01	6.97E-07	7.95E-07	2.46E-04
35	PT Outlet Contraction	2.32E-02	5.90E-02	3.56E-02	2.12E-07	2.97E-07	1.05E-04
P	Rec Inlet	2.41E-01	2.15E+00	1.89E-01	8.50E-05	3.08E-05	3.47E-03
39	Recuperator LP	1.52E+01	1.38E+02	1.19E+01	1.05E-02	2.43E-03	2.22E-01
R	Rec Outlet	6.00E-02	5.44E-01	4.69E-02	4.53E-05	9.68E-06	8.75E-04
158	RX(LP) to PC Connection	1.76E-02	1.60E-01	1.37E-02	1.33E-05	2.84E-06	2.57E-04
340	PC Inlet ducting	1.67E-02	1.51E-01	1.30E-02	1.26E-05	2.69E-06	2.43E-04
41	Pre-cooler bundle	2.05E+00	1.86E+01	1.60E+00	1.55E-03	3.31E-04	2.99E-02
47	PC Outlet ducting	1.61E-02	1.46E-01	1.25E-02	1.21E-05	2.59E-06	2.34E-04
51	LPC Intake	1.55E-03	1.41E-02	1.21E-03	1.17E-06	2.50E-07	2.26E-05
53	Low Pressure Compressor	7.51E-02	6.81E-01	5.86E-02	5.66E-05	1.21E-05	1.09E-03

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
55	LPC Diffuser	7.38E-03	6.69E-02	5.76E-03	5.56E-06	1.19E-06	1.08E-04
Y	LPC Dump	1.15E-02	1.04E-01	8.97E-03	8.67E-06	1.85E-06	1.68E-04
57	LPC Outlet Pipe	2.21E-02	2.01E-01	1.73E-02	1.67E-05	3.57E-06	3.22E-04
162	IC Inlet	2.59E-02	2.35E-01	2.02E-02	1.95E-05	4.17E-06	3.77E-04
61	Intercooler bundle	7.79E-01	7.07E+00	6.08E-01	5.88E-04	1.26E-04	1.14E-02
67	IC Outlet ducting	5.52E-03	5.01E-02	4.31E-03	4.16E-06	8.90E-07	8.04E-05
71	HPC Intake	1.94E-03	1.76E-02	1.52E-03	1.47E-06	3.13E-07	2.83E-05
73	High Pressure Compressor	3.61E-02	3.28E-01	2.82E-02	2.72E-05	5.82E-06	5.26E-04
75	HPC Diffuser	6.31E-04	5.72E-03	4.92E-04	4.76E-07	1.02E-07	9.19E-06
GG	HPC Dump	3.03E-03	2.75E-02	2.37E-03	2.29E-06	4.89E-07	4.42E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.24E-01	1.06E-02	1.03E-05	2.20E-06	1.99E-04
338	RX Inlet header pipe	1.22E-02	1.10E-01	9.50E-03	9.18E-06	1.96E-06	1.77E-04
85	Recuperator HP	2.29E-01	2.07E+00	1.78E-01	1.72E-04	3.69E-05	3.33E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	5.30E-03	7.39E-04	3.92E-08	4.36E-08	8.87E-06
89	Core Inlet Pipes(e)	1.03E-03	2.74E-03	1.44E-03	8.77E-09	1.25E-08	5.11E-06
Total plate-out in the PCU		**1.90E+01**	**1.72E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**2.75E-01**

Table 4.12: Expected plate-out in the PCU at 30 years of PBMR normal operation:

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	4.45E-02	4.08E-04	3.23E-07	7.45E-08	1.76E-05
B	HPT Inlet Volute	5.61E-03	5.46E-02	5.02E-04	3.98E-07	9.16E-08	2.17E-05
150	HPT Intake	1.26E-03	1.23E-02	1.13E-04	8.95E-08	2.06E-08	4.87E-06
9	High Pressure Turbine	1.76E-03	1.71E-02	1.65E-04	1.24E-07	2.88E-08	6.77E-06
11	HPT Diffuser	1.07E-03	1.04E-02	1.06E-04	7.58E-08	1.77E-08	4.13E-06
D1	HPT Dump	2.57E-03	2.50E-02	2.59E-04	1.85E-07	4.31E-08	1.00E-05
13	* HPT Outlet Pipe	3.20E-03	3.10E-02	3.20E-04	2.28E-07	5.32E-08	1.24E-05
F	LPT Inlet Volute	1.62E-03	1.57E-02	1.62E-04	1.16E-07	2.70E-08	6.30E-06
152	LPT Intake	1.27E-03	1.24E-02	1.27E-04	9.02E-08	2.10E-08	4.91E-06
17	Low Pressure Turbine	1.50E-03	1.44E-02	2.28E-04	1.05E-07	2.52E-08	5.74E-06
19	LPT Diffuser	1.73E-03	1.62E-02	5.73E-04	1.19E-07	3.06E-08	6.60E-06
I1	LPT Dump	2.44E-03	2.25E-02	9.69E-04	1.69E-07	4.44E-08	9.40E-06
21	* LPT Outlet Pipe	3.15E-03	2.90E-02	1.24E-03	2.17E-07	5.70E-08	1.21E-05
L	PT Volute	1.10E-02	1.02E-01	4.37E-03	7.59E-07	2.00E-07	4.24E-05
27	PT Intake	2.32E-03	2.14E-02	9.17E-04	1.59E-07	4.19E-08	8.89E-06
29	Power Turbine	1.76E-02	1.23E-01	3.09E-02	9.04E-07	3.27E-07	6.18E-05
31	PT Diffuser	6.64E-02	1.60E-01	1.45E-01	6.97E-07	7.95E-07	2.47E-04
35	PT Outlet Contraction	2.32E-02	5.97E-02	3.56E-02	2.12E-07	2.97E-07	1.05E-04
P	Rec Inlet	2.41E-01	2.31E+00	1.89E-01	8.50E-05	3.08E-05	3.73E-03
39	Recuperator LP	1.52E+01	1.49E+02	1.19E+01	1.05E-02	2.43E-03	2.39E-01
R	Rec Outlet	6.00E-02	5.87E-01	4.69E-02	4.53E-05	9.68E-06	9.42E-04
158	RX(LP) to PC Connection	1.76E-02	1.72E-01	1.37E-02	1.33E-05	2.84E-06	2.76E-04
340	PC Inlet ducting	1.67E-02	1.63E-01	1.30E-02	1.26E-05	2.69E-06	2.62E-04
41	Pre-cooler bundle	2.05E+00	2.01E+01	1.60E+00	1.55E-03	3.31E-04	3.22E-02
47	PC Outlet ducting	1.61E-02	1.57E-01	1.25E-02	1.21E-05	2.59E-06	2.52E-04
51	LPC Intake	1.55E-03	1.51E-02	1.21E-03	1.17E-06	2.50E-07	2.43E-05
53	Low Pressure Compressor	7.51E-02	7.34E-01	5.86E-02	5.66E-05	1.21E-05	1.18E-03

Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
55	LPC Diffuser	7.38E-03	7.21E-02	5.76E-03	5.56E-06	1.19E-06	1.16E-04
Y	LPC Dump	1.15E-02	1.12E-01	8.97E-03	8.67E-06	1.85E-06	1.80E-04
57	LPC Outlet Pipe	2.21E-02	2.16E-01	1.73E-02	1.67E-05	3.57E-06	3.47E-04
162	IC Inlet	2.59E-02	2.53E-01	2.02E-02	1.95E-05	4.17E-06	4.06E-04
61	Intercooler bundle	7.79E-01	7.62E+00	6.08E-01	5.88E-04	1.26E-04	1.22E-02
67	IC Outlet ducting	5.52E-03	5.39E-02	4.31E-03	4.16E-06	8.90E-07	8.66E-05
71	HPC Intake	1.94E-03	1.90E-02	1.52E-03	1.47E-06	3.13E-07	3.05E-05
73	High Pressure Compressor	3.61E-02	3.53E-01	2.82E-02	2.72E-05	5.82E-06	5.67E-04
75	HPC Diffuser	6.31E-04	6.17E-03	4.92E-04	4.76E-07	1.02E-07	9.90E-06
GG	HPC Dump	3.03E-03	2.96E-02	2.37E-03	2.29E-06	4.89E-07	4.76E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.33E-01	1.06E-02	1.03E-05	2.20E-06	2.14E-04
338	RX Inlet header pipe	1.22E-02	1.19E-01	9.50E-03	9.18E-06	1.96E-06	1.91E-04
85	Recuperator HP	2.29E-01	2.23E+00	1.78E-01	1.72E-04	3.69E-05	3.58E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	5.62E-03	7.39E-04	3.92E-08	4.36E-08	9.38E-06
89	Core Inlet Pipes(e)	1.03E-03	2.77E-03	1.44E-03	8.77E-09	1.25E-08	5.12E-06
Total plate-out in the PCU		**1.90E+01**	**1.85E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**2.96E-01**

Table 4.13: Expected plate-out in the PCU at 33 years of PBMR normal operation

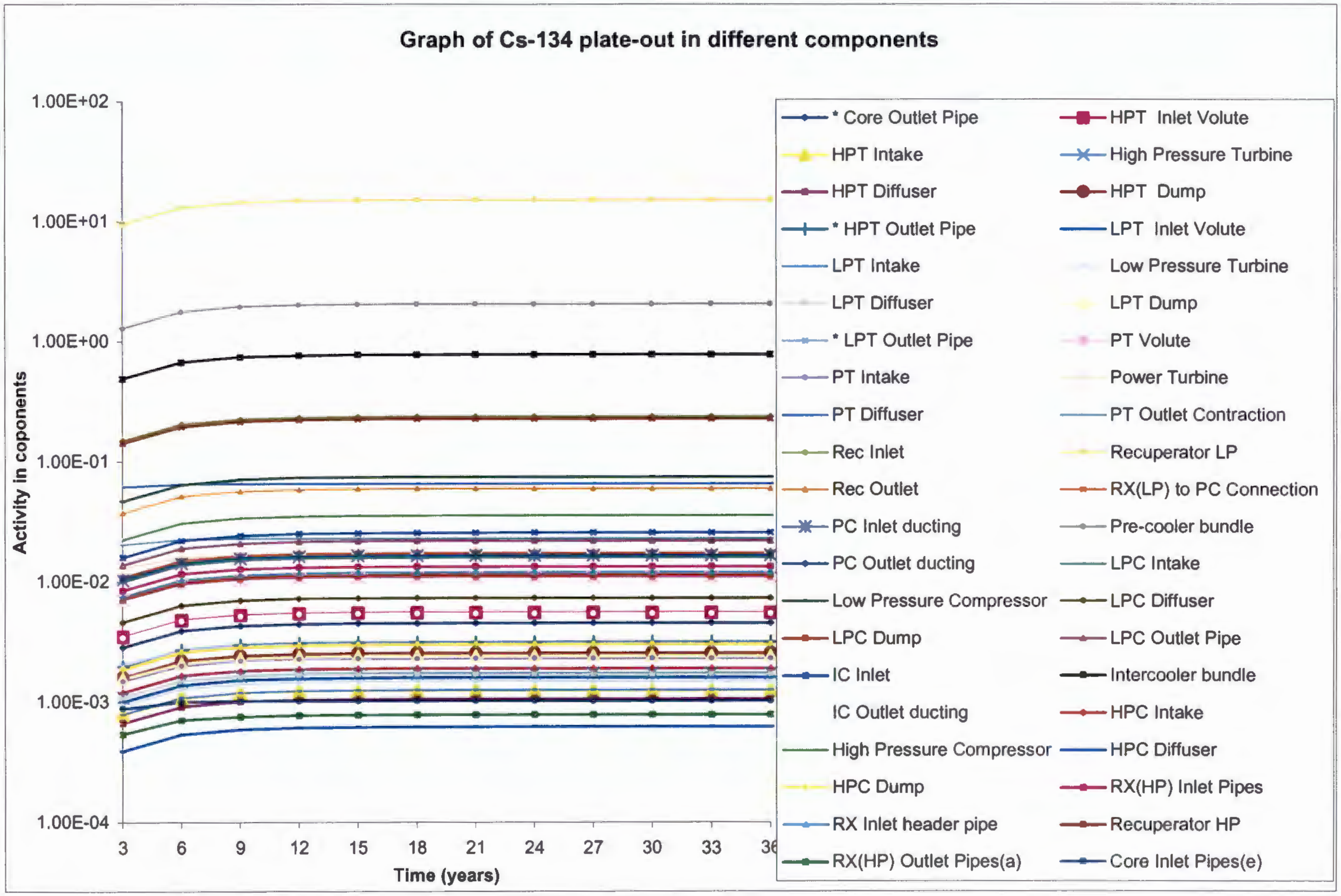
Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	4.75E-02	4.08E-04	3.23E-07	7.45E-08	1.88E-05
B	HPT Inlet Volute	5.61E-03	5.83E-02	5.02E-04	3.98E-07	9.16E-08	2.31E-05
150	HPT Intake	1.26E-03	1.31E-02	1.13E-04	8.95E-08	2.06E-08	5.19E-06
9	High Pressure Turbine	1.76E-03	1.83E-02	1.65E-04	1.24E-07	2.88E-08	7.21E-06
11	HPT Diffuser	1.07E-03	1.11E-02	1.06E-04	7.58E-08	1.77E-08	4.40E-06
D1	HPT Dump	2.57E-03	2.67E-02	2.59E-04	1.85E-07	4.31E-08	1.07E-05
13	* HPT Outlet Pipe	3.20E-03	3.31E-02	3.20E-04	2.28E-07	5.32E-08	1.32E-05
F	LPT Inlet Volute	1.62E-03	1.68E-02	1.62E-04	1.16E-07	2.70E-08	6.71E-06
152	LPT Intake	1.27E-03	1.32E-02	1.27E-04	9.02E-08	2.10E-08	5.23E-06
17	Low Pressure Turbine	1.50E-03	1.54E-02	2.28E-04	1.05E-07	2.52E-08	6.12E-06
19	LPT Diffuser	1.73E-03	1.72E-02	5.73E-04	1.19E-07	3.06E-08	7.02E-06
I1	LPT Dump	2.44E-03	2.40E-02	9.69E-04	1.69E-07	4.44E-08	9.99E-06
21	* LPT Outlet Pipe	3.15E-03	3.10E-02	1.24E-03	2.17E-07	5.70E-08	1.28E-05
L	PT Volute	1.10E-02	1.09E-01	4.37E-03	7.59E-07	2.00E-07	4.50E-05
27	PT Intake	2.32E-03	2.28E-02	9.17E-04	1.59E-07	4.19E-08	9.45E-06
29	Power Turbine	1.76E-02	1.30E-01	3.09E-02	9.04E-07	3.27E-07	6.48E-05
31	PT Diffuser	6.64E-02	1.63E-01	1.45E-01	6.97E-07	7.95E-07	2.49E-04
35	PT Outlet Contraction	2.32E-02	6.04E-02	3.56E-02	2.12E-07	2.97E-07	1.06E-04
P	Rec Inlet	2.41E-01	2.46E+00	1.89E-01	8.50E-05	3.08E-05	3.97E-03
39	Recuperator LP	1.52E+01	1.59E+02	1.19E+01	1.05E-02	2.43E-03	2.55E-01
R	Rec Outlet	6.00E-02	6.26E-01	4.69E-02	4.53E-05	9.68E-06	1.00E-03
158	RX(LP) to PC Connection	1.76E-02	1.84E-01	1.37E-02	1.33E-05	2.84E-06	2.95E-04
340	PC Inlet ducting	1.67E-02	1.74E-01	1.30E-02	1.26E-05	2.69E-06	2.79E-04
41	Pre-cooler bundle	2.06E+00	2.14E+01	1.60E+00	1.55E-03	3.31E-04	3.44E-02
47	PC Outlet ducting	1.61E-02	1.68E-01	1.25E-02	1.21E-05	2.59E-06	2.69E-04
51	LPC Intake	1.55E-03	1.62E-02	1.21E-03	1.17E-06	2.50E-07	2.59E-05
53	Low Pressure Compressor	7.51E-02	7.83E-01	5.86E-02	5.66E-05	1.21E-05	1.26E-03

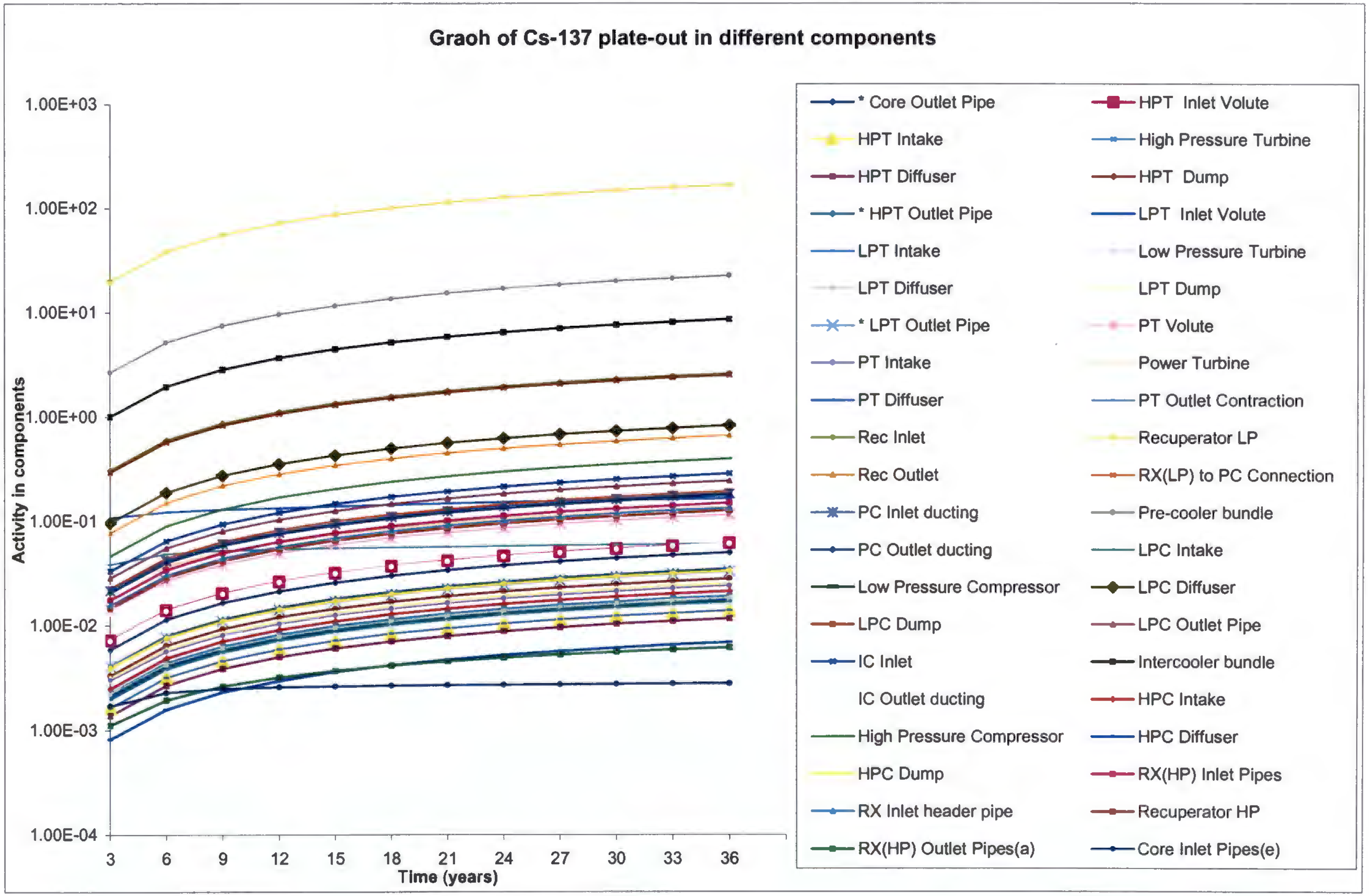
Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.38E-03	7.70E-02	5.76E-03	5.57E-06	1.19E-06	1.23E-04
Y	LPC Dump	1.15E-02	1.20E-01	8.97E-03	8.67E-06	1.85E-06	1.92E-04
57	LPC Outlet Pipe	2.21E-02	2.31E-01	1.73E-02	1.67E-05	3.57E-06	3.70E-04
162	IC Inlet	2.59E-02	2.70E-01	2.02E-02	1.95E-05	4.17E-06	4.32E-04
61	Intercooler bundle	7.79E-01	8.13E+00	6.08E-01	5.88E-04	1.26E-04	1.30E-02
67	IC Outlet ducting	5.52E-03	5.76E-02	4.31E-03	4.16E-06	8.90E-07	9.23E-05
71	HPC Intake	1.94E-03	2.03E-02	1.52E-03	1.47E-06	3.13E-07	3.25E-05
73	High Pressure Compressor	3.61E-02	3.77E-01	2.82E-02	2.72E-05	5.82E-06	6.04E-04
75	HPC Diffuser	6.31E-04	6.58E-03	4.92E-04	4.76E-07	1.02E-07	1.05E-05
GG	HPC Dump	3.03E-03	3.16E-02	2.37E-03	2.29E-06	4.89E-07	5.07E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.42E-01	1.06E-02	1.03E-05	2.20E-06	2.28E-04
338	RX Inlet header pipe	1.22E-02	1.27E-01	9.50E-03	9.18E-06	1.96E-06	2.03E-04
85	Recuperator HP	2.29E-01	2.38E+00	1.78E-01	1.72E-04	3.69E-05	3.82E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	5.92E-03	7.39E-04	3.92E-08	4.36E-08	9.85E-06
89	Core Inlet Pipes(e)	1.03E-03	2.78E-03	1.44E-03	8.77E-09	1.25E-08	5.12E-06
Total plate-out in the PCU		**1.90E+01**	**1.98E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**3.16E-01**

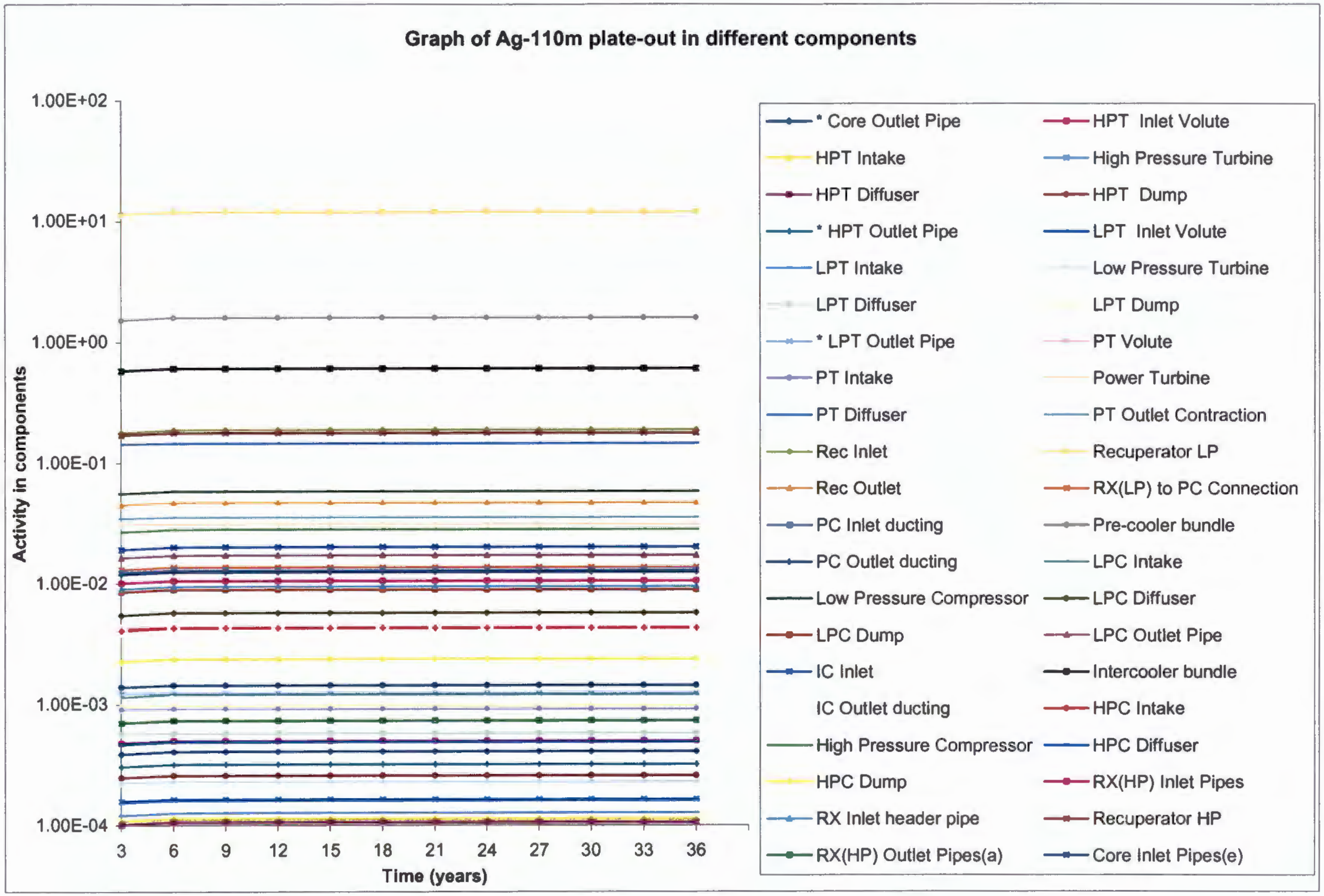
Table 4.14: Expected plate-out in the PCU at 36 years of PBMR normal operation

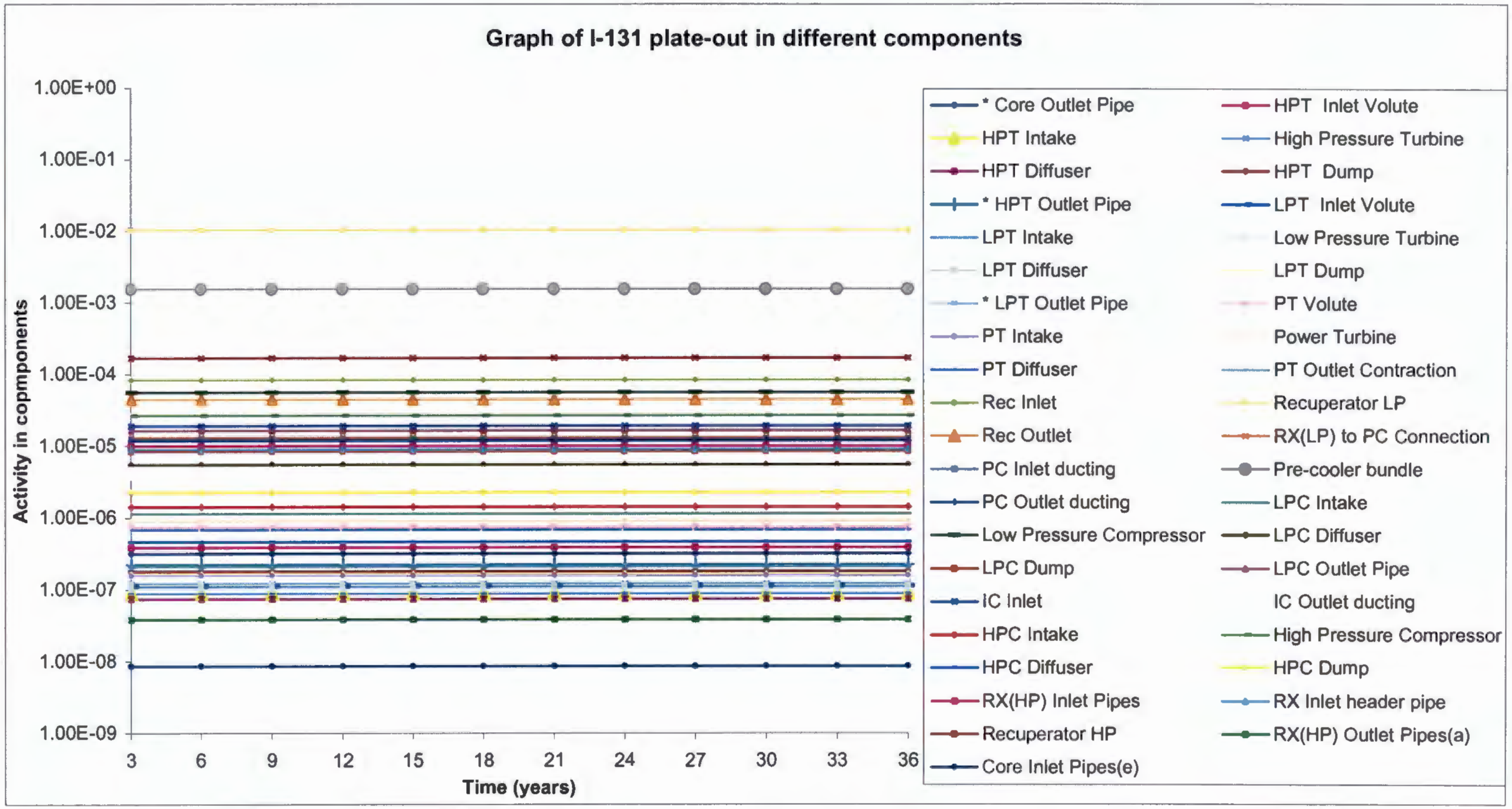
Elem	Description	GBQ					
		CS-134	CS-137	AG-110M	I-131	I-133	SR-90
7	* Core Outlet Pipe	4.57E-03	5.03E-02	4.08E-04	3.23E-07	7.45E-08	1.98E-05
B	HPT Inlet Volute	5.61E-03	6.17E-02	5.02E-04	3.98E-07	9.16E-08	2.44E-05
150	HPT Intake	1.26E-03	1.39E-02	1.13E-04	8.95E-08	2.06E-08	5.49E-06
9	High Pressure Turbine	1.76E-03	1.93E-02	1.65E-04	1.24E-07	2.88E-08	7.63E-06
11	HPT Diffuser	1.07E-03	1.17E-02	1.06E-04	7.58E-08	1.77E-08	4.65E-06
D1	HPT Dump	2.57E-03	2.82E-02	2.59E-04	1.85E-07	4.31E-08	1.13E-05
13	* HPT Outlet Pipe	3.20E-03	3.51E-02	3.20E-04	2.28E-07	5.32E-08	1.40E-05
F	LPT Inlet Volute	1.62E-03	1.78E-02	1.62E-04	1.16E-07	2.70E-08	7.10E-06
152	LPT Intake	1.27E-03	1.40E-02	1.27E-04	9.02E-08	2.10E-08	5.53E-06
17	Low Pressure Turbine	1.50E-03	1.63E-02	2.28E-04	1.05E-07	2.52E-08	6.47E-06
19	LPT Diffuser	1.73E-03	1.83E-02	5.73E-04	1.19E-07	3.06E-08	7.41E-06
I1	LPT Dump	2.44E-03	2.54E-02	9.69E-04	1.69E-07	4.44E-08	1.05E-05
21	* LPT Outlet Pipe	3.15E-03	3.28E-02	1.24E-03	2.17E-07	5.70E-08	1.36E-05
L	PT Volute	1.10E-02	1.15E-01	4.37E-03	7.59E-07	2.00E-07	4.75E-05
27	PT Intake	2.32E-03	2.42E-02	9.17E-04	1.59E-07	4.19E-08	9.97E-06
29	Power Turbine	1.76E-02	1.38E-01	3.09E-02	9.04E-07	3.27E-07	6.76E-05
31	PT Diffuser	6.64E-02	1.66E-01	1.45E-01	6.97E-07	7.95E-07	2.50E-04
35	PT Outlet Contraction	2.32E-02	6.11E-02	3.56E-02	2.12E-07	2.97E-07	1.06E-04
P	Rec Inlet	2.41E-01	2.60E+00	1.89E-01	8.50E-05	3.08E-05	4.19E-03
39	Recuperator LP	1.52E+01	1.68E+02	1.19E+01	1.05E-02	2.43E-03	2.69E-01
R	Rec Outlet	6.00E-02	6.63E-01	4.69E-02	4.53E-05	9.68E-06	1.06E-03
158	RX(LP) to PC Connection	1.76E-02	1.95E-01	1.37E-02	1.33E-05	2.84E-06	3.11E-04
340	PC Inlet ducting	1.67E-02	1.84E-01	1.30E-02	1.26E-05	2.69E-06	2.95E-04
41	Pre-cooler bundle	2.06E+00	2.27E+01	1.60E+00	1.55E-03	3.31E-04	3.63E-02
47	PC Outlet ducting	1.61E-02	1.78E-01	1.25E-02	1.21E-05	2.59E-06	2.84E-04
51	LPC Intake	1.55E-03	1.71E-02	1.21E-03	1.17E-06	2.50E-07	2.74E-05
53	Low Pressure Compressor	7.51E-02	8.29E-01	5.86E-02	5.66E-05	1.21E-05	1.33E-03

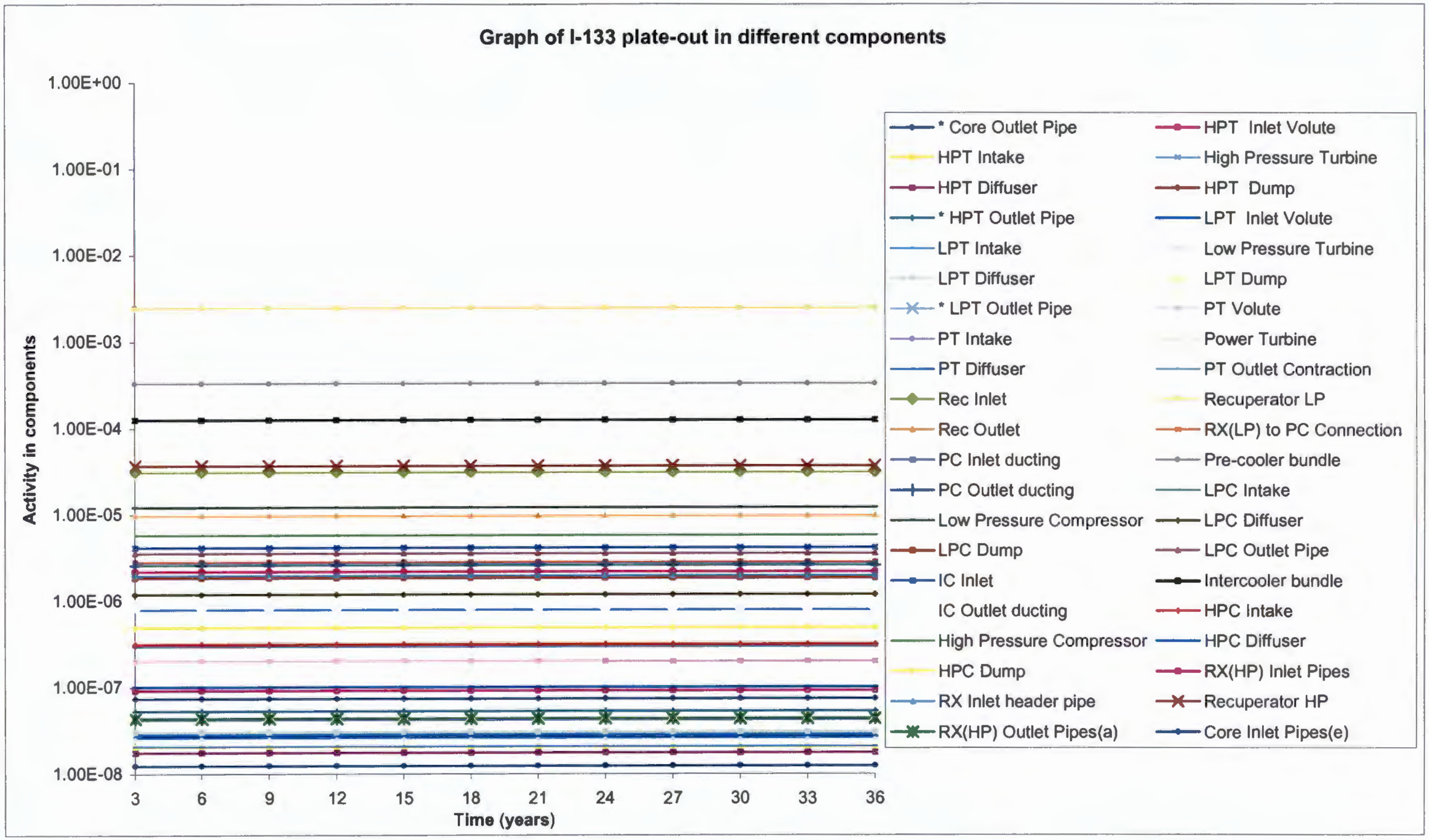
Elem	Description	GBQ					
		CS-134	**CS-137**	**AG-110M**	**I-131**	**I-133**	**SR-90**
55	LPC Diffuser	7.38E-03	8.15E-02	5.76E-03	5.57E-06	1.19E-06	1.31E-04
Y	LPC Dump	1.15E-02	1.27E-01	8.97E-03	8.67E-06	1.85E-06	2.03E-04
57	LPC Outlet Pipe	2.21E-02	2.44E-01	1.73E-02	1.67E-05	3.57E-06	3.91E-04
162	IC Inlet	2.59E-02	2.86E-01	2.02E-02	1.95E-05	4.17E-06	4.57E-04
61	Intercooler bundle	7.79E-01	8.61E+00	6.08E-01	5.88E-04	1.26E-04	1.38E-02
67	IC Outlet ducting	5.52E-03	6.10E-02	4.31E-03	4.16E-06	8.90E-07	9.76E-05
71	HPC Intake	1.94E-03	2.15E-02	1.52E-03	1.47E-06	3.13E-07	3.44E-05
73	High Pressure Compressor	3.61E-02	3.99E-01	2.82E-02	2.72E-05	5.82E-06	6.39E-04
75	HPC Diffuser	6.31E-04	6.97E-03	4.92E-04	4.76E-07	1.02E-07	1.12E-05
GG	HPC Dump	3.03E-03	3.35E-02	2.37E-03	2.29E-06	4.89E-07	5.36E-05
83	RX(HP) Inlet Pipes	1.36E-02	1.51E-01	1.06E-02	1.03E-05	2.20E-06	2.41E-04
338	RX Inlet header pipe	1.22E-02	1.34E-01	9.50E-03	9.18E-06	1.96E-06	2.15E-04
85	Recuperator HP	2.29E-01	2.52E+00	1.78E-01	1.72E-04	3.69E-05	4.04E-03
87	RX(HP) Outlet Pipes(a)	7.94E-04	6.19E-03	7.39E-04	3.92E-08	4.36E-08	1.03E-05
89	Core Inlet Pipes(e)	1.03E-03	2.80E-03	1.44E-03	8.77E-09	1.25E-08	5.13E-06
Total plate-out in the PCU		**1.90E+01**	**2.09E+02**	**1.50E+01**	**1.31E-02**	**3.01E-03**	**3.34E-01**

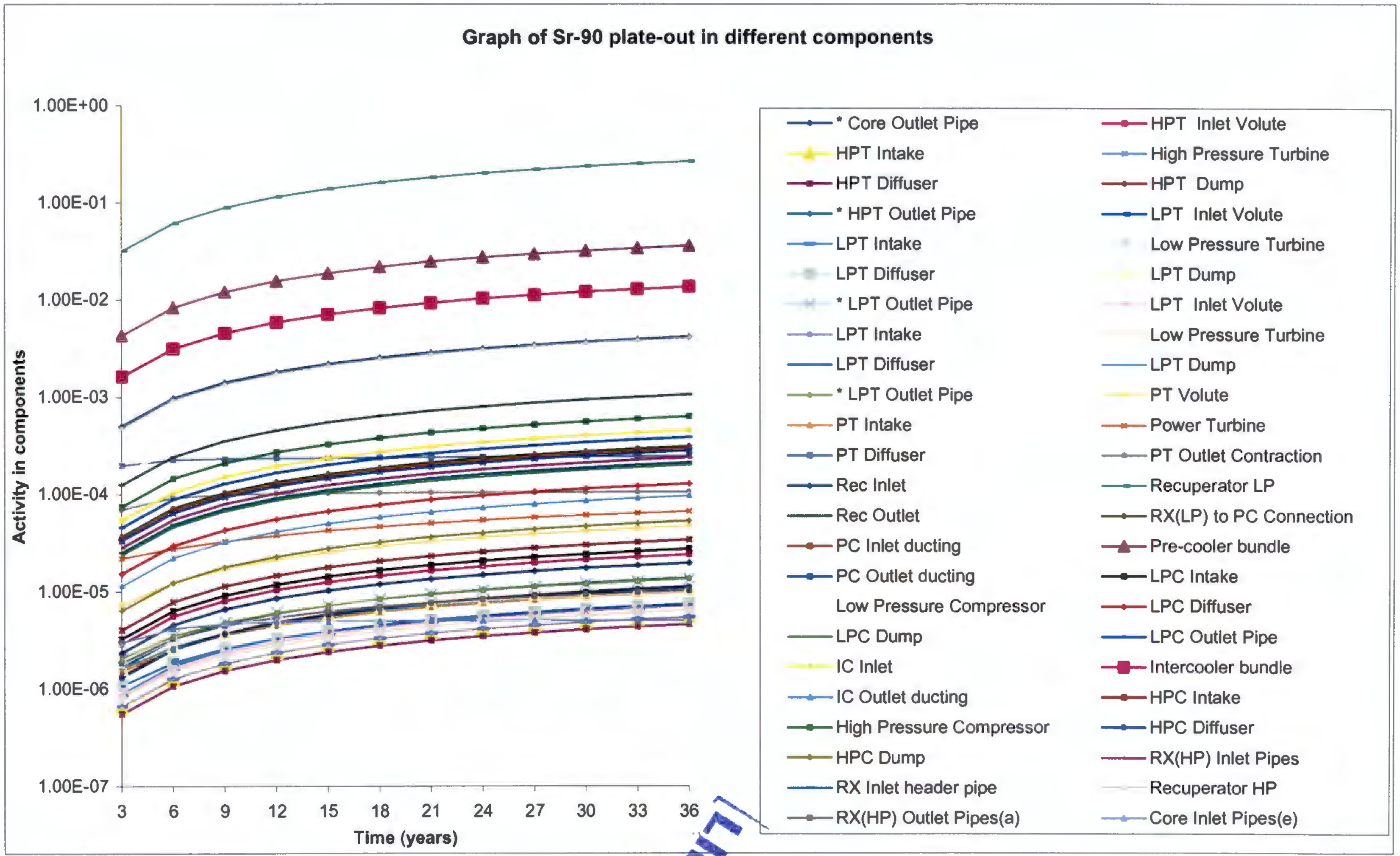

Graph of Cs-134 plate-out in different components
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
Activity in coponents
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Inlet Volute
HPT Intake
High Pressure Turbine
HPT Diffuser
HPT Dump
* HPT Outlet Pipe
LPT Inlet Volute
LPT Intake
Low Pressure Turbine
LPT Diffuser
LPT Dump
* LPT Outlet Pipe
PT Volute
PT Intake
Power Turbine
PT Diffuser
PT Outlet Contraction
Rec Inlet
Recuperator LP
Rec Outlet
RX(LP) to PC Connection
PC Inlet ducting
Pre-cooler bundle
PC Outlet ducting
LPC Intake
Low Pressure Compressor
LPC Diffuser
LPC Dump
LPC Outlet Pipe
IC Inlet
Intercooler bundle
IC Outlet ducting
HPC Intake
High Pressure Compressor
HPC Diffuser
HPC Dump
RX(HP) Inlet Pipes
RX Inlet header pipe
Recuperator HP
RX(HP) Outlet Pipes(a)
Core Inlet Pipes(e)


Graoh of Cs-137 plate-out in different components
Activity in components
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Intake
HPT Diffuser
* HPT Outlet Pipe
LPT Intake
LPT Diffuser
* LPT Outlet Pipe
PT Intake
PT Diffuser
Rec Inlet
Rec Outlet
PC Inlet ducting
PC Outlet ducting
Low Pressure Compressor
LPC Dump
IC Inlet
IC Outlet ducting
High Pressure Compressor
HPC Dump
RX Inlet header pipe
RX(HP) Outlet Pipes(a)
HPT Inlet Volute
High Pressure Turbine
HPT Dump
LPT Inlet Volute
Low Pressure Turbine
LPT Dump
PT Volute
Power Turbine
PT Outlet Contraction
Recuperator LP
RX(LP) to PC Connection
Pre-cooler bundle
LPC Intake
LPC Diffuser
LPC Outlet Pipe
Intercooler bundle
HPC Intake
HPC Diffuser
RX(HP) Inlet Pipes
Recuperator HP
Core Inlet Pipes(e)


Graph of Ag-110m plate-out in different components
Activity in components
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Inlet Volute
HPT Intake
High Pressure Turbine
HPT Diffuser
HPT Dump
* HPT Outlet Pipe
LPT Inlet Volute
LPT Intake
Low Pressure Turbine
LPT Diffuser
LPT Dump
* LPT Outlet Pipe
PT Volute
PT Intake
Power Turbine
PT Diffuser
PT Outlet Contraction
Rec Inlet
Recuperator LP
Rec Outlet
RX(LP) to PC Connection
PC Inlet ducting
Pre-cooler bundle
PC Outlet ducting
LPC Intake
Low Pressure Compressor
LPC Diffuser
LPC Dump
LPC Outlet Pipe
IC Inlet
Intercooler bundle
IC Outlet ducting
HPC Intake
High Pressure Compressor
HPC Diffuser
HPC Dump
RX(HP) Inlet Pipes
RX Inlet header pipe
Recuperator HP
RX(HP) Outlet Pipes(a)
Core Inlet Pipes(e)


Graph of I-131 plate-out in different components
Activity in copmponents
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Intake
HPT Diffuser
* HPT Outlet Pipe
LPT Intake
LPT Diffuser
* LPT Outlet Pipe
PT Intake
PT Diffuser
Rec Inlet
Rec Outlet
PC Inlet ducting
PC Outlet ducting
Low Pressure Compressor
LPC Dump
IC Inlet
HPC Intake
HPC Diffuser
RX(HP) Inlet Pipes
Recuperator HP
Core Inlet Pipes(e)
HPT Inlet Volute
High Pressure Turbine
HPT Dump
LPT Inlet Volute
Low Pressure Turbine
LPT Dump
PT Volute
Power Turbine
PT Outlet Contraction
Recuperator LP
RX(LP) to PC Connection
Pre-cooler bundle
LPC Intake
LPC Diffuser
LPC Outlet Pipe
IC Outlet ducting
High Pressure Compressor
HPC Dump
RX Inlet header pipe
RX(HP) Outlet Pipes(a)


Graph of I-133 plate-out in different components
Activity in components
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Inlet Volute
HPT Intake
High Pressure Turbine
HPT Diffuser
HPT Dump
* HPT Outlet Pipe
LPT Inlet Volute
LPT Intake
Low Pressure Turbine
LPT Diffuser
LPT Dump
* LPT Outlet Pipe
PT Volute
PT Intake
Power Turbine
PT Diffuser
PT Outlet Contraction
Rec Inlet
Recuperator LP
Rec Outlet
RX(LP) to PC Connection
PC Inlet ducting
Pre-cooler bundle
PC Outlet ducting
LPC Intake
Low Pressure Compressor
LPC Diffuser
LPC Dump
LPC Outlet Pipe
IC Inlet
Intercooler bundle
IC Outlet ducting
HPC Intake
High Pressure Compressor
HPC Diffuser
HPC Dump
RX(HP) Inlet Pipes
RX Inlet header pipe
Recuperator HP
RX(HP) Outlet Pipes(a)
Core Inlet Pipes(e)


Graph of Sr-90 plate-out in different components
Activity in components
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
3
6
9
12
15
18
21
24
27
30
33
36
Time (years)
* Core Outlet Pipe
HPT Intake
HPT Diffuser
* HPT Outlet Pipe
LPT Intake
LPT Diffuser
* LPT Outlet Pipe
LPT Intake
LPT Diffuser
* LPT Outlet Pipe
PT Intake
PT Diffuser
Rec Inlet
Rec Outlet
PC Inlet ducting
PC Outlet ducting
Low Pressure Compressor
LPC Dump
IC Inlet
IC Outlet ducting
High Pressure Compressor
HPC Dump
RX Inlet header pipe
RX(HP) Outlet Pipes(a)
HPT Inlet Volute
High Pressure Turbine
HPT Dump
LPT Inlet Volute
Low Pressure Turbine
LPT Dump
LPT Inlet Volute
Low Pressure Turbine
LPT Dump
PT Volute
Power Turbine
PT Outlet Contraction
Recuperator LP
RX(LP) to PC Connection
Pre-cooler bundle
LPC Intake
LPC Diffuser
LPC Outlet Pipe
Intercooler bundle
HPC Intake
HPC Diffuser
RX(HP) Inlet Pipes
Recuperator HP
Core Inlet Pipes(e)

To determine the amount of fission product released the graph of fractional release were plotted against time of irradiation.

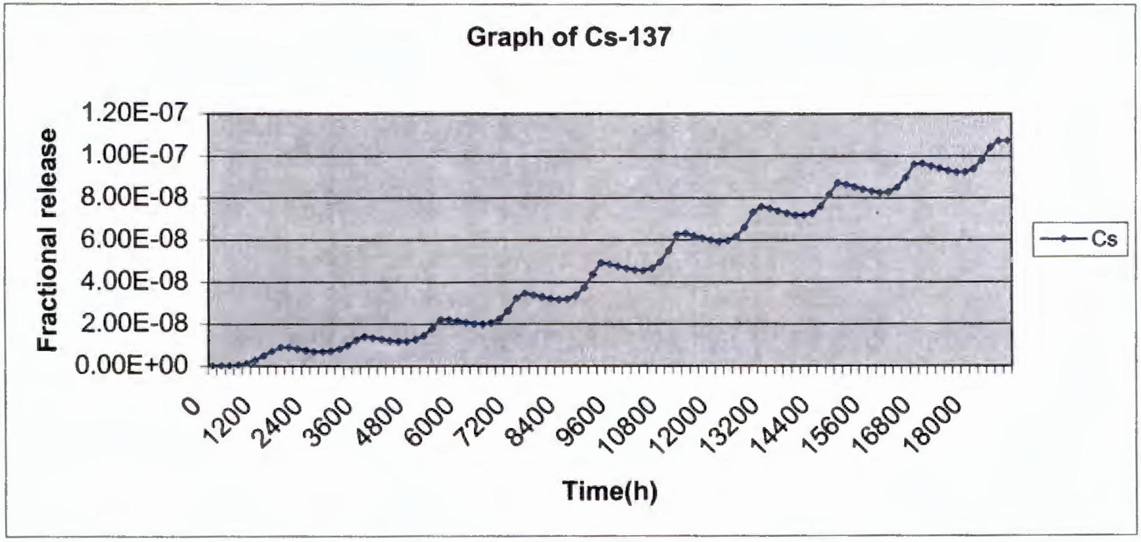


Figure 4-7:Graph of fractional release vs time(Cs-137)

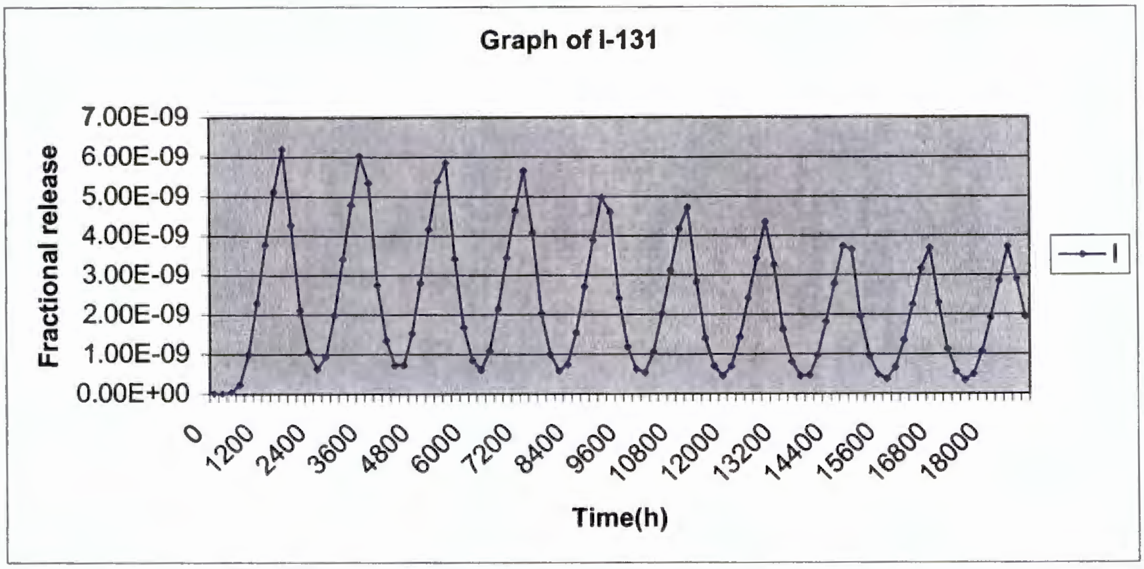


Figure 4-8: Graph of fractional release vs time(I-131)

The following are the plate-out in the PCU obtained from the linked codes, Spatra and Fresco-II.

Nuclides	**Cs-134**	**Cs-137**	**Ag-110m**	**I-131**	**I-133**	**Sr-90**
Total plate-out	0.19025E+02	0.20920E+03	0.14952E+02	0.13113E-01	0.30123E-02	0.33423E+00

Table 4.15:Expected plate-out in the PCU at 3 years of PBMR normal operation

CHAPTER 5

CONCLUSION

From the previous tables of plate-out in the PCU, it is shown that more plate-out is expected to be on the Recuperator LP. This is due to the fact that recuperator is a device for returning heat in the gas (helium) downstream of the turbines to the gas returning to the reactor, thus improving the cycle efficiency. An example of Sr-90 is shown in Figure 5-1.

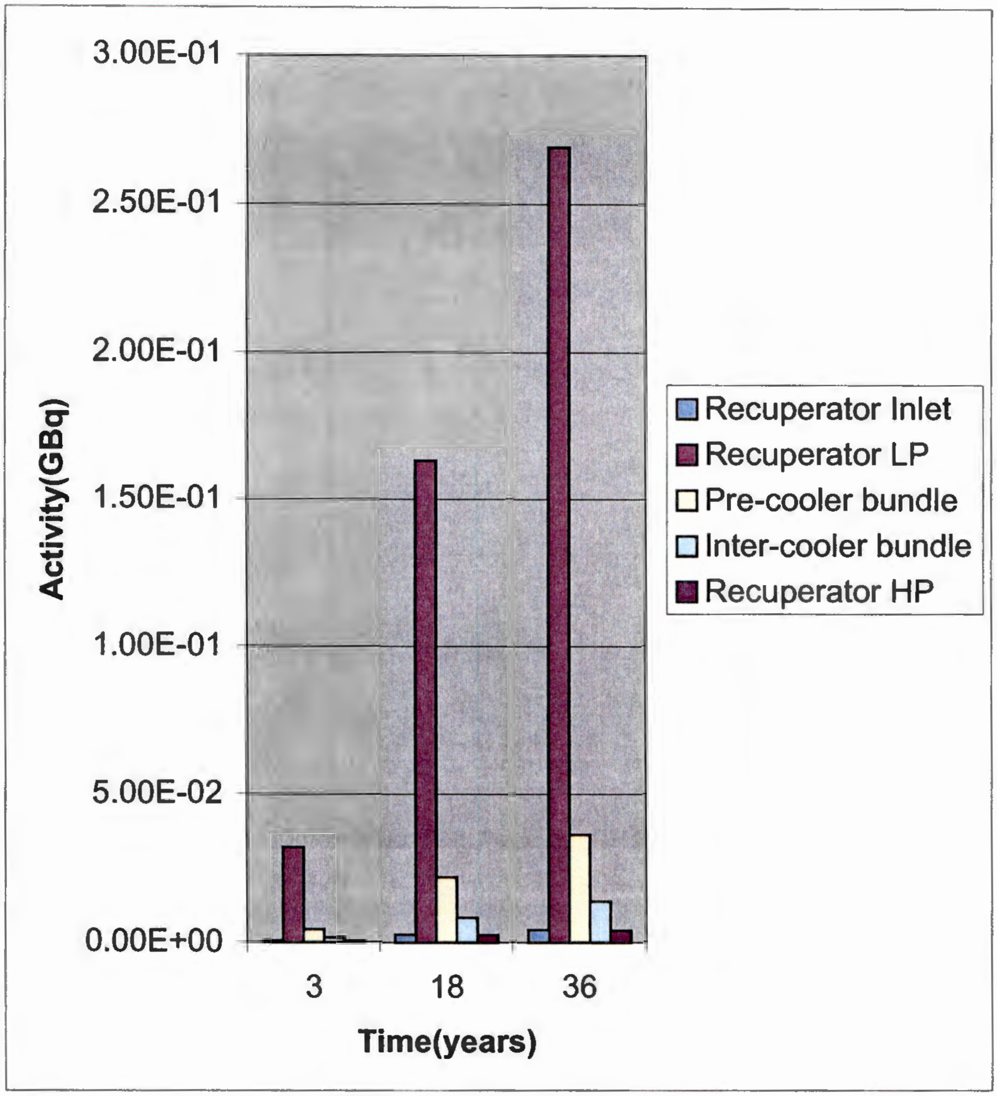


Figure 5-1: Graph of Sr-90

The results in chapter 4, shows that the fission product release rates in normal operation are comparatively high from defective particles (and from the small heavy metal contamination); substantial release from intact particles is expected only for Ag-110m. This is due to its fast diffusion in the fuel element components and bad retention on graphite.

I-131 decay before it complete its first cycle due to its short half-life (8 days). As this nuclide enters the reactor core there will be less of nuclear reaction taking place and during the process there will be build up of nuclear reaction, this is shown by big humps on the graph.

This is different from Cs-137, because it has long half-life (30.1 years) so some of the fission products will decay before it complete its first cycle whereas more will be left. As this nuclide enters the reactor core there will be more of nuclear reaction taking place and during the process there will be build up of nuclear reaction, this is shown by small humps on the graph.

DISCUSSION

For the study of the linked programmes, two approaches were investigated,

Approach A:

I. Calculation of release rate [Fresco-II code]

II. Calculation of plate-out [Fresco-Input]

III. Calculation of plate-out [Spatra code]

Approach B:

I. Calculation of plate-out [Spatra code]

II. Calculation of release rate [Fresco-II code]

III. Calculation of plate-out [Fresco-Input]

For practical reasons, approach B was followed. However, suffices to mention that the two approaches are in principle identical. We mention also that the cumulative number of defective particles must be checked independently for each nuclei species to avoid over counting of unwanted particles.

SUMMARY

The aim of this research was to link the two codes Fresco and Spatra to calculate the plate-out distribution. This is done and the results are comparable to the design values as shown in chapter 4. Therefore the linked codes can be used by PBMR since they are reliable to produce good results.

Finally, the amount of fission products released from the fuel sphere are very small and its plate-out and distribution are negligible. Then maintenance should be done regularly in order to avoid exposure to the environment, since for example Sr-90 is considered as the most hazardous bone-seeking radioisotope because of its high solubility (~25%), long biological half-life and strong resemblance to calcium [Wang Lau 1974].

RECOMMENDATIONS

From the experienced gained in this project the following recommendations can be made:

1. In order to improve the codes, more effort is needed to investigate and incorporate the good features of other competing codes such as PLAIN, PADLOC etc. into SPATRA. Similarly for FRESCO-II, more effort is needed to investigate and incorporate the good features of other competing codes such as FRESCO-I, PANAMA etc.
2. From the point of view of a user, the programs must be automated, preferably by use of a Makefile. This presupposes that the program is divided into separate subprograms.
3. Efficient programming may be desirable especially for linked codes. For example, a program that links SPATRA and FRESCO-II may be more efficient when run on a parallel machine.

Appendix A: FRESCO-II MODEL

As a part of the design process, it is necessary to describe the algorithm that one intends to implement. The following, as shown in Figure A- 1 is the flowchart that explains how Fresco-II code calculates the fractional release. The program start by initializing zero for all values i.e time and temperature since the fractional release is dependent on time and temperature. At time t and temperature T, the program determines the failure fraction of coated particles. For each time step, the numbers of defective particles formed are calculated. There are 5 ways in which fission products can be released thus, Intact coated particle, and Defective coated particle, Uranium contamination in graphite pores, Uranium contamination in coating layers, and Uranium contamination in grains.

Intact coated particle: fission products formed in the uranium dioxide particle diffuse from the kernel to coating layers, from coating layers to graphite pores. When fission occurs, the generated fission products have high kinetic energy, and travel a finite distance before being stopped by the material present. As a result, some of the fission products formed near the surface of the kernel are released directly into the buffer region due to recoil reaction.

Fission products will diffuse from the coating layers to the graphite pores. Recoil fission products formed in the coating layer will diffuse in the graphite pores and at fuel element surface, desorption is considered to take place from the graphite pores to the reactor coolant.

Defective coated particle: Some of the fission products formed in the kernel will diffuse to the graphite pores. At fuel element surface, desorption is considered to take place from the graphite pores to the reactor coolant. The fission products leaving the kernel of defective are considered to have a direct route to the particle surface. In fact, a defective particle is considered to have a bare kernel with no coatings.

Uranium contamination in graphite pores: fission products are generated in the coated particle, but there is some generation in graphite matrix because of the presence of uranium in the graphite pores. At fuel element surface, desorption is considered to take place from the graphite pores to the reactor coolant.

Uranium contamination in coating layers: recoil fission products formed in the outer coating layer due to uranium contamination escape the coating layer without diffusion Some of the fission products formed in the outer coating layer due to uranium contamination escape the coating layer without diffusion. At fuel element surface, desorption is considered to take place from the graphite pores to the reactor coolant.

Uranium contamination due to graphite grains: recoil fission products formed in the graphite grains due to uranium contamination escape the grains without diffusion. Some fission products formed in the graphite grains due to uranium contamination will diffuse in graphite pores. At fuel element surface, desorption is considered to take place from the graphite pores to the reactor coolant.

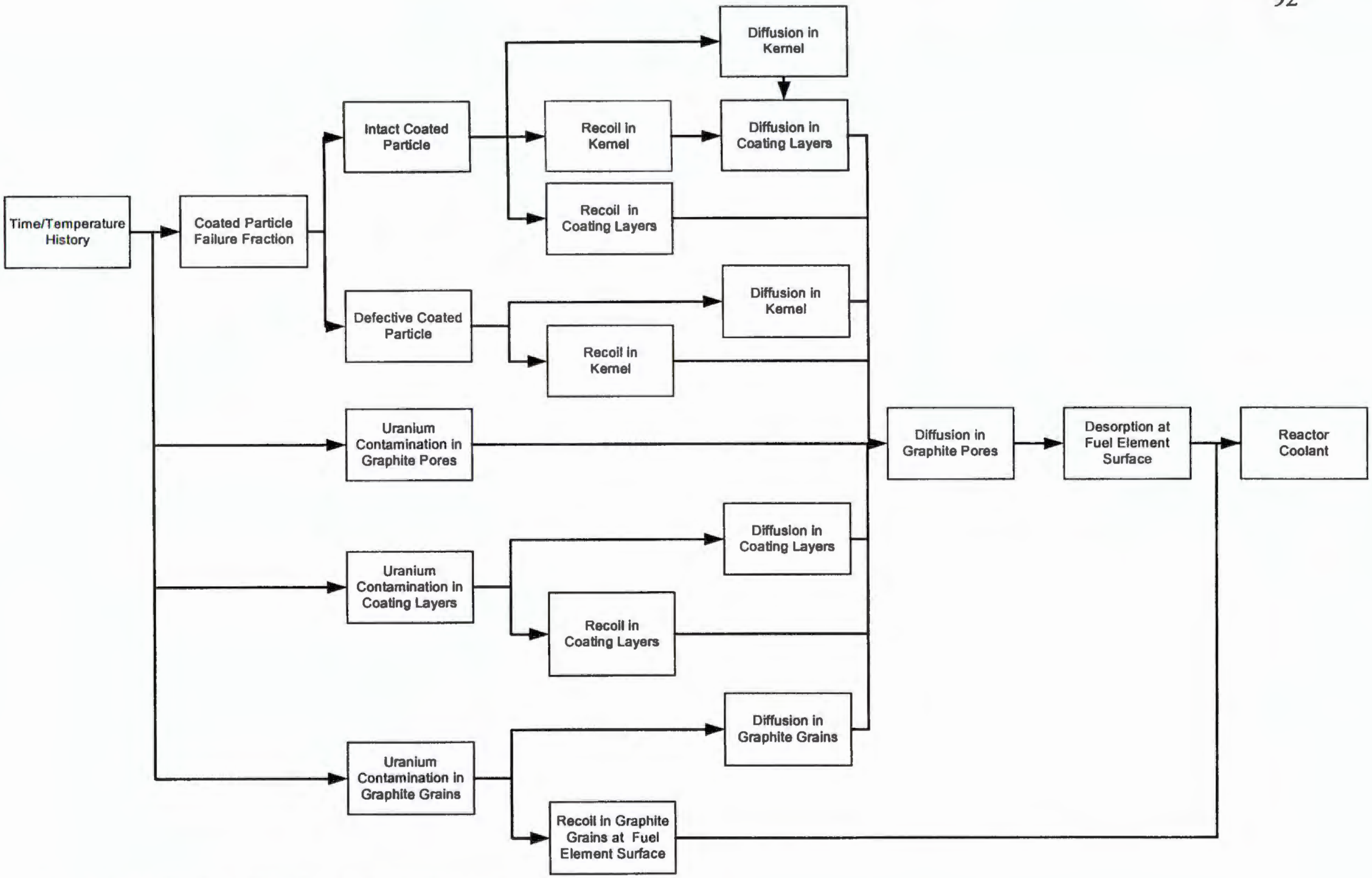


Figure A- 1: Flow chart of Fresco-II code

Glossary of terms

Abnormal Condition	An unplanned event or sequence of events that results in undesirable consequences. An incident with specific safety consequences or impacts such as damage to one or several barriers, thus leading to the release of radioactive material.
BISO	Binary Coated Particle. Fuel particle with two coatings of PyC.
Burn-up	The amount of energy produced by fission reactions in relation to the amount of fissile material originally available.
Event	A condition that deviates from normal operation.
Fuel Handling and Storage System (FHSS)	A system for loading and removal of fuel and graphite spheres from the reactor.
Helium Inventory Control System (HICS)	A system for regulating the quantity and quality of helium in the PCU.
Main Power System (MPS)	The Main Power System physically combines the functions of the Reactor Unit (RU) and Power Conversion Unit (PCU) to convert nuclear energy into electricity.
Module	A single, stand-alone PBMR, containing all systems for operation.
Pebble Bed Modular Reactor (PBMR)	A high-temperature, direct cycle, helium-cooled nuclear reactor with fully ceramic spherical fuel elements.
Power Conversion Unit (PCU)	An assembly of equipment, comprising the high-and low-pressure turbo-units, power turbine generator, a recuperator and coolers, combining to convert the heat from the helium into electricity.
Power Plant	An energy park comprising one or more (up to 10) modules. Within a Power Plant, some rooms, e.g. Control Room, may be shared by the modules.
Power Turbine Generator (PTG)	An assembly to convert fluidic helium energy into electricity.
Process	A set of interrelated activities, which transform inputs into outputs.
Reactor Pressure Vessel (RPV)	The vessel which supports the reactor core structures and forms part of the MPS pressure boundary.
Reactor Pressure Vessel Conditioning System	A system for maintaining the RPV at a

(RPVCS)	homogeneous temperature, in order to maintain operating temperatures in the range for which the materials have been qualified.
Spent Fuel	Fuel that has reached its maximum design burn-up.
TRISO	Triple-coated particle. Fuel particle with two coatings of pyrolitic carbon (PyC) and one Silicon Carbide (Sic) coating.
Used Fuel Cooling System (UFCS)	A system to remove the decay heat from the Used Fuel Storage Vessel during storage, and to protect instrumentation and the surrounding concrete walls.

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