University of North-West

P B M R

DEVELOPMENT OF A CODE FOR THE CALCULATION OF THE RELEASE OF GASEOUS FISSION PRODUCTS AND IODINE FROM A PEBBLE BED MODULAR REACTOR

PULANE MOLOKWANE

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN APPLIED RADIATION SCIENCE AND TECHNOLOGY (MARST), IN THE FACULTY OF AGRICULTURE, SCIENCE AND TECHNOLOGY, AT THE UNIVERSITY OF NORTH-WEST.

2003

b15479171
LIBRARY
TH 539.762 MOL
2004 -05- 2 5
04/20164
UNIVERSITY OF THE NORTH WEST
18454021

SUPERVISOR: Dr. J.H. VENTER (PBMR)

ACKNOWLEDGEMENTS

My greatest gratitude goes to PBMR (Pty) Ltd, for financial support during the execution of this project, to the Center for Applied Radiation Science and Technology (CARST) at the University of North-West, for guidance and helping me to focus towards the completion of the project. My appreciation goes to the most important old man who has been a leader in my studies and a father figure in general, Dr Johan Venter. Thank you for the support you gave to me in all respects, and above all, thank you for believing that I could do it. I will always remember your advice not just as my supervisor and mentor, but as a father figure as well. All the people at PBMR who contributed to the successful completion of this project are too many to mention here. They did so in terms of technical discussions, explanations of concepts that seemed so alien to me, and giving me access to simple notes that explained much of what I did not know. However, I would like to single out, Dr Eben Mulder, who worked day and night compiling data for my input files. All the wonderful people in the Fuel Design Department need special thanks – thank you. To Thabang Makubire and Jeff Victor, thank you for facilitation of my work at PBMR and getting me to keep to my deadlines.

Lastly, but by no means least, to the most wonderful woman in the whole world, my very best friend, a woman who has always loved and supported me unconditionally, 'MY MOTHER', Thank you 'Ma', my sisters and brother Thanks 'Ba-MME' for the support you have always given to your sister. May God almighty bless you all.

Thank you 'my Jehovah Jirah' for seeing me through it all, for I know I am more than a conqueror in Christ Jesus and You have plans to prosper me but not to harm me. Thank you God almighty, thank you my 'Jehovah Shammah'. Tonnes of appreciation 'my very present help in time of need'

NWU LIBRARY

DECLARATION

'I hereby declare that the work contained in this dissertation, as submitted to the University of North-West, is my own work and has not previously been submitted to this or any other institution in fulfillment of requirements for any qualification from that institution'.

P Molokwane

Pulane Molokwane

Date 12/11/2003

ABSTRACT

This dissertation entails the calculation of the release of gaseous fission products and iodine from the Pebble Bed Modular Reactor (PBMR) 400MW core under a Deppresurised Loss Of Forced Coolant (DLOFC), where the temperature history of fuel spheres is taken into account. The release is calculated by developing a computer code (RELEASE) based on a simple coated particle failure and gas diffusion model. The computer code calculates failure fraction, kernel release fraction, layer release, Iodine decay correction, core release fraction and other parameters pertaining to a PBMR. This source code is developed in the FORTRAN 77 programming language on a Compaq Visual FORTRAN Development Platform. Verification of the results is done in MathCAD and the GETTER code.

RELEASE calculations compare very well with the MathCAD calculations with percentage deviation from 0 - 5%. The effects of a number of parameters on fission product release are investigated by means of sensitivity analysis involving parameters like temperature, failure fraction and diffusion coefficient. Sensitivity analysis showed that the variation of failure fraction has the greatest effect on release of fission products in a PBMR. The RELEASE results are compared with GETTER calculations in addition to the MathCAD verification. RELEASE calculations showed an expected value of 2.00 $\times 10^{12}$ Bq whereas GETTER calculations produced an expected value of 2.13×10^{12} Bq, representing a percentage deviation of 6%.

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation or Acronym	Definition
PBMR	Pebble Bed Modular Reactor
HTR	High Temperature Reactor
TRISO	Triple Coated Isotropic
LBE	Licensing Base Events
FIMA	Fissions per Initial Metal Atom
DLOFC	Depressurized Loss of Forced Cooling
OpyC	Outer pyrolytic Carbon
IpyC	Inner pyrolytic Carbon
F (T)	Fractional release
CVD	Chemical Vapour Deposition
CFP	Coated Fuel Particle
JAERI	Japan Atomic Energy Research Institute
FZJ	ForschungZentrum Julich
GA	General Atomic
KFA	KernForschungsAnlage Julich

TABLE OF CONTENTS

Dedications and acknowledgements.....(i)

Declaration.....(ii)

Abstract.....(iii)

List of acronyms and abbreviations.....(iv)

Chapter 1.....1

Introduction.....1

PBMR core design.....3

Behavior of fission products in PBMR fuel.....5

Research Problem, Research objective.....8

Rationale.....9

Chapter 2.....10

Main processes in manufacturing fuel pebbles.....10

Research methodology.....21

Chapter 3.....23

Theoretical background.....23

Chapter 4.....36

Program description (Introduction).....36

Program verification.....45

Chapter 5.....47

Analysis of results.....47

Sensitivity analysis.....57

UNW LIBRARY

Chapter 6.....**66**
Comments and possible enhancement to the program.....66
Conclusion.....67
References.....69

Appendices.....**72**
Appendix 1.....72
Appendix 2.....73
Appendix 3.....74
Appendix 4.....75
Appendix 5.....76
Appendix 6.....85
Appendix 7.....94
Appendix 8.....101
Appendix 9.....107

CHAPTER 1: INTRODUCTION

1.1. INTRODUCTION

1.1.1. THE PEBBLE BED MODULAR REACTOR (PBMR)

The Pebble Bed Modular Reactor (PBMR) is a High Temperature Gas-cooled Reactor (HTGR). It is a small, inherently safe, robust, clean, cost- efficient, inexpensive and adaptable nuclear power plant. The key inherent safety characteristics are:

1.1.1.1. Small excess reactivity

The small excess reactivity of the core at operating conditions is achieved by using continuous fuelling and defuelling. Excess reactivity is therefore only necessary to allow for xenon fluctuations during load following.

1.1.1.2. Fission product retention

Fission product retention capability at high temperature is provided by fuel kernel coatings consisting of multiple layers of pyrolytic carbon (PyC) and of silicon carbide (SiC). These coated particles have been demonstrated to contain all radiologically significant gaseous or solid fission products up to at least 1620 °C.

1.1.1.3. Negative temperature coefficient

The large negative temperature coefficient of the core is a result of using low enriched uranium fuel in a graphite matrix. This is largely determined by the temperature dependence of the resonance absorption in the fertile material U-238. This, together with the negative moderator temperature coefficient, results in a high overall negative temperature reactivity coefficient. This means that the reactor would counteract a rise in temperature with a reduction in power.

1.1.1.4. Neutron transparency and chemical inertness of helium

The neutron-transparency of helium means that the void-coefficient of reactivity of the helium coolant is zero and that a loss of coolant cannot cause a reactivity increase. The chemical inertness of helium, even at very high temperatures, implies that it will not react chemically with the graphite or fuel. The use of a single-phase coolant also has the advantage that boiling of the coolant is impossible.

1.1.1.5. Inherent heat removal capability

The slender design of the reactor vessel allows for optimal passive heat removal from the core even under conditions of no coolant flow, with the reactor

depressurised. Heat flow by conduction and radiation to the reactor pressure vessel, and subsequent removal by the passive heat removal system in the reactor cavity, would limit the maximum fuel and vessel temperature, so that both remain in the safe region [4].

The reactor is equipped with 18 control rods. Nine of the control rods are used for reactivity control during load changes and the other nine are used to shut down the reactor [4]. The PBMR uses coated uranium dioxide (UO_2) particles encased in graphite to form a fuel sphere. In addition, the PBMR design uses helium as coolant and energy transfer medium to a closed cycle gas turbine and generator. Helium enters the reactor core from the top at a temperature of about 500 °C and leaves at the bottom of the reactor at a temperature of about 900 °C. Figure 1 depicts a schematic diagram of a Pebble Bed Modular Reactor.

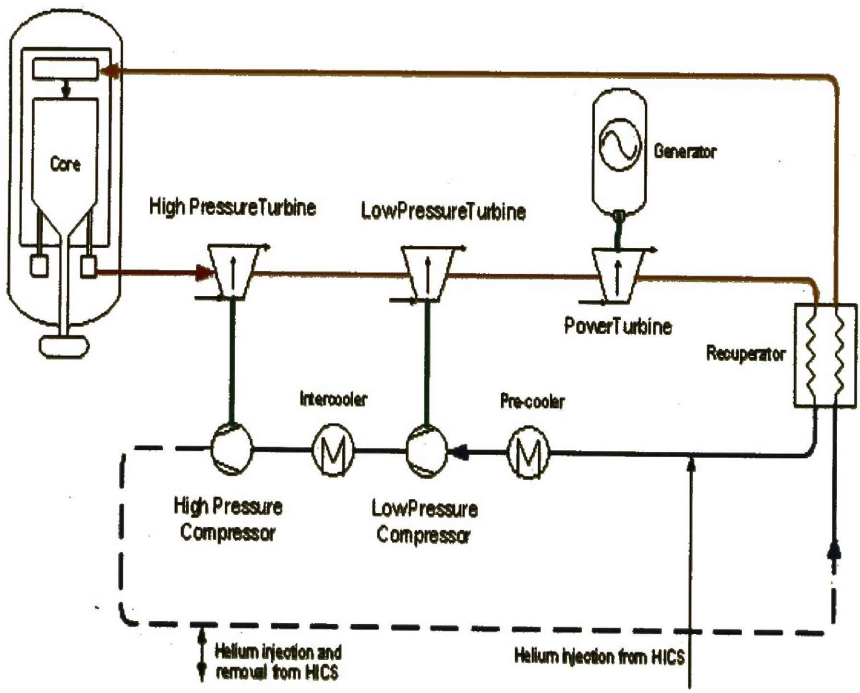


Figure 1: Pebble Bed Modular Reactor Schematic Diagram

UNW LIBRARY

1.1.2. PBMR CORE DESIGN

The PBMR core consists of three zones, an inner reflector and an outer reflector with an annular fuel region between the two reflectors. Fuel spheres are loaded around the periphery of the reactor core to form an annular fuel region (annulus) around the central reflector. Nuclear reactions take place in the fuel annulus. Figure 2 shows a diagram of a PBMR core.

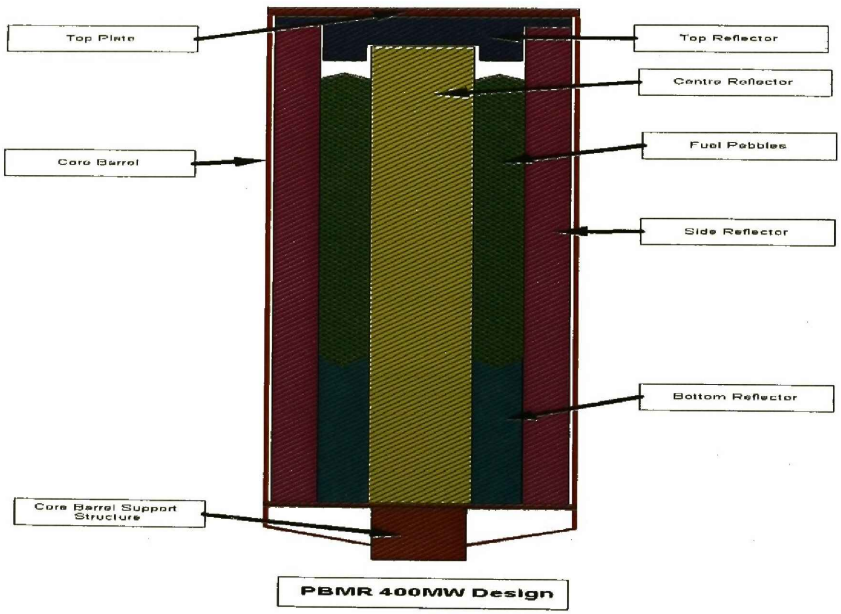


Figure 2: PBMR Core Structure

1.1.3. FUEL DESIGN

The PBMR fuel design is based on a German design using a moulded graphite sphere containing coated fuel particles of the so-called LEU-TRISO (Low Enriched Uranium Triple coated Isotropic) design. The PBMR fuel sphere consists of an inner matrix graphite region of 50mm diameter, known as the fuel region, that contains fuel

in the form of coated particles. A 5mm thick shell of matrix graphite that does not contain any coated particles, known as fuel free region, surrounds the fuel region. A coated particle consists of a kernel of uranium dioxide surrounded by four coating layers. They are, from the inside outward, a low-density buffer layer, a high-density Pyrocarbon layer, a silicon carbide layer, and a second high-density Pyrocarbon layer.

The porous buffer layer accommodates any mechanical deformation that the kernel may undergo during the lifetime of the fuel, as well as fission products released from the kernel, without over-pressurizing the coated particle. Deformation of the kernel is due to a change in density, which is caused by fission products. The pyrolytic carbon (a very dense form of heat-treated carbon) and silicon carbide layers provide an impenetrable barrier containing the fuel and the fission products that result from nuclear fission reactions. Figure 3 shows a cross section of Pebble Bed TRISO coated particle.

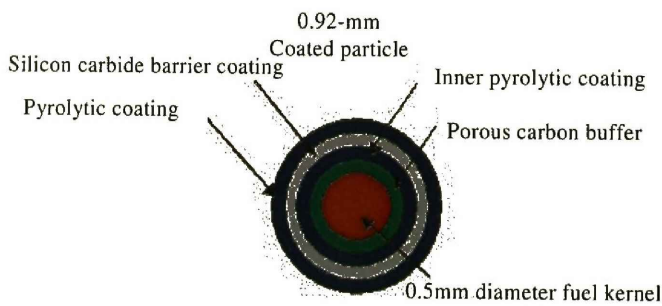


Figure 3: Pebble Bed TRISO Coated Particle Cross Section

1.1.4. FISSION

Fission is the splitting of a heavy atomic nucleus either spontaneously or as a result of an impact by another particle. Fission results in the formation of lighter nuclides that are known as fission products, most of whom are radioactive. Fission products

resulting from fission are neutron rich and decay mostly by emission of beta particles and gamma rays. Fission products can be classified as gaseous or solid.

Fission products released from fuel spheres circulate in the primary circuit of the PBMR and some, especially metallic fission products, are deposited on cool inner surfaces of components during reactor operation. Gaseous fission products remain in the reactor coolant reaching an equilibrium concentration determined by their half-lives and production rates. The study of fission product behavior is of great significance for shielding design and safety analysis in PBMR.

1.1.5. BEHAVIOUR OF FISSION PRODUCTS IN PBMR FUEL

The TRISO coated particle design with its two high-density pyrocarbon layers and silicon carbide layer ensures that almost all fission products are kept safely within the kernel and buffer layer. Gaseous fission products are totally contained by the pyrocarbon layers. However, metallic fission products like caesium and strontium diffuse through pyrocarbon at an appreciable rate at temperatures occurring in the PBMR core under normal operating conditions. The diffusion of metallic fission products from coated particles is prevented by the addition of the silicon carbide layer. The only exception is silver, which diffuses readily through all coating layers at temperatures occurring in the PBMR core during normal operating conditions. Thus, except for silver, all fission products are totally contained within intact coated particles.

However, each fuel sphere contains a very small amount of free uranium i.e. uranium not covered by an intact silicon carbide layer. This is due to;

- Coated particles damaged during pressing of fuel spheres
- Contamination of the outer surface of the outer pyrocarbon layers of coated particles by enriched uranium during the coating process
- Natural uranium and thorium contained as impurities in the natural graphite that forms the major constituent of matrix graphite.

Free uranium present in fuel spheres undergoes fission reactions in the reactor core and fission products from this source diffuse freely through the matrix graphite and are released into the coolant stream during normal operation. Fission products from

this source are the major contributor to fission product release during normal operation.

Temperature transients may cause failure of additional coated particles in the reactor core giving rise to an increase in fission product release rates as fission products released from the damaged coated particles diffuse through the matrix graphite and are released from fuel spheres.

The bounding case for fission product release is the Depressurized Loss of Forced Cooling (DLOFC) event in which it is assumed that all helium coolant is lost through a break in the primary coolant circuit resulting in core heat-up. This event results in the largest anticipated temperature transient for PBMR. The PBMR is designed in such a way that natural processes eventually cool the reactor if such an event occurs. During a DLOFC the reactor core reaches its highest temperature after about 50 hours and then slowly cools down over a long period. Although the fuel in some parts of the reactor core might reach temperatures as high as 1600^{o} C it is only a relatively small fraction of the total core volume that reaches the maximum temperature.

1.1.6. IMPORTANCE OF FISSION GAS AND IODINE

Metallic fission products released from fuel spheres during normal operation plate out on cool surfaces in the primary coolant circuit and are removed from the circulating coolant circuit. This might in time create difficulty with maintenance. Gaseous fission products remain in the circulating coolant and eventually reach an equilibrium concentration in the coolant. Thus the activity of gaseous fission products in the coolant is a direct indicator of fuel performance in the reactor core. Furthermore, all gaseous fission products present in the coolant will be released during a DLOFC event.

The behavior of iodine isotopes produced as a result of fission is very similar to the behavior of the fission gas xenon with the exception that iodine plates out readily on cooler surfaces and is thus removed from the coolant stream like metallic fission products. This results in a lower equilibrium concentration of iodine in the coolant stream with a corresponding lower release during a DLOFC event.

In the assessment of consequences of HTGR Licensing Base Events (LBE's) iodine is considered to be the most important radionuclide because of its ingestion hazard potential. Iodine-131 is formed within fuel spheres and has a half-life of 8 days. This

UNW LIBRARY

means that any ^{131}I present in a fuel sphere depends strongly on the recent power history of the fuel sphere.

1.1.7. MODELLING OF FISSION GAS AND IODINE RELEASE DURING A DLOFC

Although a number of computer codes have been developed to model the detailed behavior of gaseous fission products and iodine there is a need to develop a simple model that is easily understood to calculate the release of fission gas and iodine from a fuel sphere during a DLOFC and can be used for scoping analyses.

The processes that need to be modelled are:

- Number of initially failed coated particles
- Additional coated particle failures resulting from a DLOFC temperature transient
- Fission gas and iodine diffusion from kernel
- Fission gas and iodine release from fuel sphere

1.2. RESEARCH PROBLEM

Previously a simple fission product release model suitable for hand calculation was developed for scoping calculations of the release of gaseous fission products and iodine from the PBMR under accident conditions. Keeping the calculations quick and simple required a model to handle the temperature history of fuel spheres in the reactor that, although conservative, was not quite realistic. It is therefore necessary to refine the modeling of the temperature history prior to and during a temperature transient and to develop a computer program incorporating the new model to speed up scoping calculations.

1.3. RESEARCH OBJECTIVE

To customize/develop and test a computer program based on a simple coated particle failure and gas diffusion model that could be used to perform scoping calculations for the release of gaseous fission products and iodine during a temperature transient event for the PBMR.

1.3.1. SCOPE OF RESEARCH

An existing model and methodology for the release of gaseous fission will be used as basis for the development of the computer program. The research component will consist of the development of a better model to describe the effect of the temperature history prior to and during temperature transients due to LBE's. The scope of research will be limited to the modeling of the release of gaseous fission products and iodine.

1.4. RATIONALE

1.4.1. FISSION PRODUCTS

- The calculation for the release of ^{131}I is of great importance since iodine is the limiting fission product. It is produced in relatively large quantities by nuclear fission. Iodine is hazardous when ingested or inhaled as a gas.

- The study of fission product characteristics is of significant value for shielding design and safety analysis in High Temperature Gas-cooled Reactors.

- In order to be able to select suitable fuel and core dimensions, there is a need to carry out fission product release analysis.

1.4.2. MODEL

The model developed for PBMR 268 MW design uses tedious manual ways of calculating the release of fission products and iodine that makes it unsuitable for scoping calculations.

1.4.3. COMPUTER PROGRAMS

Other computer programs in use are based on involved models requiring fairly detailed input data and are not amenable to the performance of scoping calculations. That is why there is a need to develop a basic efficient computer program, which could be used to calculate fission product release during temperature transients resulting from Licensing Base Events (LBE's).

CHAPTER 2: LITERATURE SURVEY

2.1. MAIN PROCESSES IN MANUFACTURING FUEL PEBBLES

There are 4 major processes used to make fuel spheres [1], i.e.

1. Kernel formation
2. Coating of kernels
3. Mixing of graphite powders to make matrix graphite powder
4. Fuel sphere manufacture

2.1.1. Kernel formation

Enriched uranium in a powder form of U_3O_8 is transformed into uranium dioxide kernels by completion of the steps shown in Appendix 1[2]. The level of enrichment will always be below 20% and can thus be classified as low enriched uranium [1].

2.1.2. Coating of kernels to make coated particles

The four coating layers are deposited on kernels in a heated furnace by chemical vapour deposition (CVD) [1]. Flowing gases in the furnace suspend the kernels so that they form a fluidised bed. Gases that are chosen decompose at high temperatures and deposits certain of their constituents on the surfaces of the kernels. Materials formed by this process are described as pyrolytic [1]. The complete process for producing LEU-TRISO coated particles is shown in Appendix 2 [2].

2.1.3. Mixing of matrix graphite

Matrix graphite powder has three solid ingredients namely natural graphite powder, electro-graphite powder (graphitised petroleum coke) and phenolic resin (binder). These are mixed and milled in order to give the fuel spheres isotropic properties. See Appendix 3 for steps [1].

UNW LIBRARY

2.1.4. Fuel sphere manufacture

The fuel production facility processes coated fuel particles from coating production and graphite matrix material powders from matrix production, to produce finished fuel spheres (FS) [2]. The coated particles are first over- coated with a finely crushed graphite material. It is then embedded in a matrix of resinated graphite powder and pressed to form 'green' fuel sphere. The 'green' fuel spheres are machined on a lathe, carbonized and annealed. After the heat treatment the FS are perfectly spherical. The last step in the production line is the FS quality control with visual inspection, size control, weight control and x-raying [2]. Figure 4 shows a diagram of PBMR fuel spheres.

Steps involved in fuel sphere manufacturing are shown in Appendix 4 [2].

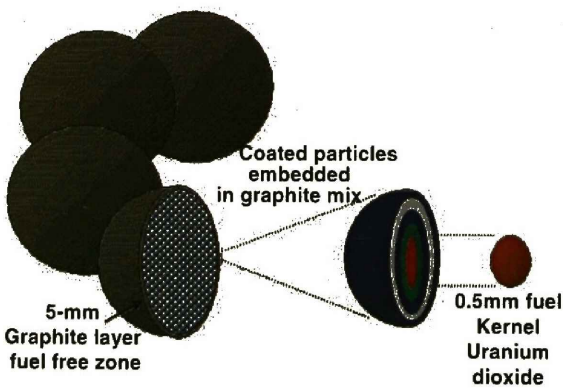


Figure 4:PBMR Fuel Pebbles/Spheres

2.2. FISSION GAS RELEASE

The dominant source of fission product release during normal operations would be particles with defective coatings [4]. It is assumed, in the safety analysis, that a fraction of 6 x 10^{-5} of manufactured coated particles in the PBMR core is defective [2].

Coated particle fuel has been developed for use in high temperature reactors. The encapsulated fuel kernel retains a significant portion of the radiologically important, short-lived fission gases such as Kr-88 and I-131. Fuel kernels will also retain long-lived, volatile, fission product metals such as Cs, Sr and Ag to some extent [4].

This LEU-TRISO coated particle has been tested in in-pile and out-of-pile applications, aimed principally to evaluate the fission product release under normal and transient conditions of high temperature reactor operation [5]. Almost all fission products are retained within the coated particles during normal operation [6], anticipated operational occurrences and accidents.

Intensive research performed in this field has shown that defective coatings result from:

- Direct contact or closeness to neighboring coated particles, and
- Damage to coatings of odd-shaped particles during the high-pressure moulding stage [4].

Direct particle-to-particle contact and closeness to neighboring particles is avoided by adding an evenly distributed layer of graphite matrix material around each coated particle. Odd-shaped coated particles caused by, for example, uneven kernels (or other reasons), are separated out prior to the pressing stage. Passing them over slightly inclined vibrating plates would remove non-round kernels and coated particles [4].

2.2.1. Damage to Coatings

The silicon carbide intermediate layer is the main fission product barrier for fuel spheres, which contain particles with a TRISO coating. It is effective at temperatures up to 1800 ^{0} C and for short periods at temperature above 2000 ^{0} C.

During accident temperature transients up to and including 1600 ^{0} C, fission products with the exception of Ag 110m, are only released from contamination or coated particles with defective SiC layers. Failure of coated particles could be due to manufacture or irradiation [7].

2.2.2. Consideration of fuel failure causes [6]

Failure of coated particles is due to design, manufacture, operations, and accidents

- Initial manufacturing defects can be quantified before irradiation and typically has a value in the order of 10^{-5}
- Operational failures due to manufacturing defects (e.g. missing or too dense buffer and very thin layers) are addressed by the coated fuel particle (CFP) sample.
- Potential operations-induced failure causes include

  - Kernel interactions with coating layers due to increased coated particle radial temperature gradient (i.e. high particle power over time)
  - SiC layer tensile failure due to increased kernel fission gas release as a result of high kernel burn-up and high temperature exerted to CFP's.
  - Pyrocarbon (PyC) initial shrinkage and later growth due to high fast neutron fluence in combination with low temperature causing PyC layer cracking or debonding from the SiC layer resulting in SiC layer cracking failure [6].
  - SiC chemical attack by lanthanides and palladium due to kernel burn-up at high temperatures

Potential accident-induced failure causes include:

Heat-up accidents

- SiC layer thermal decomposition into Si + C at very high temperature.

Reactivity accidents

- SiC layer failure due to rapid large energy deposition and temperature rise in the kernel over a short space of time.

Chemical attack accidents

- Oxidation of the CFP layers due to ingress of air flowing past the CFP's at high temperature.

Interaction of palladium (Pd) with the silicon carbide layer (SiC) is the most noteworthy phenomenon in High Temperature Reactor (HTR) TRISO fuel behavior, because the interaction deteriorates the silicon carbide coating layer. This also results in fission product release [5].

A defect fraction of 3 x 10^{-5} [3] was selected as the expected value for PBMR fuel element production. This value is typical of the fuel produced in Germany for the HTR-modul Proof Test in 1988.The radiological calculations are, however, based on a conservative design value of 6 x 10^{-5}, [4] i.e. less than one defective particle in every fuel sphere. Figure 5 shows a cross section of a defective fuel particle.

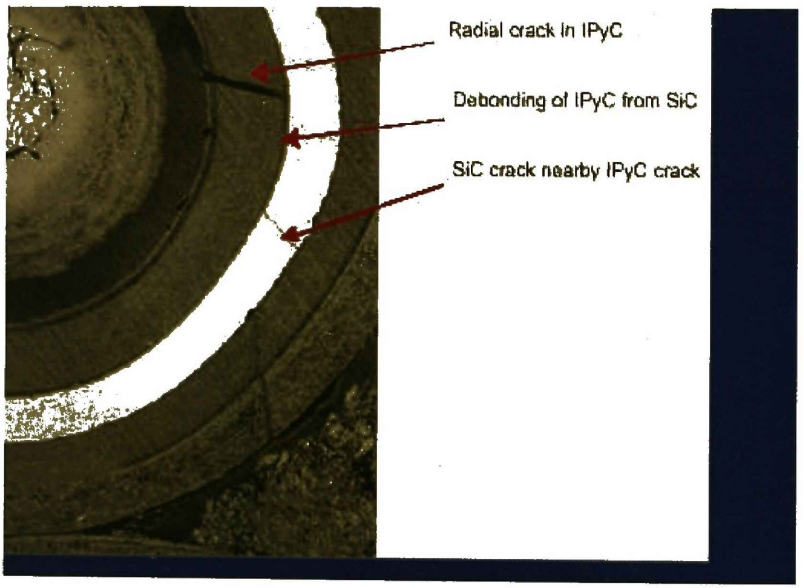


Figure 5: Photomicrograph of Defective Fuel Particle Cross-section

2.3. EVALUATION OF FISSION GAS RELEASE

Steady-state release and diffusive fraction of transient release are by means of diffusion code [8]. Table 1 shows typical diffusion properties used in such codes.

Table 1: Diffusion properties

Parameter	Dim	Krypton	Xenon
Recoil fraction from 500µm UO_2 kernel	%	2.9	2.3
Porosity of kernel	%	2.5	
Porosity of buffer layer	%	50	
Frequency factor of reduced diffusion constant D_0			
Kernel	s^{-1}	$2.5*10^{-2}$	$3.6*10^{4}$
Buffer layer 1	s^{-1}	$6.0*10^{-3}$	$1.9*10^{-7}$
Buffer layer 2	s^{-1}	2.0	$9.8*10^{-3}$
Activation energy of reduced diffusion constant D_0			
Kernel	KJ/mol	311	161
Buffer layer 1	KJ/mol	106	3305
Buffer layer 2	KJ/mol	51.1	33.5
Fraction of buffer layer 2			
<2.9 % FIMA	%	10	
>3.2 %FIMA	%	5	

[Buffer layer 1=grains with low diffusivity]

[Buffer layer 2 = amorphous component with high diffusivity]

[FIMA = Fission per Initial Metal Atom]

To take breakaway release into consideration, 0.5% of defective particle inventory is released during temperature rise as a conservative approximation for short-lived nuclides ($T_{1/2}$= 10 hours). This fraction amounts to 1% for longer-lived nuclides (I-131,I-133,Xe-133m,Xe-133) [6].This contribution is valid irrespective of burn-up during increases in fuel temperature from 50 -200°C above the maximum value occurring during the preceding 0.5% FIMA [8].

A classical release model has been assumed for design basis accidents in which 100% of noble gases, 25% of the iodine and 1% of the other fission products are released [9], In the temperature range 1100°C to 1800°C, the release of gaseous fission products from fuel elements with TRISO particles remains very small, even

after a longer period of heating. Any ^{85m}Kr activity due to contamination is driven off during heating up. When defects occur in the coating, fission gases are released from fuel particles [7]. About 50 percent of the fission gas inventory of a particle is released spontaneously at 1600 ^{0}C to 1800 ^{0} C. The release fraction is calculated using the formula, Release activity (A_t) calculated from measurements (Bq) divided by inventory activity (A) (Bq).

$$A_t = I_t \frac{e^{\lambda t}}{f_E} \quad [7] \qquad [1]$$

[A_t (Bq) = activity released at time t calculated at end of irradiation]

[I_t (1/s) = measured pulse rate from released activity at time t]

[λ(1/s) = decay constant]

[t(s) = time from end of irradiation]

[f_E = calibration factor]

For nuclides with short half lives, where the rate of birth and rate of decay during irradiation are equal (birth/decay equilibrium), the relative release is defined as R/B = Release rate /Birth rate.

For the long-lived ^{85m}Kr, no R/B equilibrium is established during irradiation. The measured release rate is therefore related to the inventory N (at the end of the of irradiation). The release rate R for Xenon-133 or Krypton-85 is determined from the relation [7]

$$R = \frac{\Delta I}{\Delta t} \frac{e^{\lambda t}}{\lambda f_E} \qquad [2]$$

[$\frac{\Delta I}{\Delta t}$ = slope in release curve in area of equilibrium release]

Iodine-131 is evaluated directly by a computer connected to the test rig using a special program [7]. At temperatures up to 1000 ^{0} C a rapid release is observed. The fractional release however remains below the recoil fraction. A significant contribution

from the kernel is visible only when temperatures exceed 1300 ^{0} C. The release increases steeply up to 100% if temperatures reach about 1700 ^{0} C. The kernel release shows the expected poorer retention at higher burn up. In the recoil fraction region, increasing burn-up reduces the fractional release [10]. The solution of the diffusion equation involving emission from traps (sites at which iodine may be confined in the material) can be approximated in a general way for the trapped species under isothermal heating conditions. Fractional release is represented as:

$$F(t) = \left(1 - e^{\sqrt{(-t/\tau)}}\right) f_{burst}\ (T) \qquad [3]$$

[F(t)= fractional release]

[f_{burst} (T) =temperature dependent fraction of occupied traps released at a fixed temperature]

[τ (T)= time dependent parameter for the emission rate]

2.4. TEMPERATURE DEPENDENCE

The release of ^{85m}Kr from pebble fuel increases monotonously with temperature where the release levels depend on the degree of exposed uranium. The release is controlled by bulk diffusion in the graphite grains of the compact matrix. The release from loose coated particles was found to be fairly the same as that of Xenon diffusion in the pyrolytic carbon layer [5].

Silver (Ag) 110m is the only fission product that diffuses through intact Silicon carbide coatings at high irradiation temperatures (1000 ^{0} C to 1200 ^{0} C) and from fuel elements. After long irradiation at 1000 ^{0} C to 1200 ^{0} C Ag 110m is released in similar quantities as after a few hundred hours at 1600 ^{0} C. Iodine-131 and Xenon-133 release in the temperature range 1000 ^{0} C to 1200 ^{0} C does not rise at the same rate as the temperature, but has a delayed relatively steep rise (burst), which is followed by a much lower release [7]

UNW
LIBRARY

2.5. MODEL DESCRIPTIONS

2.5.1. Fission gas release

In the JAERI model, fractional release of short-lived fission gas is expressed in terms of the ratio of release rate to birthrate, because radioactive equilibrium is established under normal operating conditions. The model was developed to accurately predict fission gas release fraction from a fuel compact with low failure fraction [7]. ^{88}Kr is released from through-coatings failed particles and uranium contamination in the fuel compact matrix and the result showed that the(R/B) ratios from the uranium contamination are much larger than those from the through-coatings failed particles through operation.

The FZJ model treats only the release from through- coatings failed particles. This means that the gas release in the FZJ calculation is dominated by the contribution from failed particles. This is composed of the initially through coating defect fraction and the gradually increasing irradiation induced failure fraction of particles, which have fabricated. SiC layer defects show no defects initially. The total ^{88}Kr gas release fraction agrees with the JAERI result [11].

The iodine release from the GA model indicates that for the maximum conduction cool down temperature occurring, a small fraction of the iodine released by SiC corrosion and temperature decomposition mechanisms is escaping through the intact OPyC layer. The GA model considers retention by the kernel and OPyC layer. KFA/ISF is based on the recommended diffusion coefficient for krypton in which the pyrocarbon predicts complete retention of iodine in the OpyC layer under the given time and maximum temperature conditions. No iodine release is predicted for the average temperature history in KFA/ISF model calculations, where the PANAMA code was used [12].

2.5.2. Booth model

It has been found experimentally that the fraction (f) of Xenon-133 evolved in a standard laboratory heating test on irradiated fuel samples is independent of the size of the sinter body (i.e. the pellet size). This is interpreted to mean that the rate-controlling step is diffusion out of the crystallites composing the sinter [13]. The subsequent process of migration out along the grain boundaries is very much faster

and can be ignored except when considering short time intervals. For analysis, one must idealize by choosing a parameter that will serve to represent approximately the system.

The procedure followed in this model is to consider the diffusion system to be an assembly of uniform spherical regions. The controlling parameter is then the radius of these hypothetical spheres, irrespective of their identity with the visible grain structure. The Booth model has the advantage that it is easily handled mathematically [13]. This model assumes that a sphere initially contains a uniform concentration of a stable fission product with zero concentration on the sphere surface [13]. Production and decay of fission product during diffusion is not considered [13].

2.5.3. THE PBMR SOURCE TERM

2.5.3.1. Failure fraction

The release source term from PBMR fuel elements is calculated using free uranium fraction data from fuel produced for the German HTR-Modul Proof Test. The failure fraction data is obtained from generic irradiation tests on Phase 1 fuel elements and temperature data was obtained from VSOP calculation. The release fraction data from coated particle kernels is calculated using the Booth model [14].

The two (fuel produced for the German HTR-Modul Proof Test and Phase 1 fuel elements) German fuel types used are very similar to PBMR fuel elements. The number of coated particles for the German fuel types spans the value for the PBMR fuel elements, while Uranium enrichment values are higher than that for PBMR fuel [14]. The latter was caused by a reduction in the free uranium fraction values from 1981 to 1988. This was brought about by the introduction of sorting of coated particles during manufacture to remove unround coated particles and by the replacement of manual overcoating process by an automated process. Both these processes are incorporated in the PBMR fuel manufacturing process and it is therefore expected that the free uranium fractions for PBMR fuel elements will be similar to those obtained for German Proof Test fuel elements. A number of fuel elements irradiated during the phase 1 generic fuel test program containing 82 000

coated particles were heated to 1600 ^{0}C to simulate a DLOFC temperature transient. The particle failure fraction values found were combined to establish a relationship between coated particle failure fraction and temperature for PBMR fuel. It was assumed that the failure fraction increases exponentially with temperature between 1200 ^{0}C and 1600 ^{0}C [14].

2.5.3.2. Kernel release fraction

When a coated particle fails, it is considered to consist only of a bare kernel and no credit is taken for any retention of fission products by remnants of the outer coating layers of the coated particle or the surrounding graphite matrix of the fuel element. Fission products that reach the surface of the fuel element are released freely into the coolant gas surrounding the fuel element. The fuel sphere is assumed to contain a uniform concentration of a stable fission product with zero concentration on the sphere surface [14], in the release according to the Booth model.

The diffusion constant used for PBMR iodine release calculation consists of two Arrhenius-type expressions and reduced diffusion constant values for PBMR kernel dimensions were calculated for each temperature [14].

2.5.4. RESEARCH METHODOLOGY

As previously stated, a failure fraction curve for PBMR fuel elements was calculated using German data obtained for two fuel types produced in Germany in the 1980s.Temperature distributions for PBMR fuel elements were calculated using a core design program VSOP. To be able to calculate the average failure fraction for each layer, an analytical expression for the relationship between failure fraction and temperature is needed. If an exponential relationship is assumed, the variation of the failure fraction with temperature above 1200 ^{0} C is described using an expression of form: F = A*exp (Bθ), where A and B constants, θ is the temperature in degrees Celsius. Figure 6 depicts the variation of failure fraction with temperature.

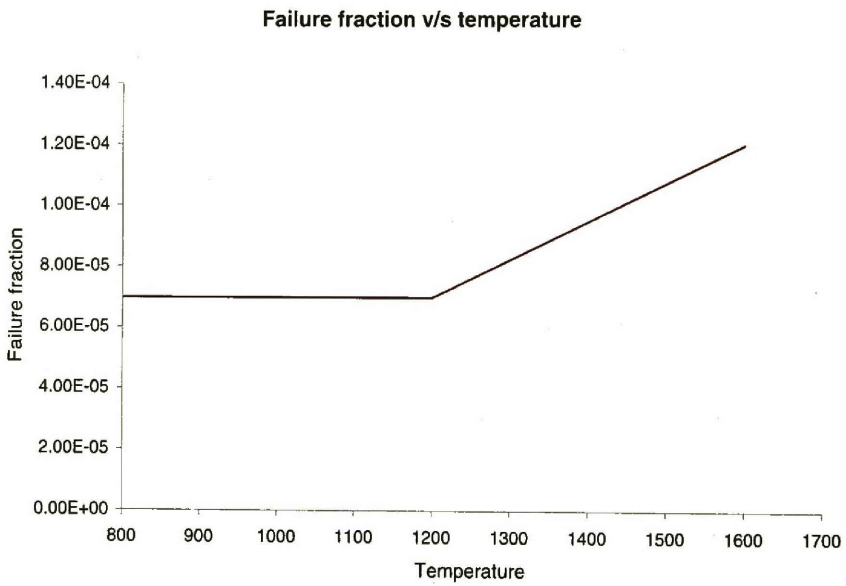


Figure 6: Variation of the failure fraction with temperature above 1200 ^{0} C

It is assumed that the failure fraction remained constant at the failure fraction value for equilibrium fuel [14] for temperatures below 1200 ^{0} C. In order to be able to calculate the kernel release fraction one need to have the diffusion constant and the reduced diffusion constant. Reduced diffusion constant values for PBMR kernel dimensions were calculated for each layer at the average absolute temperature values.The objective that this research is trying to achieve is to come up with a

simplified basic method that could be used in scoping of calculation for the release of gaseous fission products and iodine using both MathCAD and Fortran 90 computer programs. The sequence in which the work is will be done is as follows:

- Using MathCAD calculate
  - the Failure fraction, Kernel release fraction and Core release fraction
  - the release of fission gas and iodine during transient conditions
- Develop a flow chart for selected cases from the above calculations and change it to a Fortran 90 program.
- Run other PBMR sample problems using this program.
- Compare the results from the developed computer program and the results from the PBMR source term calculation.

CHAPTER 3: DISCUSSION OF RESEARCH METHODOLOGY

3.1. THEORETICAL BACKGROUND

The PBMR core is continuously replenished with fresh or re-useable fuel from the top of the reactor, while used fuel is removed from the bottom after each cycle through the reactor. Each fuel pebble is measured to determine the amount of fissionable material that is still left after each cycle. If a pebble still contains a usable amount of fissile material, it is returned to the top of the reactor for a further cycle. Each cycle takes about five months [18].

When a fuel sphere has reached a burn-up of 92 000 MWd/t (megawatt days per tonne) of uranium metal, it is removed and sent to the spent fuel storage facility. Each fuel pebble passes through the reactor about 6 times, and a reactor will use 10 to 15 total fuel loads in its design lifetime. A fuel sphere will last about two and a half years.

The extent to which the enriched uranium is used to depletion (called the extent of 'burn-up') is much greater in the PBMR than in conventional power reactors. There is therefore minimal fissile material that could be extracted from depleted PBMR fuel. This, coupled with the level of technology and cost required to break down the barriers surrounding the spent fuel particles, protects PBMR fuel against the possibility of nuclear proliferation or any other covert use. During reactor shutdown, residual heat is removed by active and/or passive cooling of the system.

Even though the unit is rated as a base-load plant, it can load follow and run according to a prescribed daily cycle. As a typical example, the following load following profile was successfully analysed to meet the Depressurized Loss of Forced Cooling (DLOFC) criterion:

- eight hours operation at 60% nominal power,
- followed by 14 hours at 100% nominal power,
- followed by two hours operation at 120% nominal power.

This means that the heat the reactor loses through its surface (via the same process that allows a standing cup of tea to cool down) is more than the heat generated by the decay fission products in the core. Hence the reactor can never (due to its thermal inertia) reach the temperature at which a meltdown would occur. The plant can never be hot enough for long enough to cause damage to the fuel [19].

3.1.1. Fission product release by coated fuel particle

Fission products are formed within the fuel kernel, and then diffuse out to the pyrocarbon layer. Metallic fission products then diffuse slowly through the pyrocarbon layer into the Silicon Carbide layer. The SiC layer of coated particles is regarded as the decisive transport barrier for fission gas, iodine and metallic fission products. For intact-coated particles fission products are retained safely within the coated particle by the SiC layer, whereas for defective particles fission products diffuse out of the coated particle. This release of fission products is determined by containment in the kernel of the particle [20]. Temperature increases during operation increases the defect fraction.

3.1.2. Failure fraction

As previously stated, a failure fraction curve for PBMR fuel elements was calculated using German data obtained for two fuel types produced in Germany in the 1980s. Temperature distribution for PBMR fuel elements was calculated using a core design program VSOP. The ORIGEN code can be used to determine the fission product quantities that are distributed in the core.
The important characteristics of the two fuel types produced in Germany in 1980 are compared in table 2.

Table 2: Comparison of fuel Characteristics

Fuel element type	Phase 1	Proof test	PBMR
Year of production	1981	1988	-
Coating batch size (UO_2)	5kg	5kg	5kg
Number of coated particles per fuel element	16 400	14 600	14 500
U-235 Enrichment	9.8%	10.6%	9.6%
Free uranium fraction	35 $\times 10^{-6}$	10.6×10^{-6}	-
Number of burn leach tests	5	10	-
Number of failed particles from burn leach tests	3	3	-

From the above comparison, it is clear that the two fuel types are very similar to PBMR fuel elements. The number of coated particles for the two German fuel types spans the value for PBMR fuel elements, whereas the enrichment values are somewhat higher than that for PBMR fuel. There was a reduction in the free uranium data fraction values from 1981 to 1988. This was brought about by the introduction of sorting of coated particles during manufacture to remove unround coated particles and by the replacement of the manual overcoating process by an automated process. Both

these processes are incorporated in PBMR fuel manufacturing process and thus it is expected that free uranium fractions for PBMR will be similar to those obtained for German Proof Test fuel elements [14]. Assuming that a Poisson distribution can describe the number of failed particles per fuel element, an expected value and an upper 95% confidence level value for the failed particle fraction can be calculated for as-manufactured German Proof Test fuel.

From table 2, a total of three failed particles were found in 10 burn-leach tests for Proof Test fuel elements. The 10 fuel elements in the test contained 1.46×10^{5} coated particles. Thus the expected failure fraction for the Proof Test production lot from burn-leach test results is 2.05×10^{-5}. The number of failed particles at the upper 95% confidence level is 8.767 and the corresponding failure fraction is 6.00×10^{-5}.

In the Generic phase of German fuel qualification tests using fuel elements, a total number of 211 936 coated particles were irradiated to burn-up values ranging from 7.5% FIMA to 14.7% FIMA at temperatures ranging from 800^{0}C to 1300^{0}C. A variety of samples including fuel elements, small spheres, compacts and coupons were used in the irradiation tests. Using a Binomial distribution and the fact that no particles failed during irradiation, an upper 95% confidence failure fraction was found to be 2×10^{-5} [14].

A number of fuel elements irradiated during phase 1 generic fuel test program, containing 65 500 coated particles were heated to 1600^{0}C to simulate a DLOFC temperature transient. No particle failure was observed during the heating test. In this regard the upper 95% confidence value was found to be 5×10^{-5}. The particle failure fraction found above were combined so as to establish the relationship between coated particle failure fraction and PBMR fuel temperature, as shown in Table 3.

Table 3: Relationship between failure fraction and temperature

Temperature (^{0}C)	Expected Failure Fraction	Upper 95% Confidence Level Failure Fraction (Design Value)
800	3.5×10^{-5}	7.0×10^{-5}
1200	3.5×10^{-5}	7.0×10^{-5}
1600	8.05×10^{-5}	1.20×10^{-4}

UNW LIBRARY

It was assumed that the failure fraction increases exponentially with temperature between 1200 ^{0}C and 1600 ^{0} C. Figure 7 shows the behaviour of failure fraction with temperature.

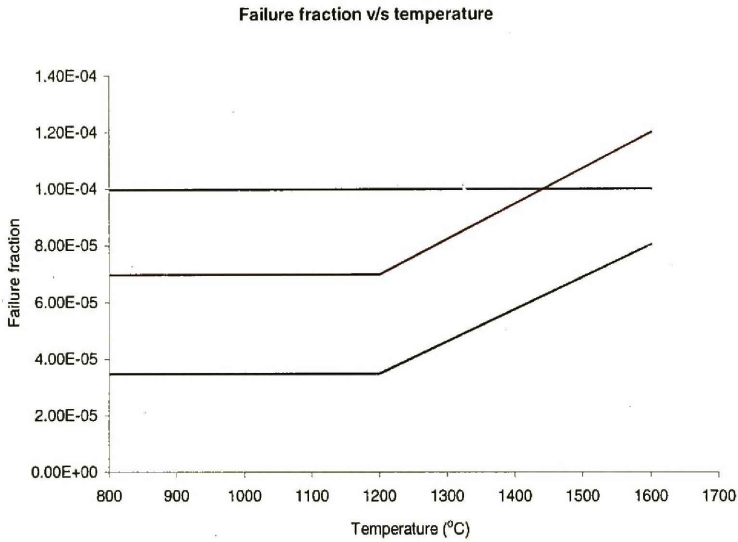


Figure 7:Coated particle failure fraction v/s temperature for PBMR fuel (Design values and expected values)

3.2. CALCULATION OF TEMPERATURE

The core design computer program VSOP (Very Superior Old Programs) was used to calculate the temperature distribution for PBMR fuel elements during a DLOFC temperature transient. Samples of VSOP calculations are shown in Appendix 9. Figure 8 shows a PBMR VSOP model.

The VSOP code enables the user to calculate the reactor life history from the loading to criticality, starting up the reactor and running the reactor towards the equilibrium core conditions. Repeated calculation of the different physics features ensures consistency in their feedback during the proceeding burn-up, the simulation of the fuel shuffling, and variations in the core power rating. Accident phenomena can be analyzed in a quasi-static approximation by repeatedly analysing the reactivity distribution in the reactor core. Characteristics of the life history of the fuel elements are used to calculate the decay power.

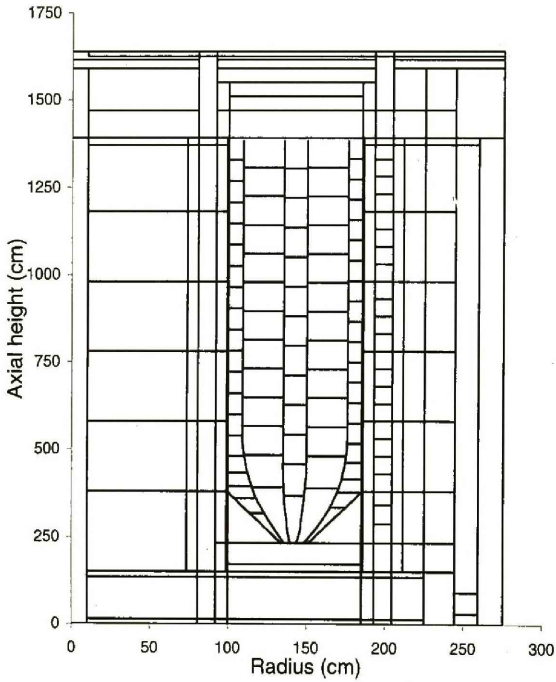


Figure 8: PBMR 400MW VSOP model

VSOP is a set of codes employed to numerically simulate the neutron physical and thermal hydraulic behaviour of thermal reactors. This code is especially adapted for calculating typical layout characteristics of pebble bed high-temperature reactors. These characteristics entail the processing of cross-sectional data, determination of the neutron spectra, double heterogeneous fuel layout calculation, 2-D (r-z) or 3-D (ø-r-z) diffusion calculation, fuel burn up, fuelling mode simulation and conversion parameters, reactor control and 2-D thermal hydraulic consideration under quasi-stationary conditions. These calculations treat the pebble bed area in a cylindrical configuration (i.e. excluding the thermal-dynamic effects of the noses). The VSOP had been applied mostly in the area of graphite moderated high temperature reactors, with both pebble and prismatic fuel types. For this reactor type the most extensive test data exists.

Figure 9 depicts the calculation process followed during the core analyses.

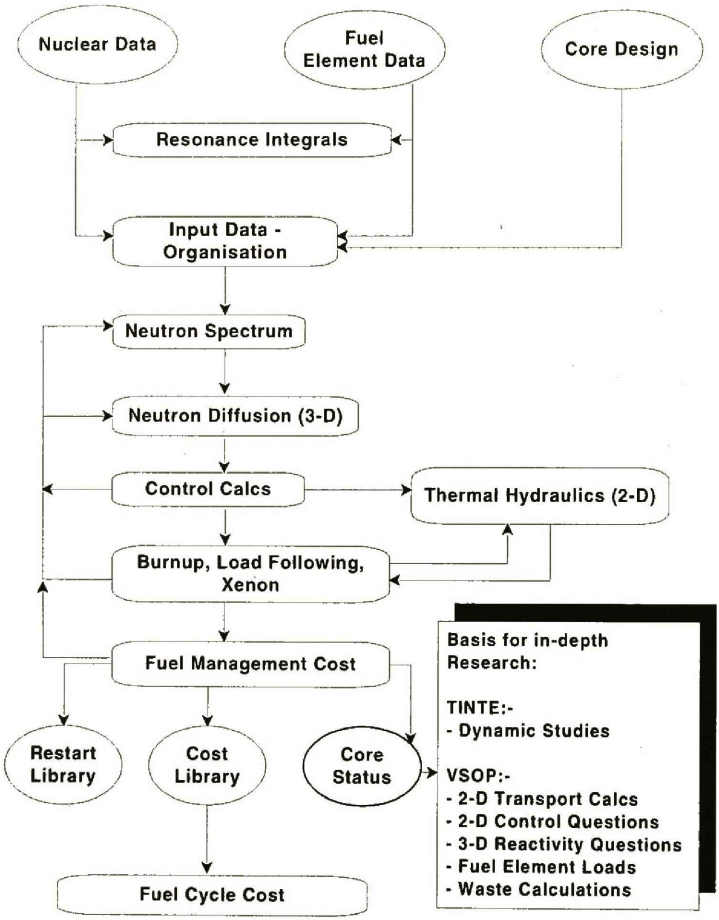


Figure 9: Schematic representation of the VSOP calculation process

The VSOP results used in this research are divided into 5 flow channels of 19,18,18,19. Looking at Figure 8, a flow channel is an area from an axial height of 1500 to 250 and a radius 100 to about 150, whereas a layer is the area between axial height 1500 to 1250 and radius 100 to about 150. Temperature distribution through the reactor core is calculated at different times. At a specific time there are 92 layers. Kernel release fraction is calculated for a time step. Then the kernel release is used calculate the layer release. Finally the summation of all the layer release for a time-step is used to compute the core release fraction (a detailed explanation of how the calculations were done is in chapter 4 of this document.).

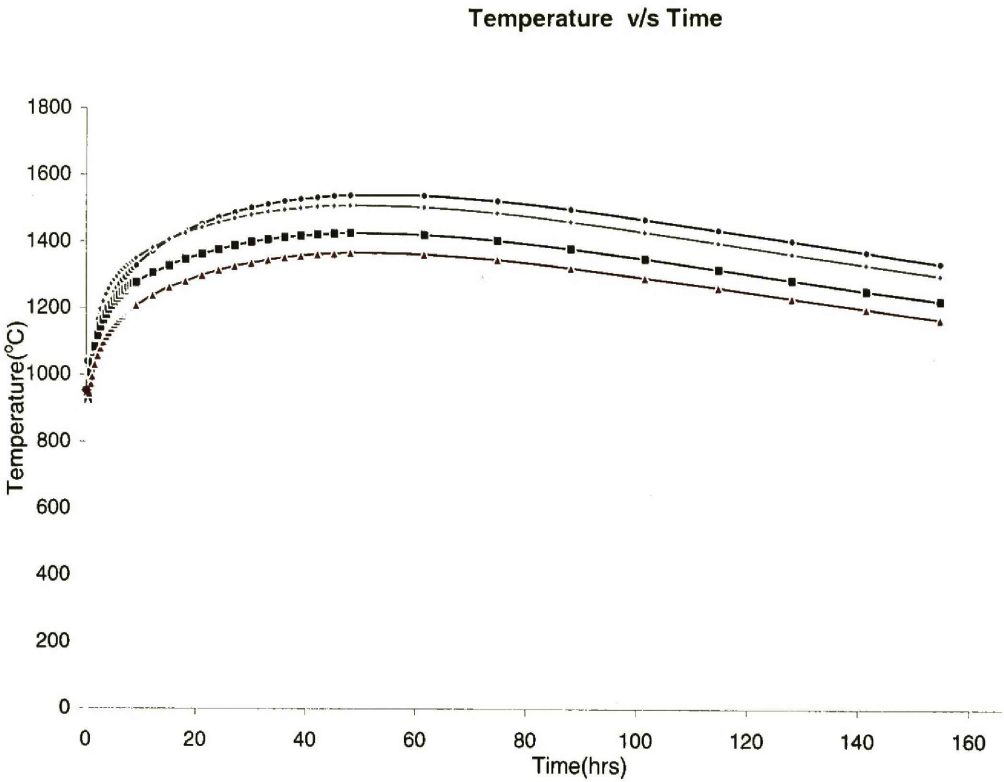


Figure 10: Temperature v/s temperature history during a DLOFC event.

Figure 10 shows examples of the relationship between time and temperature as provided by VSOP for selected layers. Layer 8 is the layer with the highest temperature value of 1538 ^{0}C as shown in table 4.

Table 4: Time-temperature history for layer 8

Time(hrs)	Temperature	Time(hrs)	Temperature	Time(hrs)	Temperature	Time(hrs)	Temperature
0	1042	3.5	1196	12	1373	48	1538
0.1	916	4	1215	15	1405	61.333	1536
0.167	931	4.5	1232	18	1432	74.667	1519
0.233	944	5	1247	21	1454	88	1494
0.3	955	5.5	1261	24	1473	101.333	1463
0.533	989	6	1273	27	1488	114.667	1430
0.767	1017	6.5	1285	30	1501	128	1396
1	1041	7	1295	33	1512	141.333	1362
1.5	1084	7.5	1305	36	1521	154.667	1328
2	1119	8	1314	39	1527	168	1296
2.5	1148	8.5	1323	42	1532		
3	1174	9	1331	45	1536		

3.3. CALCULATION OF FAILURE FRACTION

To be able to calculate the average failure fraction for each temperature value, an analytical expression for the relationship between failure fraction and temperature is needed. If an exponential relationship is assumed, and using the values in table 2, the variation of the failure fraction with temperature above 1200^0C is described using an expression of form:

$$F = Ae^{B\theta} \qquad [4]$$

Where F is the failure fraction, A and B are constants, and θ is the temperature in ^{0}C [14]. At temperatures below 1200^0C, it is assumed that the failure fraction remains constant at the failure fraction value for equilibrium fuel [14].

In order to be able to calculate the kernel release fraction one needs the diffusion constant and reduced diffusion constant. Reduced diffusion constant values for PBMR kernel dimensions were calculated for each layer at the average absolute temperature values. Expected values are the best estimate value while design values take uncertainties into account. Table 5 shows the constants used in equation 4.

Table 5: Values for temperature constants

Constant	Expected value	Design Value
A	1.66×10^{-6}	1.39×10^{-5}
B	2.43×10^{-3}	1.35×10^{-3}

3.4. CALCULATION OF KERNEL RELEASE FRACTION

The release of iodine from a bare kernel can be described in terms of the Booth model. This model assumes diffusion from a sphere $0 \leq r < a$ where a is the sphere radius. The sphere initially contains a uniform concentration of a stable fission product with zero concentration on the sphere surface. Production and decay of the fission product during diffusion are not considered [14]. The temperature dependence of the diffusion constant can be expressed in terms of an Arrhenius equation:

$$D = D_0 e^{-\frac{Q}{RT}} \qquad [5]$$

where D is the diffusion constant for the fission product species in UO_2, D_0 is the frequency factor, Q is the activation energy, R is the universal gas constant and T is the absolute temperature. The reduced diffusion constant (D') is calculated using the following equation:

$$D' = \frac{D}{a^2} \qquad [6]$$

where D is the diffusion constant and $a(=250\times10^{-6}m)$ is the kernel radius

The exact solution for diffusion from a sphere of radius a, where the concentration c of the diffusing substance is initially c_0, uniform throughout, and there is no back diffusion into the sphere from the external phase is obtained by solving the following equation [13]:

$$r \cdot \frac{\partial c}{\partial t} = D \cdot \frac{\partial^2 (cr)}{\partial r^2} \qquad [7]$$

[c=0 at r=a]

[c= c_0 at t=0]

which gives c as a function of r (the distance center) and the time t,thus,

$$c = \frac{-2c_0 a}{r\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} e^{\frac{(-n^2\pi^2 Dt)}{a^2}} \cdot \sin\frac{n\pi r}{a} \qquad [8]$$

Integrating the amount passing through the surface and dividing by the total amount in the sphere initially gives the following equation:

$$f = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{\frac{(-n^2\pi^2 Dt)}{a^2}} \qquad [9]$$

where f is the fraction diffused out of the sphere in time t [13].

The above equation involves the parameter a, which in the present case is the radius of the hypothetical spheres, and hence unknown. Assuming this is constant for any given sinter we can write a new constant as follows:

$$D' = \frac{D}{a^2} \qquad [10]$$

so that the equation becomes a function of t only,

$$f = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2\pi^2 D't} \qquad [11]$$

The modified diffusion constant is valid only for the given sinter on which the experimental determination was made. A reduced diffusion coefficient applicable to a fuel kernel can be determined from diffusion measurements and applications of equation 11.

The infinite series in equation 11 converges rapidly when $\pi^2 D't \geq 1$ and the first term only is then excellent approximation, thus:

UNW LIBRARY

$$f = 1 - \frac{6}{\pi^2} e^{-\pi^2 D't} \quad \pi^2 D't \geq 1 \qquad [12]$$

On the other hand when $\pi^2 D't \leq 1$, it can be shown that

$$f = 6 \cdot \sqrt{\frac{D't}{\pi}} - 3D't \qquad [13]$$

is a good approximation. At $\pi^2 D't = 1$, both approximations are fairly good, but outside these ranges they rapidly become valueless [13]. For the purpose of evaluating D', equation [13] is almost always applicable since it holds reasonably well up to $f = 0.20$ and the fraction evolved is almost always less than this. As previously stated, the diffusion constant used for PBMR iodine release calculation consists of a combination of two Arrhenius-type expressions. The values for the constants are given in Table 6.

Table 6: Arrhenius equation values used in diffusion constant calculations

Temperature range (^{0}C)	D_0 (cm^2/s)	D' (s^{-1})	Q (kJ/mol)
800 to 1300	8.8×10^{-11}	1.408×10^{-7}	54
1300 to 1600	6.0×10^{-3}	9.6×10^{6}	480

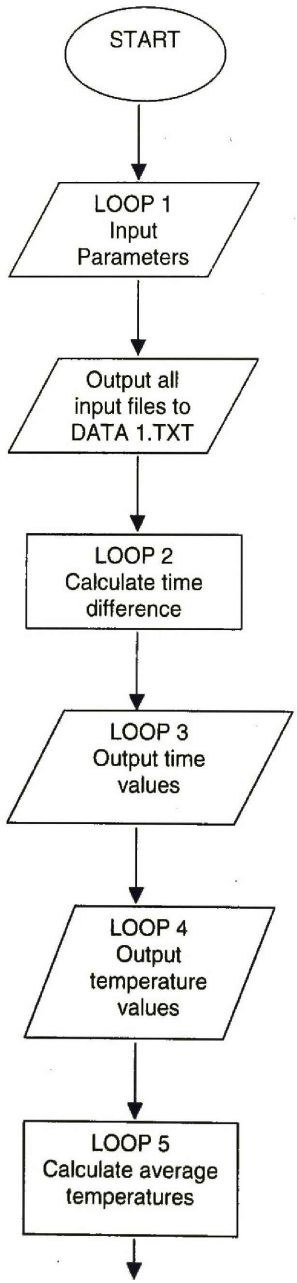
3.5. THE CALCULATION OF IODINE DECAY CORRECTION

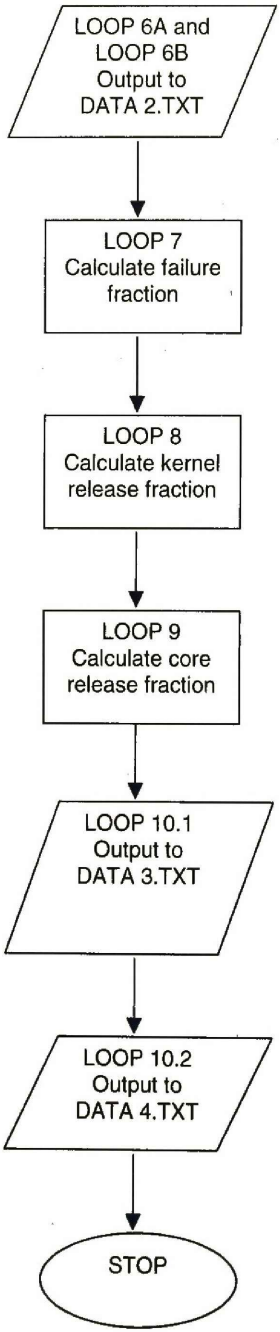
The fission product inventory for the PBMR core was calculated for an equilibrium burn-up mixture of PBMR fuel elements with an average burn-up of 45MWd/t. The half-life of ^{131}I was taken to be 8.0207 days and the decay constant λ of $1.0002\times10^{-6}\ s^{-1}$ was used [14]. The iodine inventory is calculated from the following equation

$$I = e^{-\lambda t} \qquad [14]$$

3.6. LEVEL ONE FLOW DIAGRAM

The following flow diagram indicates in general the steps that were followed when doing the calculations in FORTRAN.




LOOP 6A and
LOOP 6B
Output to
DATA 2.TXT
LOOP 7
Calculate failure
fraction
LOOP 8
Calculate kernel
release fraction
LOOP 9
Calculate core
release fraction
LOOP 10.1
Output to
DATA 3.TXT
LOOP 10.2
Output to
DATA 4.TXT
STOP

CHAPTER 4: PROGRAM DESCRIPTION

4.1. INTRODUCTION

The FORTRAN program, RELEASE, was designed to calculate parameters associated with release of gaseous fission products and iodine for a Pebble Bed Modular Reactor. The theoretical background to the parameters and how they are related is given in Chapter 3 of this dissertation. The specific parameters computed by this program are

(a) the coated particle failure fraction

(b) the kernel release fraction

(c) decay correction

(d) the core release fraction.

The program was developed in Fortran 77 on a Compaq Visual Fortran development platform. Section 4.2 describes the equations used in the calculation of the failure fraction (FF), Section 4.3 describes the equations used to calculate the kernel release fraction (RF) and Section 4.4 of this chapter outlines the relevant equations and relations used in the computation of iodine release. Section 4.5 is a detailed description of the program itself and Section 4.6 is a description of the output files and their contents.

4.2. CALCULATION OF FAILURE FRACTION, FF

The average failure fraction for each layer is calculated using equation 4.

$$F = Ae^{B\theta}$$

where A and B are constants and θ is the temperature in degrees Celsius. This expression applies for temperatures above 1200°C. For temperatures below 1200°C, the failure fraction remains constant at a level of the failure fraction for equilibrium fuel.

4.3. CALCULATION OF KERNEL RELEASE FRACTION

The kernel release fraction (denoted by RF in the program) is calculated from Equation 11,

$$rf = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 \pi^2 D_p \, \delta t}$$

where δt is a time step given by

$$\delta t = t_j - t_{j-1}$$

D_p is given by the expression [8, 9]

$$D_p = D_{01} e^{-\frac{Q_1}{RT_K}} + D_{02} e^{-\frac{Q_2}{RT_K}}$$

where D_{01}, D_{02}, Q_1 and Q_2 are constants. The temperature T_K is given by $T_K = \theta_K + 273$ where θ_K is in degrees Celsius. The expression for the kernel release fraction contains a series, which converges rapidly for $\pi^2 \, \delta t \geq 1$. For this, a first approximation for the kernel release fraction is given by equation 12,

$$f_1 \approx 1 - \frac{6}{\pi^2} e^{-\pi^2 D_p \, \delta t}$$

For $\pi^2 \, \delta t \leq 1$, the convergence of the series is not rapid and an approximation given by expression 13 may be used.

$$f_2 \approx 6\sqrt{\frac{D_p \, \delta t}{\pi}} - 3 D_p \, \delta t$$

4.4. CALCULATION OF DECAY CORRECTION

The iodine decay correction (denoted by DN in the program) is calculated from Equation 14

$$I = e^{-\lambda t}$$

where λ=1.0002 E-6 /s

4.5. DESCRIPTION OF THE PROGRAM AND FILES

4.5.1. The Program Structure

The program carries out three basic operations (a) reading data from an input file and computing intermediate values for use later in the program (b) the computation of the release parameters for the Pebble Bed Modular Reactor and (c) output results of those parameters. A modular approach to the design of this program was considered and discarded because the program is not very sophisticated. The flow diagram in Appendix 5 outlines the general structural flow of the program.

4.5.2. The source code

The source code for RELEASE (VERS34.FOR) was developed in Fortran 77 on a Compaq Visual Fortran platform. The program source code is accessible for editing and alterations, using an appropriate development platform. Also available is an executable file (VERS34.EXE), which is not editable but has the advantage of being platform independent.

It will run on machines that do not have Fortran installed.

4.5.2.1. Main Variables

'T': a one-dimensional array containing time values in hours. Thus 'T' has a range T(1..NTIME) where NTIME is the number of time values for which computation is being done. For the two files that have been used as input files, NTIME=46 for input file TEMPDATA1.TXT and 40 for TEMPDATA2.TXT.

'TSTEP': a one-dimensional array containing the time steps. These are the time differences between adjacent time values. Thus TSTEP(3)=T(3)-T(2). In general, TSTEP(J)=T(J)-T(J1). A related variable is the array 'DELT' which contains the time steps in seconds. Thus they are related by

DELT(J)=3600xTSTEP(I)

'THETAC': a two-dimensional array containing temperatures in degrees Celsius as they are represented in 'TEMPDATA.TXT'. The first dimension of 'THETAC' corresponds to the layer and the second to the time variable. Thus THETAC(2,34) refers to the temperature for the 34^{th} time value (see Table A) for layer 2. 'THETAC' has the range THETAC(1..NLAYER,1..NTIME) to cater for the two input files being used.

'THETAV' : a two-dimensional array containing temperature averages. This array is related to 'THETAC' by averaging temperatures of adjacent time values using the formula

THETAV(J,I)=(THETAC(I,J)+THETAC(I,J+1))/2

where the J index refers to a time value.

'RF': is a two-dimensional array containing the kernel release fraction. It has the range RF(1..NTIME,1..NLAYER)

'RL' is a two-dimensional array containing the layer release fraction. It has the range RL(1..NTIME,1..NLAYER).

'RLRF' is a two-dimensional array containing the layer release i.e. the release of fission products from a specific layer. It has the range RLRF(1..NTIME,1..NLAYER).

'DN' is a two-dimensional array containing the iodine inventory. It has the range DN(1.NTIME,1..NLAYER).

'CRF1' is a one-dimensional array containing the core release fraction. It has the range CRF (1..NTIME)

The source code, VERS34.FOR, is given in Appendix 6. In the description of the operations of the program, reference will be made to loop numbers as they appear in the source code.

Loop 1: Reads Input File

This part of the program reads the constants D01, D02, Q1, Q2, A, B, FFZERO, R, AA, PI, NLAYER, NTIME and AMBDA from the input file, to be used in the calculations. NLAYER is the number of layers and NTIME is the number of time values for which temperature is recorded. Array T, containing the time values, is read next using an implicit loop. Lastly the temperature values are read using a DO loop. The reading of these data is done using a free format READ statement, which avoids the need to format the input file in any specific manner. In the same loop, the constant data read from the input file are written to an output file called 'DATA1.TXT'.

Loop 2: Calculation of time differences

This is done using a DO loop executed over the number of time values, NTIME. The time step or differences are the difference between adjacent time values given by TSTEP (I)=T(I)-T(I-1) for I=1..NTIME. The time differences are also calculated in seconds and stored in array DELT.

Loop 3: Outputs time values

This loop outputs the time values and differences to the same data file DATA1.TXT.

Loop 4: Outputs temperatures

This loop outputs temperature values for each layer to the output data file DATA1.TXT.

Loop 5: Calculation of average temperatures

This loop uses temperatures stored in array THETAC to calculate average temperatures and stores them in array THETAV.

Loop 6A and 6B: Output time and temperature data to DATA2.TXT

These loops create a file 'DATA2.TXT' containing all the time and temperature data.

Loop 7: Calculation of Failure Fraction

This is a nested loop to calculate the failure fraction 'FF'. The inner DO loop calculates over time values and the outer DO loop calculates for each layer. The inner loop uses an IF-ELSE construct to test the temperature values and then applies different computing criteria to calculate 'FF'.

Loop 8: Calculation of RF, RFAPPROX, IODINE and LAYER RELEASE (RLRF) (Incorporating Loops 8.1 and 8.2)

This nested loop carries out most of the work of the whole program. For each layer, the program computes the kernel release fraction 'RF' and its approximation 'RFAPPROX', together with the Iodine inventory 'DN' at every value of time. The computation of RF requires

obtaining the convergence of an infinite sum given in Equation 11. DO Loop 8.2 is used to accomplish this, by summing the terms of the series either up to 20 000 terms or exiting the loop if convergence to an accuracy of 1.0e-16 is obtained. Note that this convergence test can be made any value required. If convergence is not obtained after 20 000 terms are added, a message is sent to the screen to that effect. This convergence test proved adequate on all the data in the input files used. In fact, the series converged rather rapidly, with the slowest taking just over 5000 terms to converge to that accuracy. The program can also be altered to indicate whether convergence was obtained and after how many terms by removing the comment label in the DO loop.

The kernel release fraction (RF) can be approximated by Equation 12 when the condition $\pi^2 \delta t \geq 1$ holds or by Equation 13 when $\pi^2 \delta t \leq 1$. This has been taken into consideration in the DO loop 8.1 to calculate 'RFAPPROX'.

Loop 9A: Calculation of the Core Release Fraction (CRF)

The Core Release Fraction (CRF) is obtained for each time value by adding the layer release fraction (RL) for all the layers. Thus, CRF is a function of the time values. This is accomplished by simple nested simple DO loops. The CRF values are output to file 'CRF.TXT'. In addition to the computation of the CRF, this section computes the integral CRF and the averaged CRF over the number of layers. The program allows the user to do calculations of the CRF or the differential CRF, using a SELECT CASE construct.

UNW LIBRARY

Loop 9B: Calculation of the Core Release Fraction (CRF1)

The Core Release Fraction (CRF1) is obtained for each time value by adding the layer release fraction (RLRF) for all the layers. Thus, CRF1 is a function of the time values. This is accomplished by simple nested simple DO loops. The CRF1 values are output to file 'CRF1.TXT'. In addition to the computation of the CRF1, this section computes the integral CRF1 and the averaged CRF1 over the number of layers. Like in Loop 9A, the program allows the user to do calculations of the CRF1 or the differential CRF1, using a SELECT CASE construct.

Loop 10: Creation of Output Files (incorporating Loops 10.1 and 10.2)

This section of the program creates two output data files DATA3.TXT and DATA4.TXT. DATA3.TXT contains the kernel release fraction (RF) and DATA4.TXT contains the kernel release fraction (RF), the failure fraction (FF), the iodine inventory (DN) and the layer release RLRF.

4.5.2.2 Program Verification and Accuracy

Program verification is a process whereby tests are carried out to check whether the results being produced are what the program is expected to produce. This is usually done with a set of data for which the results are already known from other sources and preferably using another different computing platform. MathCAD has been used to verify the accuracy of the results obtained using this program. Accuracy in computation can be affected by factors beyond the control of the programmer. Such factors include the electronic properties of the computer being used and factors such as the word length that can be handled. Furthermore,

the computation of release parameters involves the manipulation of a mixture of very large and very small numbers. In computations of this nature, rounding off and truncation errors are common, there is a high chance of rounding and truncating errors affecting the results. The use of double precision arithmetic has ensured that this is minimized as much as possible.

4.5.3. The Input files

The program is able to accept differently dimensioned input files using an interactive feature that allows the user to give the name of the input file. The input files that have been used in the computations presented are 'TempData.Txt' and 'TempData2.Txt'. Both are text files containing all the constants and the temperature history for all layers used in the calculation. For different conditions constants as FFZERO, A and B can also be varied in the same input files (i.e. FFZERO=7×10^{-5}, A=1.3895×10^{-5} and B=1.348×10^{-3}(for variation of coated particle failure fraction in sensitivity analysis)). The temperature data and the number of times (in hours) for which the data are available are contained in the input files. The data are held as time (in hours) against temperature (in degrees Celsius). There are 46 values of time where temperatures are given for 92 layers in 'TEMPDATA1.TXT' and 40 values of time where temperatures are given for 92 layers in 'TEMPDATA2.TXT'. This gives a 46 by 92 or 40 by 92 matrices for the computations. The values of time are kept in an array T(J) where J=1..NTIME. This array is reproduced in Table 1 in Appendix 7.

Associated with each of the time values in matrix T(j), there are NTIME temperature values for each layer. These are held in a two-dimensional matrix THETAC (I, J) where the first

dimension corresponds to the layer and the second dimension corresponds to the time variable. For lack of space in this report, it is not possible to reproduce all the temperature data but a sample of the temperature data for the first layer is given in Appendix 7. Note that there are 92 sets of such data, one set for each layer. The complete input data files 'TEMPDATA1.TXT' and 'TEMPDATA2.TXT' are stored on the CD included in this dissertation.

4.5.4. Output files – Sample Results

A number of files contain the output of the program. These are DATA1.TXT, DATA2.TXT, DATA3.TXT, and DATA4.TXT. These are normal text files which may be viewed using Windows Notepad or for larger ones, using WordPad. Below is a description of the contents of each data file. Once again, these are very large files and could not be fitted in a dissertation of this size. However, they are all saved on the CD included with the dissertation. Only samples are given here.

4.5.4.1. DATA1.TXT

Table 1 contains all the constants from the input file, time values in hours, seconds and time steps finally and the temperature history. A sample output from DATA1.TXT is shown in Table 1 of Appendix 7. This sample shows the temperature history for only layer 1. There are 92 layers in all. The temperature history is the relationship between the time and temperature for a given layer. The first column indicates the counter for the time values. Thus in the first row, temperatures 571, 569, 576 etc correspond to times T(1), T(2) and T(3) respectively i.e. 0.0, 0.1 and 0.167 hours respectively. In the second row, temperatures 617, 627 and 643 correspond respectively to T(7), T(8) and

T(9) respectively. DATA1.TXT serves to check that the program is reading the input data file correctly.

4.5.4.2 DATA2.TXT

Data file 'DATA2.TXT' contains time data once again just like DATA1.TXT in addition to temperature averages. Temperature averages rather than temperatures themselves, are needed for some calculations. A sample output from data2.txt is shown in Table 2 (of Appendix 7) with only 1 of 92 layers shown.The first temperature average THETAV(1,1)=570 in 'DATA2.TXT', is the average of the first (THETAC(1,1)=571) and second (THETAC(1,2)=569) temperature values in DATA1.TXT, the second value THETAV(1,2)=572.5 is the average of the second (THETAC(1,2)=569) and third (THETAC(1,3)=576) temperature values in DATA1.TXT and so on. Thus there are 45 values of the average temperature in file DATA2.TXT and it is clear that the average temperatures are being computed correctly.

4.5.4.3. DATA3.TXT

DATA3.TXT is the third output data file produced by the program. It contains values of the kernel release fraction (RF) computed using Equation 11 and the approximate values computed using Equation 12 or 13 depending upon the condition $\pi^2 \delta t \geq 1$ or $\pi^2 \delta t \leq 1$. Table 3 of Appendix 7 is a representative sample of the contents of DATA3.TXT.

4.5.4.3. DATA4.TXT

DATA4.TXT contains data for the kernel release fraction, the failure fraction, the iodine inventory and the layer release fraction for layers 1 to 92. A representative sample is shown in Table 4 of appendix 7.

4.5.4.4. CRF.TXT

The data file CRF.TXT contains all the data relating to the core release fraction CRF. It also contains the integral values of the CRF and the averaged CRF over the number of layers. A sample of this data file is shown in Table 5 of Appendix 7.

4.5.4.4. CRF1.TXT

The data file CRF1.TXT contains all the data relating to the core release fraction CRF1. It also contains the integral values of the CRF1 and the averaged CRF1 over the number of layers. A sample of this data file is shown in Table 6 of Appendix 7.

4.6. PROGRAM VERIFICATION

An independent calculation of parameters in a program is an acceptable way to verify any program. In this case, some computations for layer number 1 were carried out using MathCAD and compared with the results of Fortran program RELEASE. The calculations are shown in Appendix 8 and the results are summarised in Table 7. The best agreement between RELEASE and MathCAD results was achieved for the iodine inventory, where exactly the same results were obtained (% deviation being 0%). The results of the kernel release fraction

and the layer release showed a deviation that ranged from about 1% to a maximum of about 5%. Further verification of the RELEASE calculations is reported in Section 6.2.

Table 7: Comparison of values

RELEASE	MathCAD	Deviation (%)
Kernel release fraction		
5.1756×10^{-4}	5.117×10^{-4}	1.15
6.7749×10^{-4}	6.6429×10^{-4}	1.99
8.1142×10^{-4}	7.9342×10^{-4}	2.27
9.3868×10^{-4}	9.1211×10^{-4}	2.91
1.3239×10^{-3}	1.2596×10^{-3}	5.10
Iodine decay correction		
9.9964×10^{-1}	9.9964×10^{-1}	0
9.994×10^{-1}	9.994×10^{-1}	0
9.9916×10^{-1}	9.9916×10^{-1}	0
9.9892×10^{-1}	9.9892×10^{-1}	0
9.9808×10^{-1}	9.9808×10^{-1}	0
Layer release		
2.0695×10^{-8}	2.0461×10^{-8}	1.14
2.7083×10^{-8}	2.6565×10^{-8}	1.95
3.243×10^{-8}	3.1729×10^{-8}	2.21
3.7507×10^{-8}	3.6476×10^{-8}	2.83
5.2854×10^{-8}	5.0342×10^{-8}	4.99

CHAPTER 5: RESULTS

5.1. ANALYSIS OF RESULTS

It can be seen from Appendix 9 that the maximum temperature for the core under equilibrium conditions is below 1200 ^{0}C. At temperatures below 1200 ^{0}C, the failure fraction does not change with temperature, and the fission product release during a temperature transient is not increased by the changes in the temperature distribution among fuel elements at these temperatures. Thus for additional DLOFC release, only temperatures above 1200 ^{0}C need to be considered. Looking at different layers in the temperature range above 1200 ^{0}C, it can be seen that the kernel release fraction in a layer increases with time, reaches a maximum value, and then decrease again.

The failure fraction for the temperature range above 1200^0 C never decreases despite the fact that the temperature value goes down. The reason behind that is that as soon as the reactor is in operation and a particle gets damaged or starts to fail (depending on the operation conditions), the said particle cannot be healed or be repaired. It is either the failure fraction increases or it remains constant, as shown by the Figure 11. Figure 11 shows that the failure fraction from the 42nd hour became constant until the 168th hour. This is basically how all the layers behave.

UNM LIBRARY

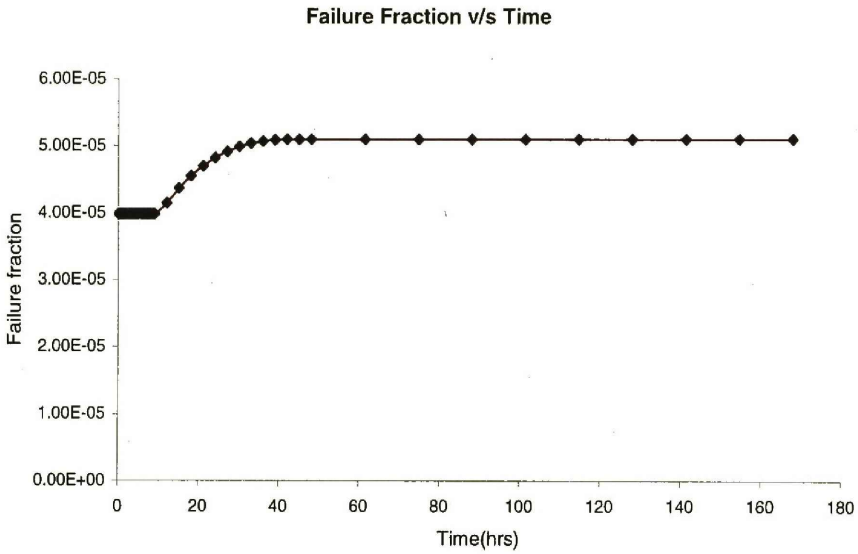


Figure 11: Graph of failure fraction v/s time

The graph of the decay correction against time in Figure 12 shows that the decay factor is decreasing with time.

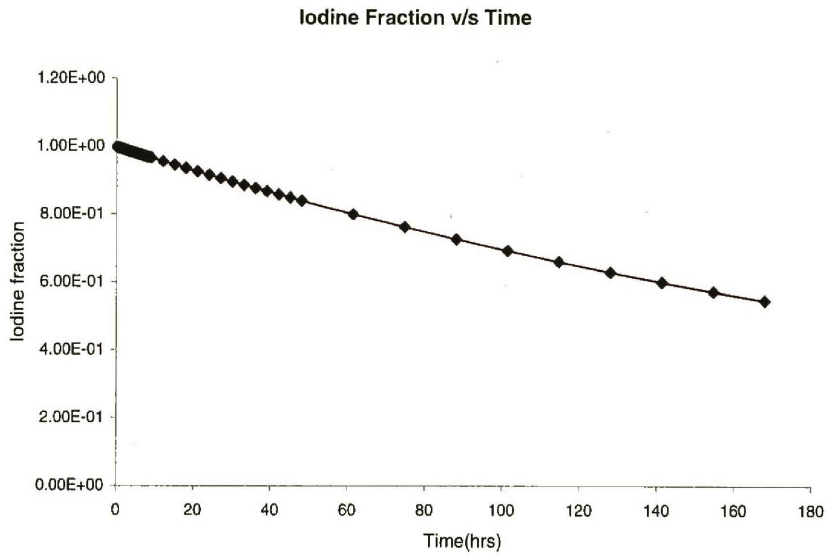


Figure 12: Graph of iodine fraction v/s time

The kernel release is calculated by using reduced diffusion coefficients from table 6 together with equation 11.

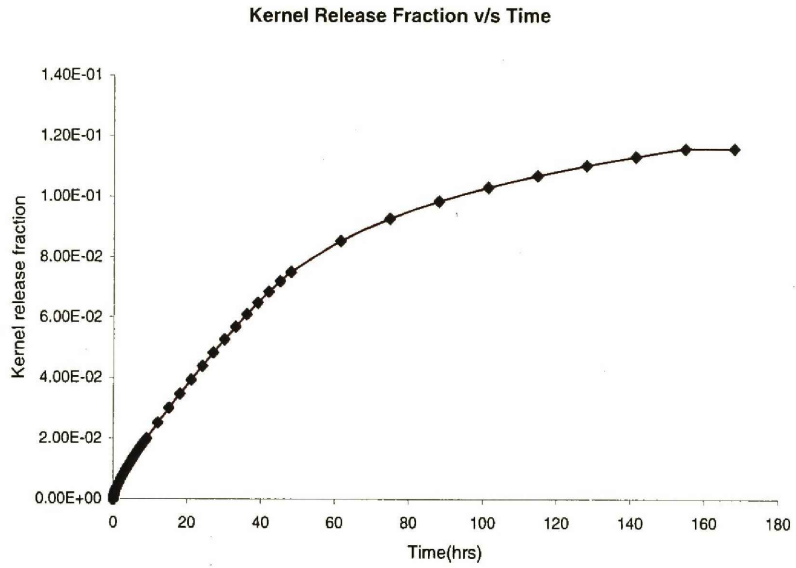


Figure 13: Graph of kernel release fraction v/s time (for layer 4)

The product of failure fraction, decay correction and the kernel release fraction calculated the layer release for all the layers. The release of fission products for a layer shows a decrease from the 114.667th hour till the 168th hour. This is due to a decrease in the decay correction. Figure 14 shows how the layer release relates to time during a DLOFC event. The approximation for kernel release fraction behaves in the same fashion as the kernel release fraction. In the validation of this program, it is found that MathCAD calculation gave a value of 5.117×10^{-4} whereas the Fortran gave a value of 5.176×10^{-4} for layer 1 at a temperature average of 570^{0} C. The two values are very close to each other.

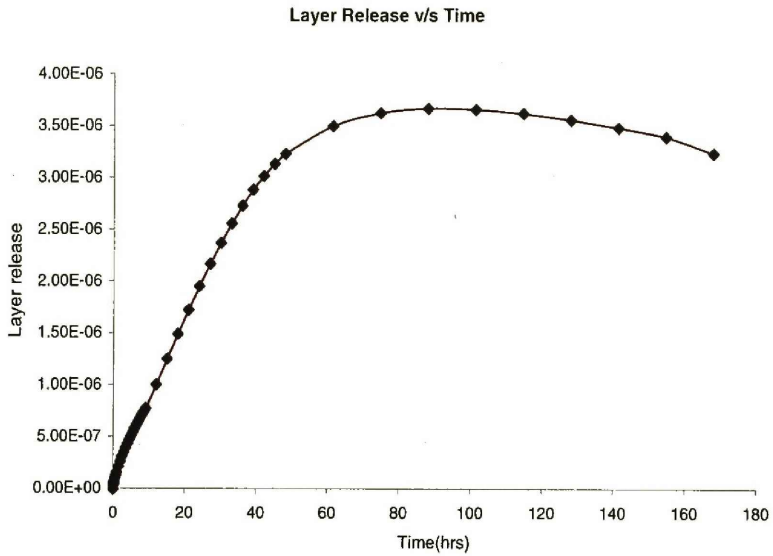


Figure 14: Graph of layer release fraction v/s time (for layer 4)

This slight reduction in layer release therefore causes a decrease in the core release fraction since the core release fraction was calculated by summing up all the layer releases for a time-step. Figure 15 clearly indicates the decrease in the core release.

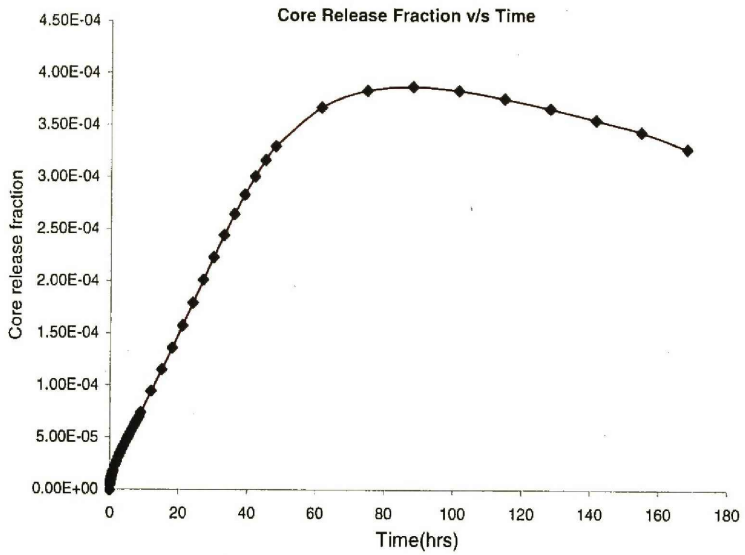


Figure 15: Graph of core release fraction v/s time

Taking layer 4 as an example, for temperatures above 1200^{0}C, the results show that for 30 hours into a DLOFC transient, the kernel release fraction is 5.7149×10^{-2}, the failure fraction is $5.0501E\times10^{-5}$, iodine fraction is 8.8796×10^{-1} and the layer release is 2.5628×10^{-6}. The kernel release fraction increases until it has reached a maximum of 1.1588×10^{-5} at the 168th hour. The iodine decay correction decreases from a maximum value of 1.00 at the beginning of DLOFC transient to a value of 5.4612×10^{-1}. The failure fraction increases from 4.000×10^{-5} to 5.1119×10^{-5}.

As for the layer release it increases until it reaches a maximum value of 3.6708×10^{-6} at the 88th hour. The release of fission products for a layer then starts to decrease from the 101.333th hour until its value is 3.2351×10^{-6} at the 168th hour. As a result the core release fraction starts to decrease as shown in Figure 15.

Figure 16 shows the release of fission products per unit time. According to this graph the core release is decreasing with time whereas the integral core release fraction is increasing with time as shown in Figure 17.

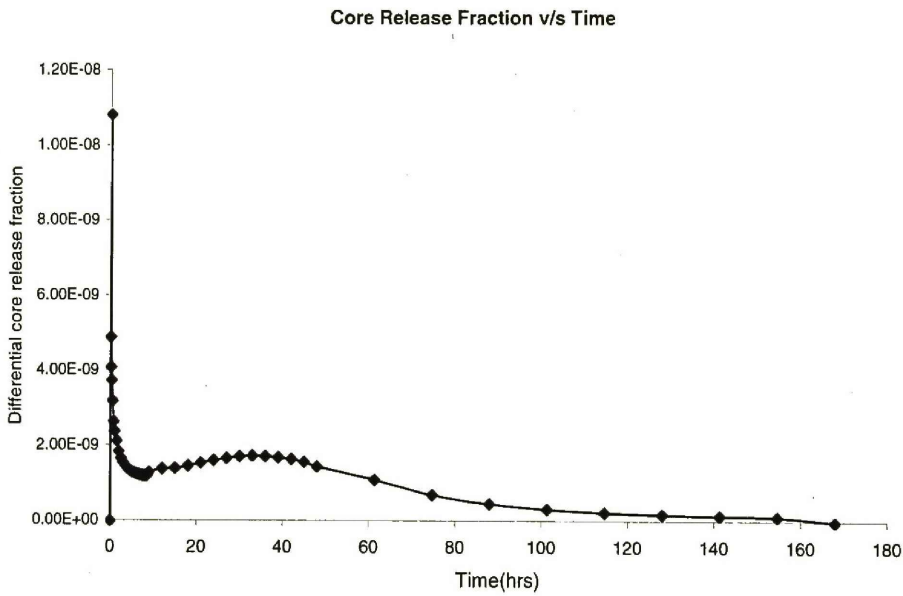


Figure 16: Graph of differential core release fraction v/s time (expected values)

UNW LIBRARY

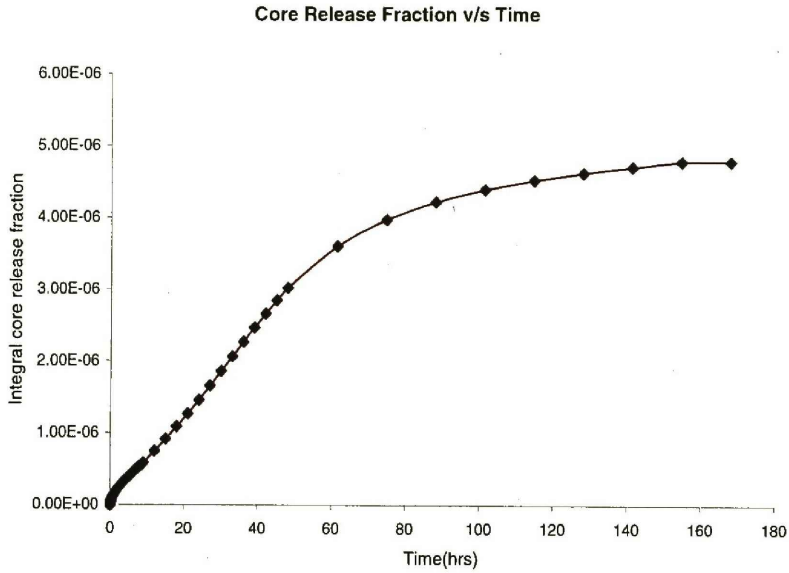


Figure 17: Graph of integral core release fraction v/s time (expected values)

5.2. SENSITIVITY ANALYSIS

The objective of this analysis is to establish the effect different uncertainty factors have on the release of fission products. Uncertainty in the coated particle failure fraction and in the temperature time distribution for the PBMR core was taken into account. In this analysis the diffusion constant that is used to calculate the fission product release fraction from the kernels of failed particles has a major impact on fission product release. Figure 18 depicts the variation of failure fraction with temperature for design values and Figure 19 for expected values.

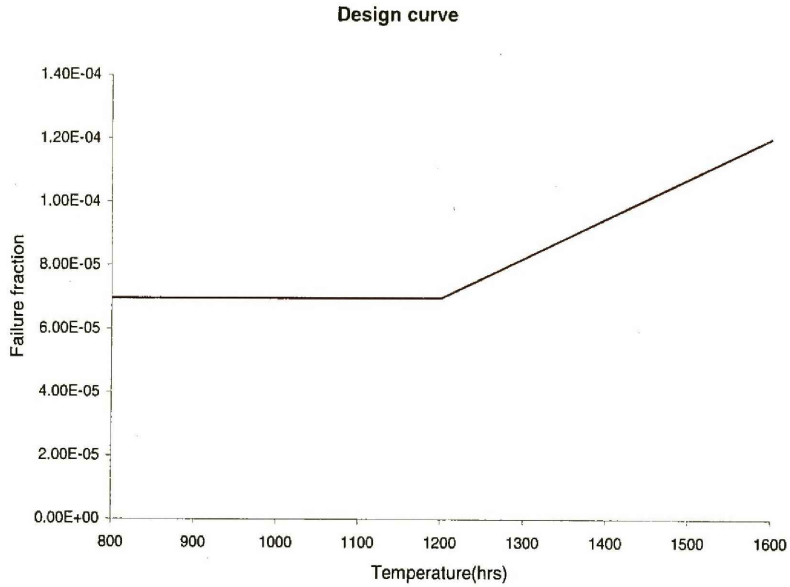


Figure 18: Design values

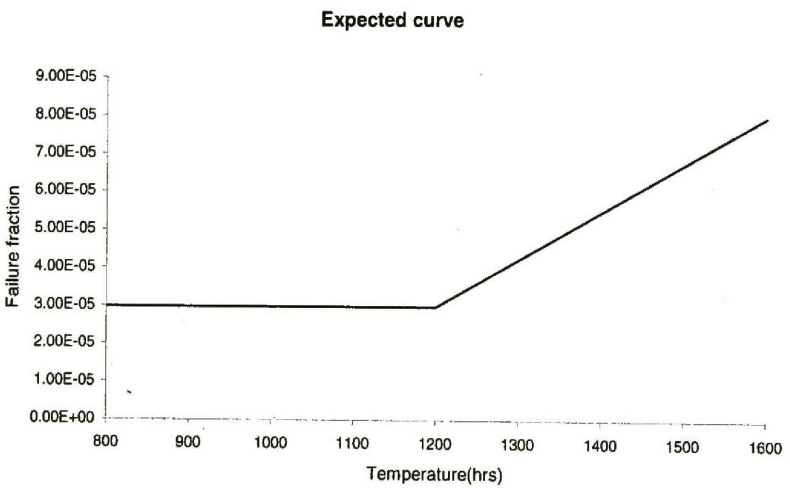


Figure 19: Expected values

Table 8: Different cases calculated

Parameters calculated	Parameters varied	Case
Failure Fraction	Expected failure fraction curve (Figure 19)	1
	Design failure fraction curve (Figure 18)	3
Kernel Release Fraction	DLOFC time-temp histoiy +10% Decay heat	4
	Diffusion coefficient × 2	2

Case 1:The kernel release fraction is calculated with the value for the failure fraction for all temperatures below 1200^0C assumed to be 3×10^{-5} whilst all the other failure fraction values above 1200^0C are calculated using equation [4]. This is the reference case.

Case 2: In order to assess the influence of variations in the diffusion coefficient value the calculation in case 1 is repeated with the value of the diffusion coefficient increased by a factor of two.

Case 3: The kernel release fraction is calculated (using the same data as case 1) with the value for the failure fraction for all temperatures below 1200^0C assumed to be 7×10^{-5} (i.e. the failure fraction was varied). As a result the values of constants A and B also changed.

Case 4: In order to assess the influence of variations in temperature values the calculations were repeated with a set of data from PBMR 400 MW DLOFC plus 10 percent afterheat.

Figure 20 shows that the core release fraction increases with time and that the core release fraction for case 2 is somewhat higher than that of case 1. The combined results show that the core release fraction increased from 4.7849×10^{-6} to 6.5492×10^{-6}.

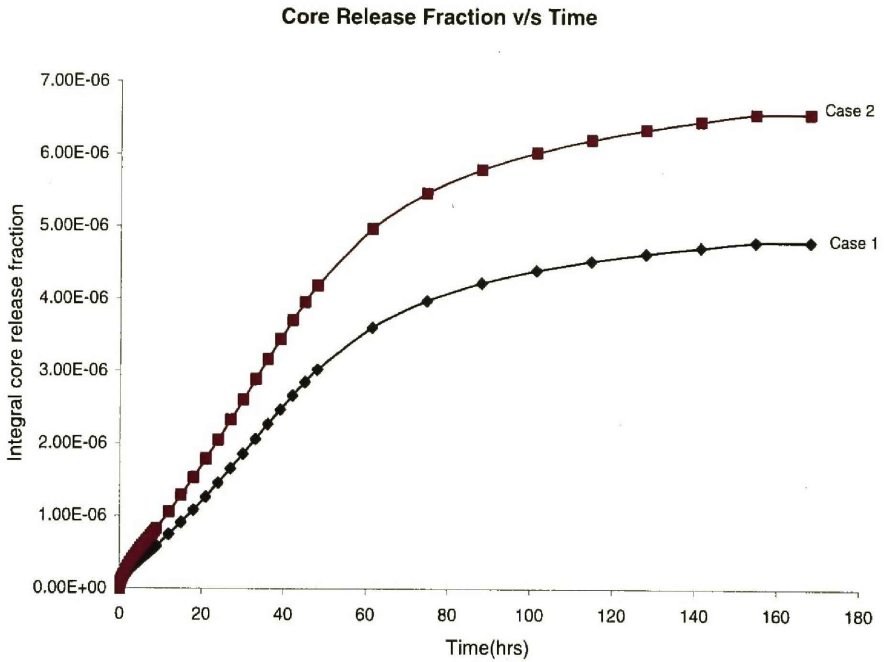


Figure 20: Comparison between integral core release fractions for case 1 and 2.

Figures 21 shows the results of core release fraction for case 4 whereas Figure 22 shows the results of case 3. Figure 23 shows the comparison for the four cases.

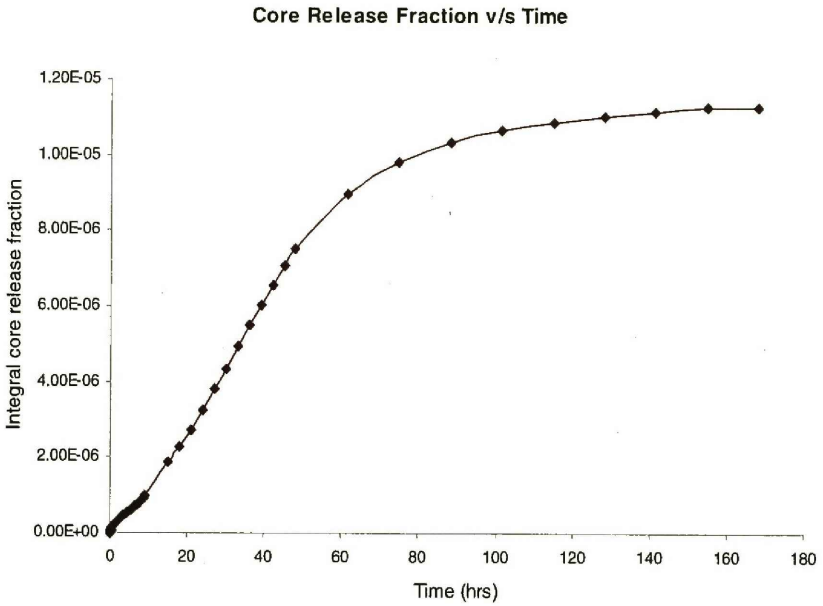


Figure 21: Graph of integral core release fraction v/s time (case 4)

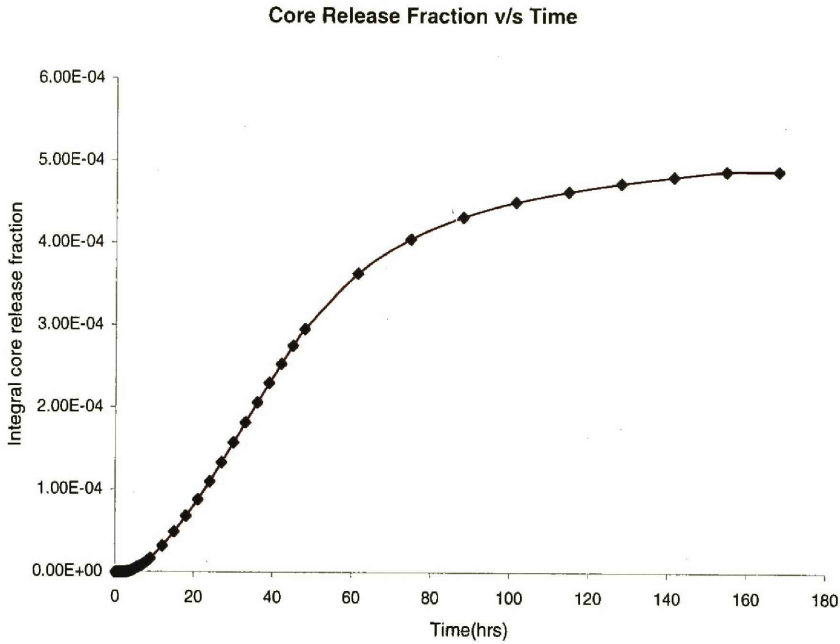


Figure 22: Graph of integral core release fraction v/s time (case 3)

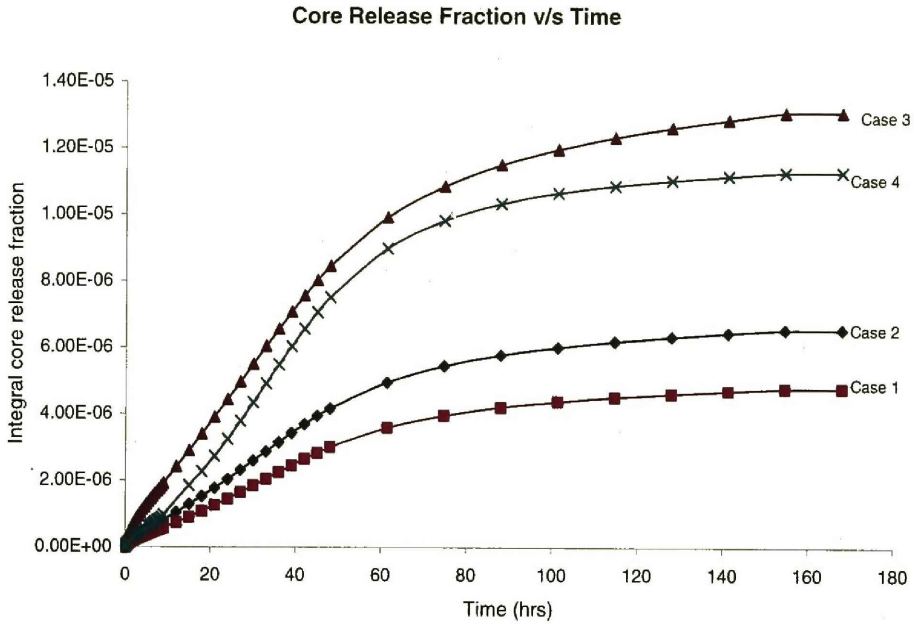


Figure 23: Comparison between core release fractions for case 1, case 2, case 3 and case 4.

Table 9 shows the results of core release fraction as interpreted by Figure 23. As shown by Figure 23 and table 9 the core release fraction for the case 3 seems to be higher than the other three cases. This is an indication that the failure fraction affects the core release fraction.

Table 9: Sensitivity analysis results

Expected value for failure fraction (Case 1)	Diffusion increased by a factor of two (Case 2)	Design value for failure fraction (Case 3)	DLOFC+10% increase in afterheat (Case 4)
4.7849×10^{-6}	6.5492×10^{-6}	1.31×10^{-5}	1.13×10^{-5}

Looking at Figure 23 and table 9, the difference between case 1 and case 2 is named Δ1, the difference between the case 1 and case 3 is Δ2 and the difference between case 1 and case 4 Δ3.The nominal value or expected value (case 1) acts as a reference value.

Errors are calculated as follows:

$\Delta 1=1.7643\times10^{-6}$

$\Delta 2=8.315\times10^{-6}$

$\Delta 3=6.515\times10^{-6}$

$\Delta 1$/Nominal value$=3.687\times10^{-1}$

$\Delta 2$/Nominal value$=1.738$

$\Delta 3$/Nominal value$=1.362$

Statistical uncertainty factor:

$$\pm\sqrt{(3.687\times10^{-1})^2+(1.738)^2+(1.362)^2}$$

$$\pm\sqrt{5.24}$$

$$\pm 2.29$$

Rounding up a statistical uncertainty factor of 3 is found.

Design value =expected value× 3.

However there could also be a number of systematic errors in the calculation, which are hard to quantify. For this type of analysis a systematic uncertainty of 2 is normally assumed. This uncertainty is added to the statistical uncertainty of 3 to get a total uncertainty of 5. Thus the design value for the I-131 release for the 400 MW PBMR core is $4.7849\times10^{-6}\times 5=23.925\times10^{-6}$. The calculated I-131 inventory for a fuel sphere of average burn-up in the PBMR core is calculated as 9.2×10^{17} atoms by means of a computer program ORIGEN-S. This can be converted to an activity:

$A = N\lambda$

$= (9.2\times10^{17})\,(1.0002\times10^{-6})$

$= 9.2018\times10^{11}$ Bq per fuel sphere

There are about 452 000 fuel spheres in the PBMR core. Thus the total expected I-131 released after 168 hours is:

Total number of spheres × I-131 activity per fuel sphere × Core release fraction

$= 452\,000 \times 9.2018 \times 10^{11}$ Bq $\times 4.7849 \times 10^{-6}$

$= 2.0 \times 10^{12}$ Bq

= 54.05 Ci

The design value is:

Expected Iodine release × Total uncertainty factor

$= 2.0 \times 10^{12}$ Bq × 5

$= 1.0 \times 10^{13}$ Bq

= 270.3 Ci

Iodine isotopes and other fission gases behave in the same manner, thus the activity release for other iodine isotopes and fission gases can be calculated in the same manner by using appropriate decay constants and performing similar calculations.

CHAPTER 6: COMMENTS AND CONCLUSIONS

6.1. Comments and Possible Enhancements to the Program

This section deals with possible improvements to the program to make it more versatile. The first major aspect to consider here is that in its present form, the program is non-interactive. It does not communicate with the user. This is a limitation in the sense that no changes for different circumstances can be accommodated when the program is already running. Every time a change has to be made, it has to be made in the source code. The introduction of an interactive nature will enable users to specify what they want to do exactly without changing the source code. The interactive aspect will enable the users:

6.1.1 to enter a different input file with different temperature data not limited by the fixed values of 'NLAYER' and 'NTIME' by allowing the user to enter these values interactively;

6.1.2 to carry out specific computations rather than all computations – for example, the user should be able to carry out computations of only the failure fraction (FF) or the kernel release fraction (RF) if that is what is wanted, or to carry out computations for specific layers, without doing all the other computations;

6.1.3 to specify what outputs are required – for example, the user may only want to output the contents of data file DATA2.TXT. There is no reason then to create all the other output files.

Secondly, in its present form, the program accepts data prepared in a specific manner, notably, a text file currently prepared in Notepad or WordPad. An improvement should be made such that it can handle direct data import from other popular data manipulation packages such as Microsoft Excel and other spreadsheets. This should make it a lot more versatile.

Thirdly, the current program is best used in source code form. This is because, as mentioned above, any changes in the circumstances require changes in the source code. Although this can be of advantage in certain circumstances, it leaves the program open to the introduction of programming errors when the changes are being made. When the interactive aspects are

introduced, it would be a good idea only to create an executable version (VERS34.EXE) and only use that. The executable version will then be platform independent i.e. can run on computers without Fortran being installed on them and cannot be changed in error.

Lastly, the 'dimension' declarations limit the program's versatility to the storage allocation specified by these statements. This means that if larger arrays are to be handled, the source code must be altered to introduce the larger array bounds. There is space wastage as well when arrays to be handled have much smaller dimensions than the declared array bounds. Dynamic Memory Allocation (DMA), which is currently implemented in Fortran, can be used to overcome this problem. Using DMA, storage space is allocated dynamically during the execution of the program. This means that only the space required is allocated and wastage is therefore avoided. This program can be enhanced by the introduction of DMA rather than the static memory allocation currently used.

6.2. Conclusion

Using a computer code GETTER, calculations of the release of iodine from fuel elements of the PBMR core under a DLOFC event were performed [21]. The computer code GETTER is a diffusion code developed to handle experimental and operational conditions. GETTER calculates the release from fuel elements during normal and during a DLOFC event in one combined run. The results are then post-processed by a table calculation scheme in order to determine the release from the core cavern into the depressurised circuit.

Using specific parameters for the 400MW PBMR core and best estimates of all material data, expected values of the release rates from the fuel spheres were determined. The transfer of activities released from fuel spheres out of the core cavern (core release) was calculated taking into account the thermal expansion of the helium remaining in the core. Deposition of released products on cold surfaces in the core and on the way through the relatively cold reflector was not considered. Equally neglected was the plate out during the fluid dynamic transport from the core structure to the break of the Main Power Supply. The maximum released inventory (I-131) of 2.13×10^{12} Bq [21] was obtained in these calculations.

The program RELEASE calculates some of the parameters that the GETTER code calculates. In particular, the RELEASE program calculates the failure fraction, indicating, in the sensitivity analysis, that the failure fraction has the greatest impact on the core release fraction. This is clearly indicated by the results in Chapter 5.1.2. In general RELEASE is basically doing what is expected of it, in the sense that the values obtained in RELEASE calculations compare very well with the verification by MathCAD and the GETTER code. A comparison of the MathCAD and RELEASE calculations is shown in Table 7 of Chapter 4. The GETTER code calculations of the maximum released inventory (I-131) of 2.13×10^{12} Bq (57.56Ci), compares very well with the RELEASE calculated total activity of 2.00×10^{12} Bq (54.05Ci) for the PBMR 400MW core, representing a percentage difference of only 6%.

In this dissertation, modeling of temperature history prior to and during a temperature transient has been refined (research problem) and a computer program based on a simple coated particle failure and gas diffusion model that could be used to do scope calculations for the release of gaseous fission products and iodine been developed and tested (research objective). The objective of the research project has therefore been accomplished.

Finally, Section 6.1 highlights the changes and improvements that could be carried out on the source code of the program to make it more versatile and universally usable.

6.3. REFERENCES

1. Brown, K, T, **'How PBMR fuel is made'**, PBMR Document no.: FP-PLN-1021, 13 March 2000

2. Heit, W, Huscha, H, and Rind, W, **'Status of qualification of HTR fuel element spheres'**, Publication, 18 October 1984

3. Murray and Roberts Engineering solutions (Ltd), **'Process description: Area F- Fuel sphere production'**, PBMR Document no.: 6376-FPF-P420-01, 16 November 2001

4. http://www.pbmr.co.za/docs/doc_21Technical_Description.htm**'Technical Description'**

5. Fukuda, K, and Iwamoto,K, **'Research on in-pile release of fission products from coated particle fuel'**, IAEA Technical Documents, Conference article, Specialists meeting on fission product release and transport in gas cooled reactors, Berkeley (UK), 22-25 October 1985

6. Rubin, S, D, **'Irradiation and accident condition testing of advanced HTGR fuel'**, Conference article, www.bnl.gov/nsrc/pdf conf 02/Monday-Rubin, 28 October 2002

7. Schenk, W., Pitzer, D, and Nabielek,H, **'Fission product release profiles from spherical HTR fuel elements at accident temperatures'**, KFA Julich 2234, September 1988

8. Zellen, H, **'Quantitative Evaluation of the performance of the German HTR under normal operating and under accident conditions'**, Institut fur Werkstoff in der Energie technik, KFA, December 1993

9. Munteanu, I, Denning, D, **'Evaluation of costs and benefits of MPBR containment concept'**, Conference paper, http//ans.mne.psu.edu/conf/paper pdf/7_1_Munteanu.pdf, undated

10. Christ, A, Mehner, W, and Schenk,W, **'The release of iodine from HTR fuel under steady state'**, IAEA Technical Documents, Conference article, Specialists meeting on fission product release and transport in gas cooled reactors held in Berkeley (UK), 22-25 October 1985

11. Sawa, K, Ueta, S, Sumita, J, Verfondern, K, **' Prediction of fuel performance and fission gas release behavior during normal operation of the high temperature engineering test reactor by JAERI and FZJ modeling approach'**, Journal of Nucl. Sci. and Technology, Volume 38, no.6, June 2001

12. Verfondern, K, Dunn, T,D, and Bolin, J,M, **'Comparison of US/FRG Accident condition models for HTR fuel failure and radionuclide release'**, ISSN 0366- 0885, Institut fur Sicherheitsforschung and reaktortechnik Julich 2458, March 1991

13. Booth, A.H, **'A method of calculating fission gas diffusion from UO_2 fuel and it's application to the X-2-f loop test'**, CRDC-721, AECL 496, September 1957

14. Venter,J.H, **'PBMR source term (268 MW design): Release of gaseous fission products and iodine'**, PBMR Document no.: 010501-344, February 2002

15. http:// www.pbmr.co.za/1 about pbmr.htm **'About PBMR'**

16. http://www.pbmr.co.za/industrial.htm **'Industrial'**

17. http://www.pbmr.co.za/Project_Status/project_status_content.htm **'Project Status'**

18. www PBMR.com/3_PBMR_technical information/3_separational_control.htm

'Separation control '

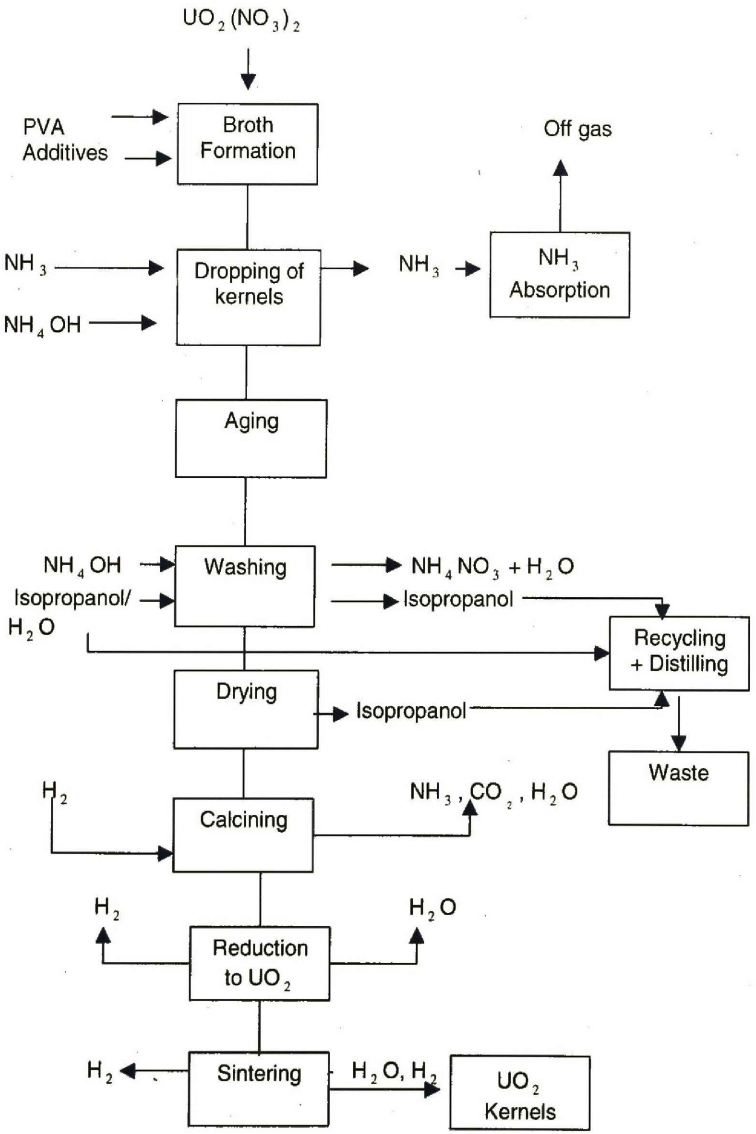
19. http://www.eskom.co.za./nuclear/pebble_bed/pebble_bed.htm **'Pebble bed'**

20. Moormann,R, Verfonden, K, **'Methodology of comprehensive probabilistic safety analysis for future HTR concepts '**, Status report, Volume 3, 1996

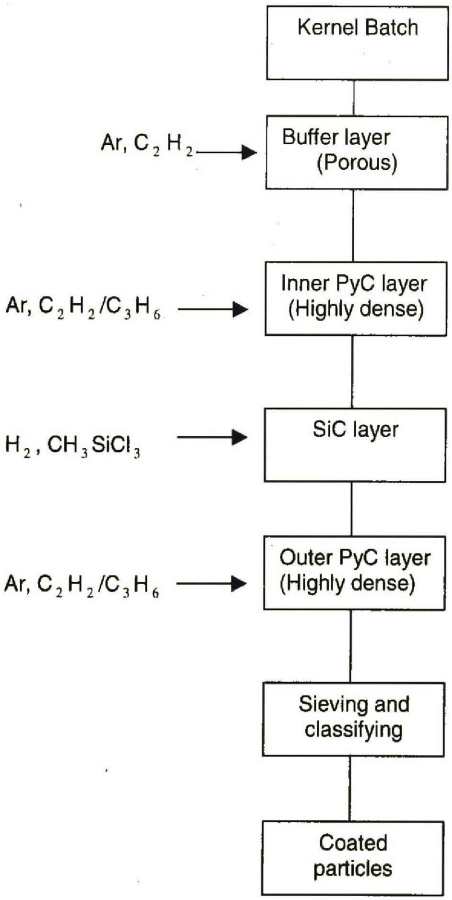
21. Van der Merwe,H, **'Preliminary GETTER calculated caesium and iodine release from the PBMR core during a DLOFC accident PBMR'**, Document no.:PP350-015395-3340,23rd January 2003

UNW LIBRARY

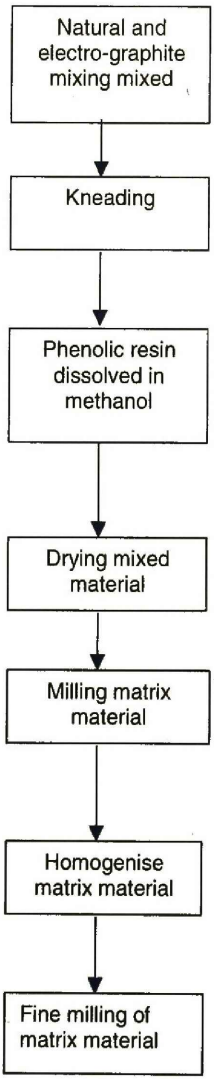
APPENDIX 1: KERNEL FORMATION



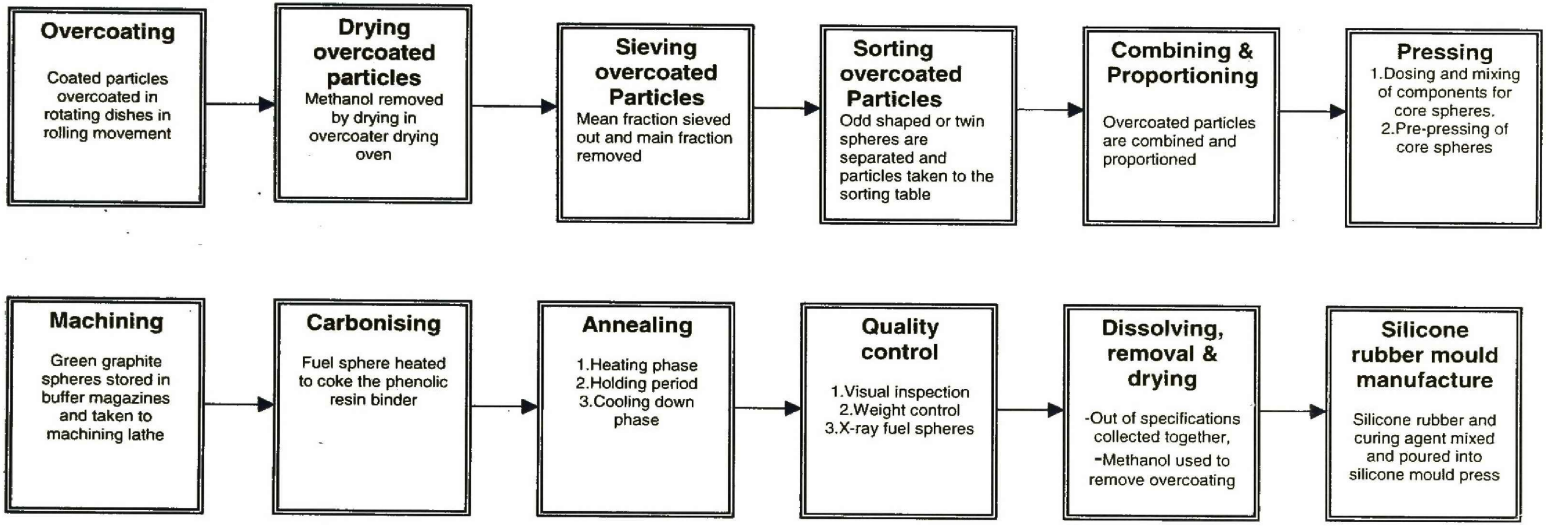
APPENDIX 2: COATING OF FUEL KERNEL



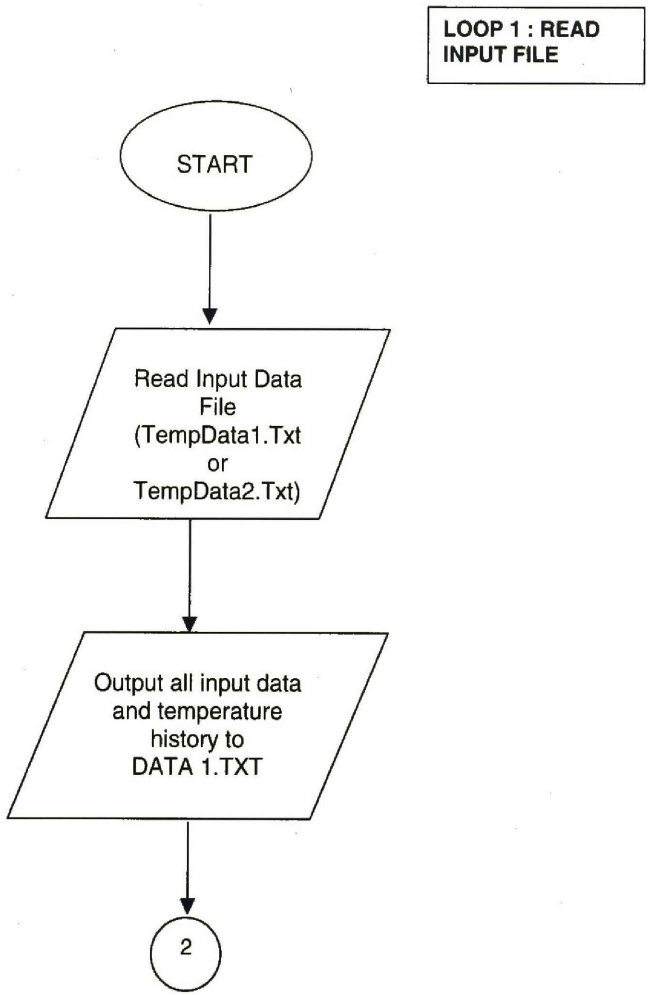
APPENDIX 3: MIXING OF MATRIX GRAPHITE POWDER

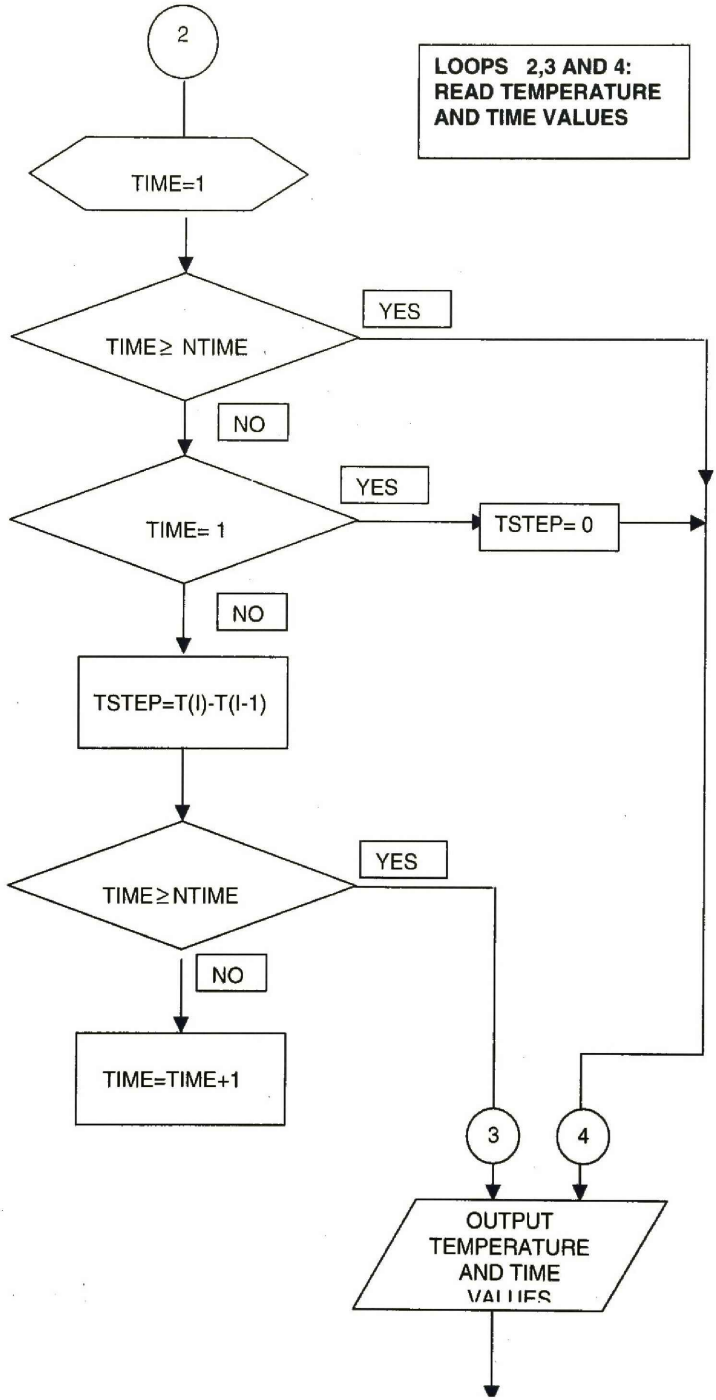


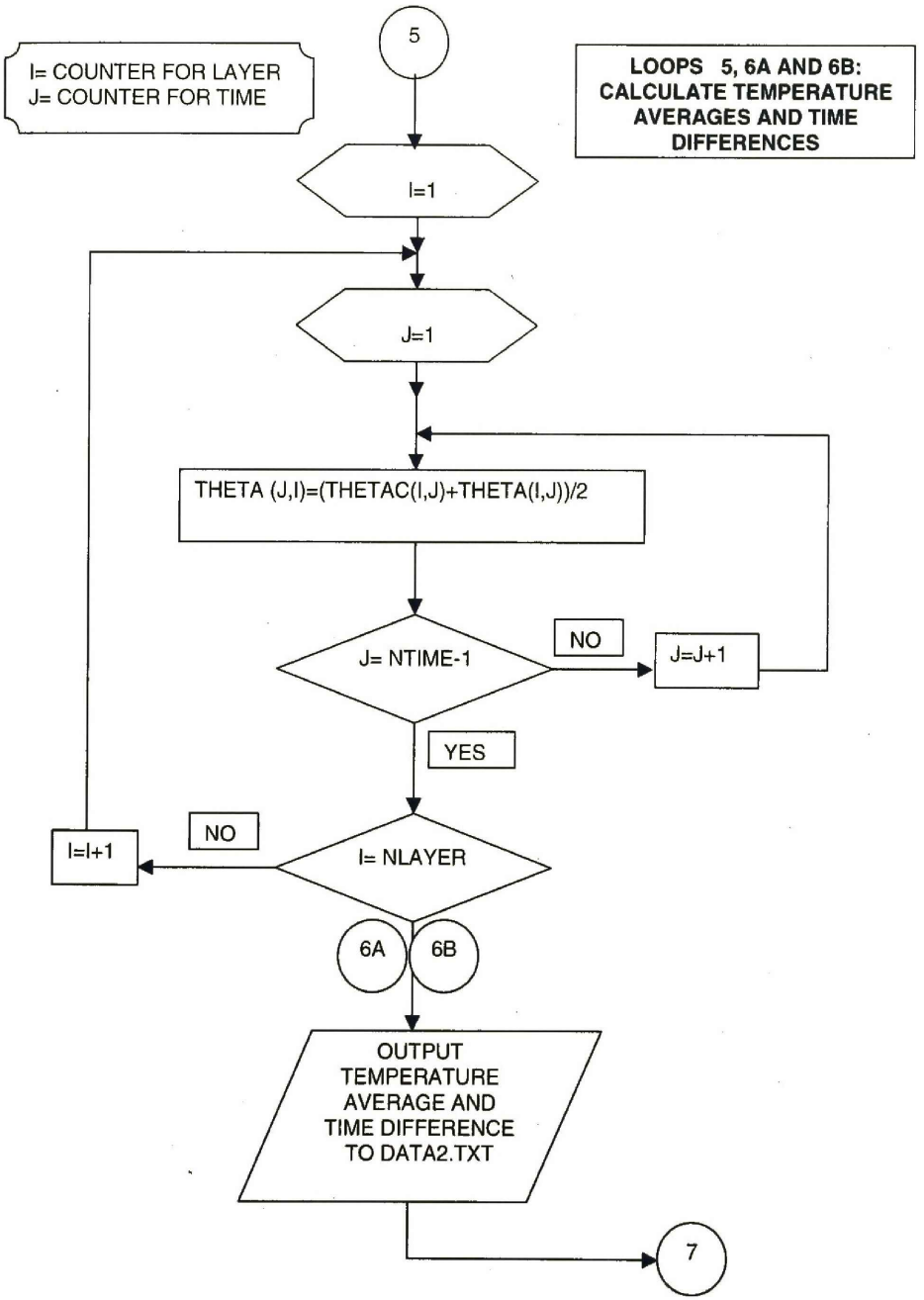
APPENDIX 4: STEPS INVOLVED IN FUEL SPHERE PRODUCTION



APPENDIX 5 : DETAILED FLOW DIAGRAM




2
LOOPS 2,3 AND 4:
READ TEMPERATURE
AND TIME VALUES
TIME=1
TIME≥ NTIME
YES
NO
TIME= 1
YES
TSTEP= 0
NO
TSTEP=T(I)-T(I-1)
TIME≥NTIME
YES
NO
TIME=TIME+1
3
4
OUTPUT
TEMPERATURE
AND TIME
VALUES


I= COUNTER FOR LAYER
J= COUNTER FOR TIME
5
LOOPS 5, 6A AND 6B:
CALCULATE TEMPERATURE
AVERAGES AND TIME
DIFFERENCES
I=1
J=1
THETA (J,I)=(THETAC(I,J)+THETA(I,J))/2
J= NTIME-1
NO
J=J+1
YES
I= NLAYER
NO
I=I+1
6A
6B
OUTPUT
TEMPERATURE
AVERAGE AND
TIME DIFFERENCE
TO DATA2.TXT
7

LOOP 7: CALCULATE FAILURE FRACTION

I= 1

FF(1,I)=FF0

J=2

J,I)=A $e^{B \times thetaV(j,i)}$

NO

THETAV(J,I) <1200

YES

FF(J,I)=FF0

F(J,I)= MAX((FF(j-,I),FF(I,j))

NO

FF(J,I) < FF0

YES

FF(J,I)=FF0

J=NTIME

NO

J=J+1

YES

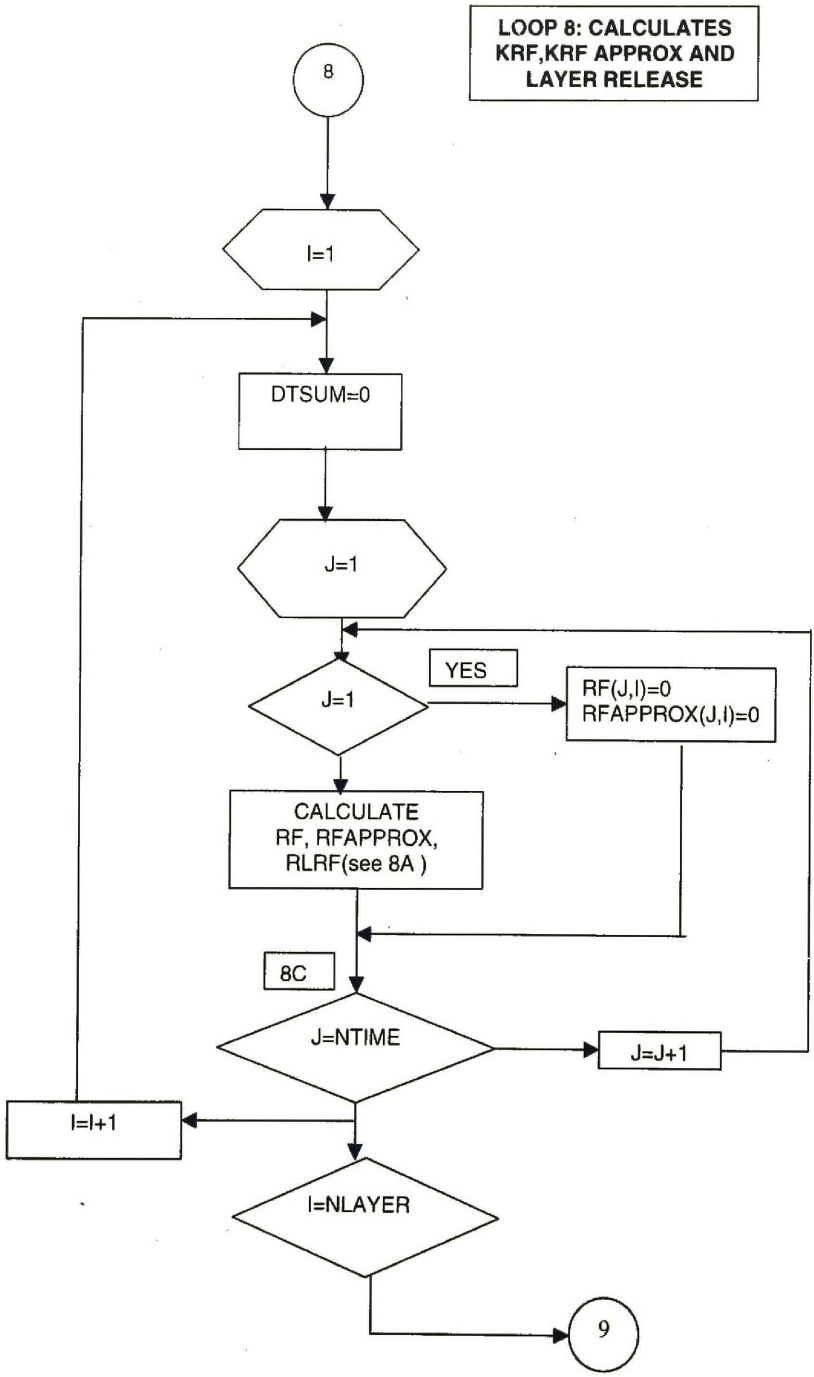
I=I+1

NO

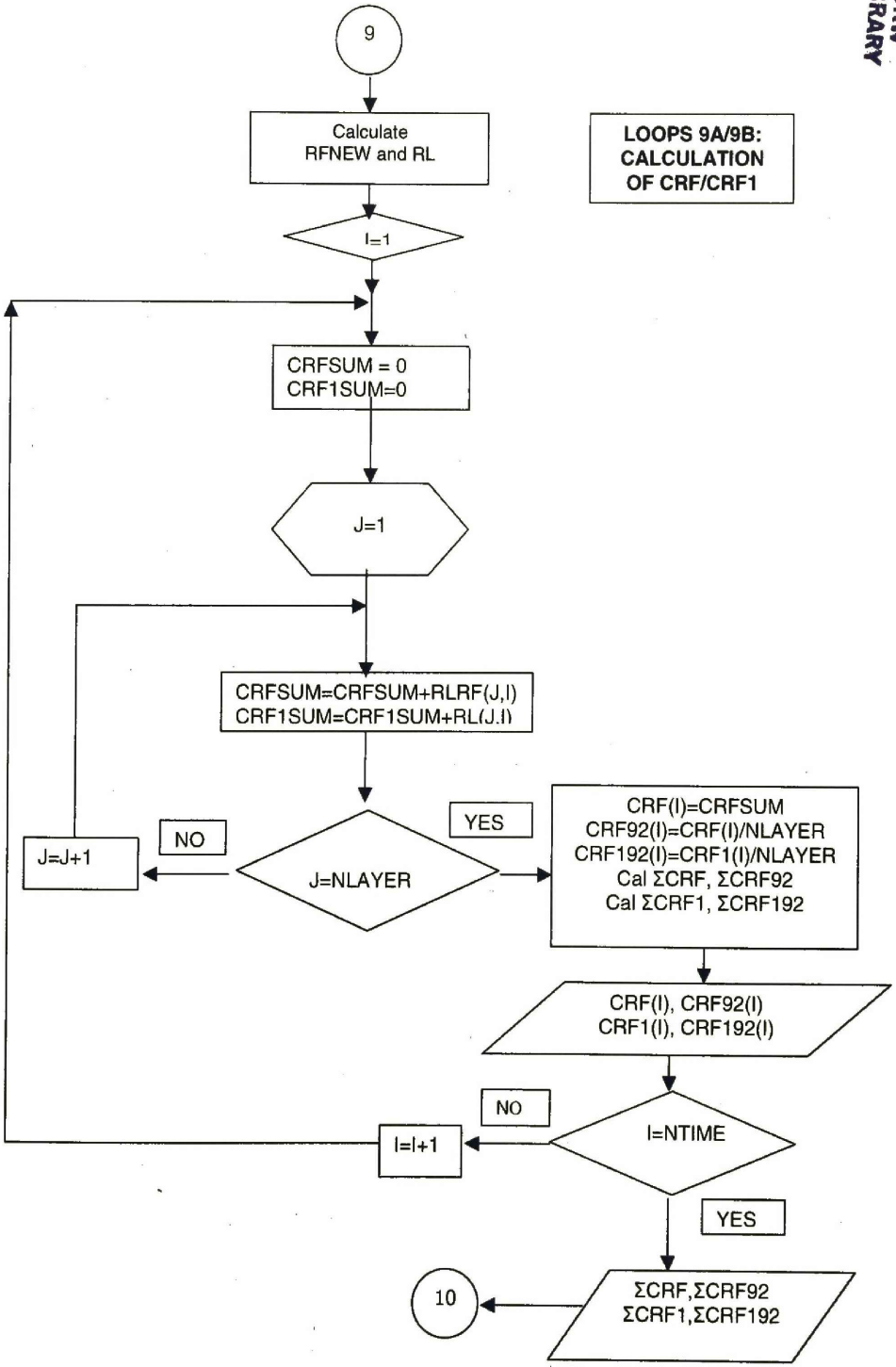
I=NLAYER

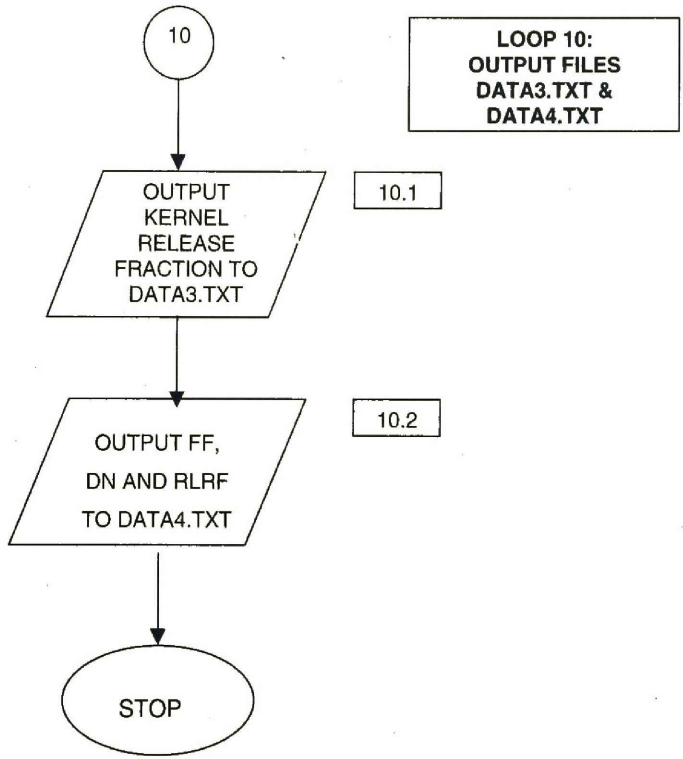
8

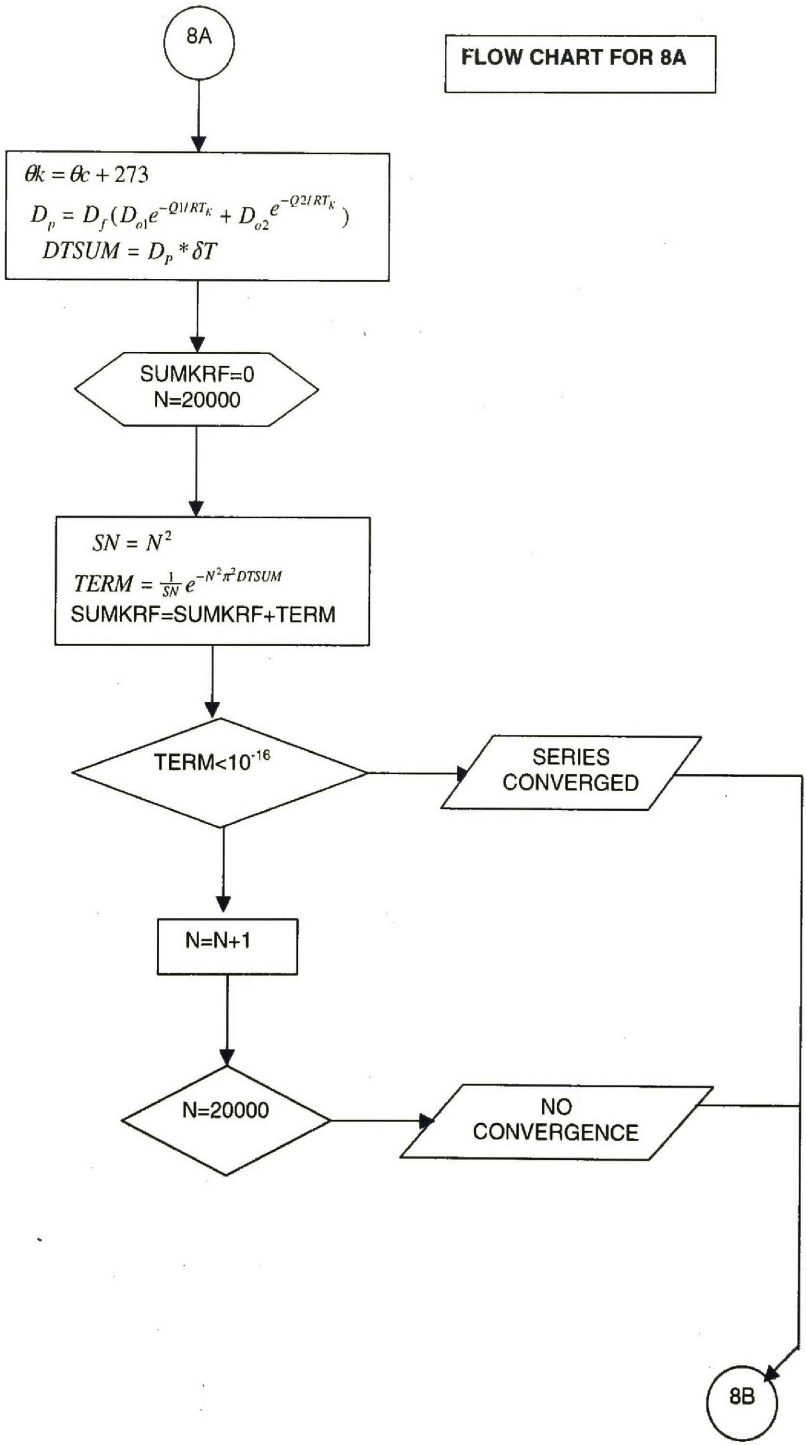
YES

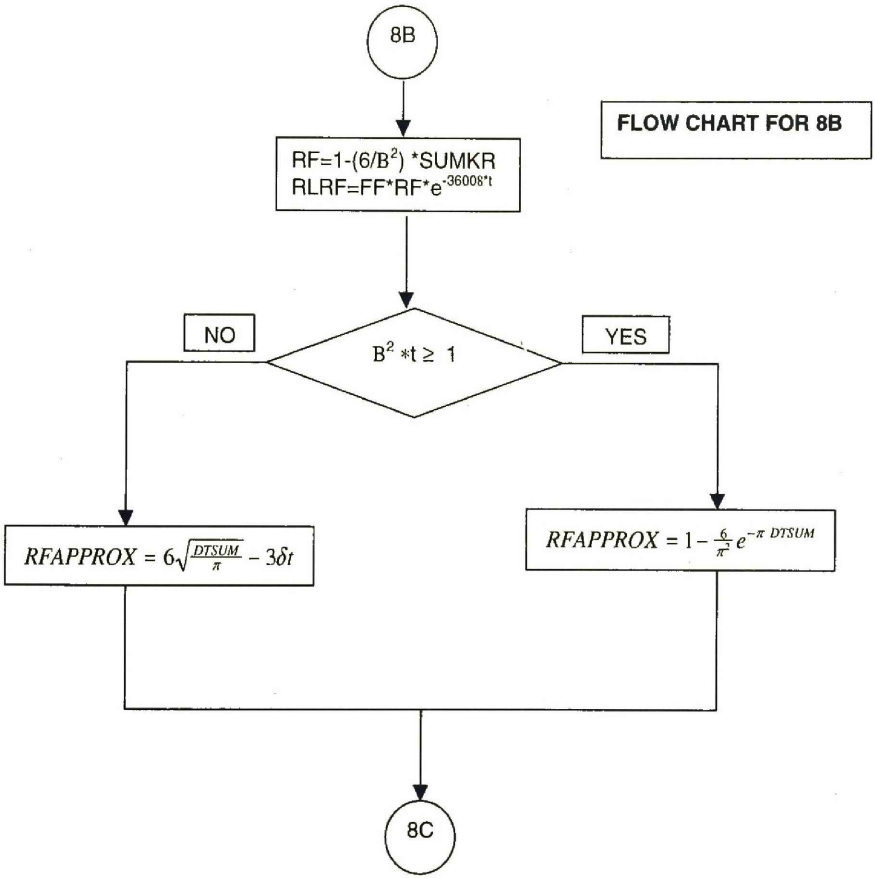

LOOP 8: CALCULATES KRF,KRF APPROX AND LAYER RELEASE
8
I=1
DTSUM=0
J=1
J=1
YES
RF(J,I)=0
RFAPPROX(J,I)=0
CALCULATE RF, RFAPPROX, RLRF(see 8A)
8C
J=NTIME
J=J+1
I=I+1
I=NLAYER
9

UNW LIBRARY


9
Calculate RFNEW and RL
LOOPS 9A/9B: CALCULATION OF CRF/CRF1
I=1
CRFSUM = 0
CRF1SUM=0
J=1
CRFSUM=CRFSUM+RLRF(J,I)
CRF1SUM=CRF1SUM+RL(J,I)
J=NLAYER
NO
YES
J=J+1
CRF(I)=CRFSUM
CRF92(I)=CRF(I)/NLAYER
CRF192(I)=CRF1(I)/NLAYER
Cal ΣCRF, ΣCRF92
Cal ΣCRF1, ΣCRF192
CRF(I), CRF92(I)
CRF1(I), CRF192(I)
I=NTIME
NO
I=I+1
YES
10
ΣCRF,ΣCRF92
ΣCRF1,ΣCRF192


10
LOOP 10:
OUTPUT FILES
DATA3.TXT &
DATA4.TXT
OUTPUT
KERNEL
RELEASE
FRACTION TO
DATA3.TXT
10.1
OUTPUT FF,
DN AND RLRF
TO DATA4.TXT
10.2
STOP


8A
FLOW CHART FOR 8A
θk = θc + 273
$D_p = D_f(D_{o1}e^{-Q1/RT_K} + D_{o2}e^{-Q2/RT_K})$
DTSUM = $D_p * \delta T$
SUMKRF=0
N=20000
SN = N^2
TERM = $\frac{1}{SN}e^{-N^2\pi^2 DTSUM}$
SUMKRF=SUMKRF+TERM
TERM<10^{-16}
SERIES CONVERGED
N=N+1
N=20000
NO CONVERGENCE
8B


8B
FLOW CHART FOR 8B
RF=1-(6/B^2) *SUMKR
RLRF=FF*RF*e$^{-36008*t}$
NO
B^2 *t ≥ 1
YES
$RFAPPROX = 6\sqrt{\frac{DTSUM}{\pi}} - 3\delta t$
$RFAPPROX = 1 - \frac{6}{\pi^2} e^{-\pi\ DTSUM}$
8C

APPENDIX 6 : SOURCE CODE FOR RELEASE (VERS34.FOR)

```
C       PROGRAM RELEASE
C       PROGRAM TO CALCULATE CORE RELEASE FRACTION AND
C       OTHER PARAMETERS FOR A PEBBLE BED MODULAR REACTOR
C       PROGRAM NAME    :       RELEASE
C       VERSION         :       1.34
C       AUTHOR          :       PULANE MOLOKWANE
C       DATE            :       SEPTEMBER 2003
C
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)

        DIMENSION THETAC(100,100),T(100),DELT(100),TSTEP(100)
        DIMENSION THETAV(100,100),FF(100,100),RF(100,100),RFNEW(100,100)
        DIMENSION RFAPPROX(100,100),DN(100,100),DNF(100,100)
        DIMENSION RLRF(100,100),RL(100,100),CRF(100),CRF1(100)
        DIMENSION CRFAV(100),CRF1AV(100)
        DATA    DIFF_FACTOR/1.0/

C       FOR SENSITIVITY ANALYSIS, CHANGE DIFF_FACTOR ABOVE TO 2/3/4 ETC

C       ---------------------------------------
C       LOOP 1: READ INPUT FILE
C       ---------------------------------------

        OPEN(3,FILE='TEMPDATA1.TXT',ACCESS='SEQUENTIAL', STATUS='OLD')
        READ(3,*)D01,D02,Q1,Q2,A,B,FFZERO,R,AA,PI,NLAYER,NTIME,AMBDA
        READ(3,*)(T(I),I=1,NTIME)

        DO J=1,NLAYER
          READ(3,*)LAYER
          READ(3,*)(THETAC(J,K),K=1,NTIME)
        ENDDO
        CLOSE(3)

C       OUTPUT TO DATA1.TXT

        OPEN(UNIT=4,FILE='DATA1.TXT', STATUS='NEW')
        WRITE(4,*)'CONSTANTS USED IN INPUT FILE: '
        WRITE(4,17)
        WRITE(4,10)'D01    =        ', D01
        WRITE(4,10)'D02    =        ', D02
        WRITE(4,10)'Q1     =        ', Q1
        WRITE(4,10)'Q2     =        ', Q2
        WRITE(4,10)'A      =        ', A
        WRITE(4,10)'B      =        ', B
        WRITE(4,10)'FFZERO =        ', FFZERO
        WRITE(4,10)'R      =        ', R
        WRITE(4,10)'AA     =        ', AA
        WRITE(4,10)'LAMBDA =        ', AMBDA
```

```
      WRITE(4,15)'NO OF LAYERS     = ',NLAYER
      WRITE(4,15)'NO OF TIME VALUES = ',NTIME
      WRITE(4,16)
C     ---------------------------------------------------------
C     LOOP 2 : CALCULATE TIME DIFFERENCES
C     ---------------------------------------------------------

      DO I=1,NTIME
            IF(I.EQ.1)THEN
                  TSTEP(I)=0.0
            ELSE
                  TSTEP(I)=T(I)-T(I-1)
            ENDIF
            DELT(I)=3600.0*TSTEP(I)
      ENDDO
C     ------------------------------------------------
C     LOOP 3 : OUTPUT TIME VALUES
C     ------------------------------------------------

      WRITE(4,*)'TIME VALUES IN HOURS'
      WRITE(4,17)
      ISTEP =6
      ISTART=1
      ISTOP =6
      IEND  =NTIME
      DO WHILE(ISTART.LE.NTIME)
            IF(ISTOP.GT.IEND)THEN
                  ISTOP=IEND
            ENDIF
            IDIFF=ISTOP-ISTART
            IF(IDIFF.EQ.6)THEN
                  WRITE(4,8)ISTART,(T(K),K=ISTART,ISTOP)
            ELSE
                  WRITE(4,8)ISTART,(T(K),K=ISTART,ISTOP)
            ENDIF
            ISTART=ISTOP+1
            ISTOP=ISTOP+ISTEP
      ENDDO

C     ------------------------------------------------------
C     LOOP 4 : OUTPUT TEMPERATURES
C     ------------------------------------------------------

      WRITE(4,16)
      WRITE(4,*)'TEMPERATURE HISTORY'
      WRITE(4,17)
      DO J=1,NLAYER
            WRITE(4,16)
            WRITE(4,*)'LAYER NUMBER :',J
            WRITE(4,17)
            ISTEP =6
```

```
            ISTART=1
            ISTOP =6
            IEND=NTIME
            DO WHILE(ISTART.LE.NTIME)
                  IF(ISTOP.GT.IEND) THEN
                        ISTOP=IEND
                  ENDIF
                  IDIFF=ISTOP-ISTART
                  IF (IDIFF.EQ.6) THEN
                      WRITE(4,8) ISTART,(THETAC(J,K),K=ISTART,ISTOP)
                  ELSE
                      WRITE(4,8)ISTART,(THETAC(J,K),K=ISTART,ISTOP)
                  ENDIF
                  ISTART=ISTOP+1
                  ISTOP=ISTOP+ISTEP
            ENDDO
      ENDDO
      CLOSE(4)
C     ------------------------------------------------------------------
C     LOOP 5 : CALCULATE AVERAGE TEMPERATURES
C     ------------------------------------------------------------------

      DO I=1,NLAYER
            DO J=1,NTIME-1
                  THETAV(J,I)=(THETAC(I,J)+THETAC(I,J+1))/2
            ENDDO
      ENDDO
C     ------------------------------------------------------------------------------
C     LOOP 6A : OUTPUT TIME DIFFERENCE DATA TO DATA2.TXT
C     ------------------------------------------------------------------------------
      OPEN(UNIT=4,FILE='DATA2.TXT',STATUS='NEW')
      WRITE(4,*)'TIME DIFFERENCES'
      WRITE(4,17)
      ISTEP =6
      ISTART=1
      ISTOP =6
      IEND=NTIME-1
      DO WHILE(ISTART.LE.NTIME-1)
            IF(ISTOP.GT.IEND)THEN
                  ISTOP=IEND
            ENDIF
            IDIFF=ISTOP-ISTART
            IF(IDIFF.EQ.6)THEN
                  WRITE(4,8)ISTART,(DELT(K),K=ISTART,ISTOP)
            ELSE
                  WRITE(4,8)ISTART,(DELT(K),K=ISTART,ISTOP)
            ENDIF
            ISTART=ISTOP+1
            ISTOP=ISTOP+ISTEP
      ENDDO
C     ------------------------------------------------------------------------------
```

```
C     LOOP 6B : OUTPUT TEMPERATURE DATA TO DATA2.TXT
C     ------------------------------------------------------------------------------

      WRITE(4,16)
      WRITE(4,*)'TEMPERATURE AVERAGES (CELSIUS)'
      WRITE(4,17)
      DO I=1,NLAYER
            WRITE(4,17)
            WRITE(4,*)'LAYER NUMBER :',I
            WRITE(4,17)
            ISTEP =6
            ISTART=1
            ISTOP =6
            IEND=NTIME-1
            DO WHILE(ISTART.LE.IEND)
                  IF(ISTOP.GT.IEND) THEN
                        ISTOP=IEND
                  ENDIF
                  IDIFF=ISTOP-ISTART
                  IF (IDIFF.GE.6) THEN
                        WRITE(4,8)ISTART,(THETAV(J,I),J=ISTART,ISTOP)
                  ELSE
                        WRITE(4,8)ISTART,(THETAV(J,I),J=ISTART,ISTOP)
                  ENDIF
                  ISTART=ISTOP+1
                  ISTOP=ISTOP+ISTEP
            ENDDO
      ENDDO
      CLOSE(4)
C     ---------------------------------------------------------------
C     LOOP 7: CALCULATE FAILURE FRACTION (FF)
C     ---------------------------------------------------------------

      PI2=PI*PI
      DO I=1,NLAYER
            FF(1,I)=FFZERO
            DO J=2,NTIME
                  IF(THETAV(J,I).LT.1200)THEN
                        FF(J,I)=FFZERO
                  ELSE
                        FF(J,I)=A*DEXP(B*THETAV(J,I))
                  ENDIF
                  IF(FF(J,I).LT.FFZERO)THEN
                        FF(J,I)=FFZERO
                  ELSEIF(J.GT.2) THEN
                        FF(J,I)=MAX(FF(J-1,I),FF(J,I))
                  ENDIF
            ENDDO
      ENDDO
```

```
C     ------------------------------------------------------------------------
C     LOOP 8 : CALCULATE KERNEL RELEASE FRACTION(RF)
C     RFAPPROX,IODINE AND LAYER RELEASE(RLRF)
C     ------------------------------------------------------------------------

      DO I=1,NLAYER
            DTSUM=0.0

C           LOOP 8.1 : FOR EACH TIME VALUE

      DO J=1,NTIME
       IF(J.EQ.1) THEN
                  RF(J,I)=0.0
                  RFAPPROX(J,I)=0.0
                  DN(J,I)=DEXP(-AMBDA*DELT(J))
                  DNF(J,I)=1.0

       ELSE
            THETAK=THETAV(J,I)+273.0
            DPRIME=D01*DEXP(-Q1/(R*THETAK))+D02*DEXP(-Q2/(R*THETAK))
            DPRIME=DIFF_FACTOR*DPRIME
            DT=DPRIME*DELT(J)
            DTSUM=DTSUM+DT
            SUMKRF=0.0

C           LOOP 8.2 :  CARRY OUT SERIES CALCULATION
C                 EXIT SUMMATION LOOP IF ACURACY
C                 OF 1.E-16  IS ACHIEVED ELSE TERMINATE
C                 LOOP AT N=20000, THEN MESSAGE TO  SCREEN

            DO N=1,20000
                  SN=DFLOAT(N*N)
                  TERM=(1.0/SN) * DEXP(-SN*PI2*DTSUM)
                  SUMKRF=SUMKRF+TERM
                  IF (TERM.LT.1.0E-16)THEN
                        EXIT
                  ENDIF
                  IF(N.EQ.20000)THEN
                        WRITE(6,*)'SERIES DID NOT CONVERGE'
                        WRITE(6,*)'N = ',N
                        EXIT
                  ENDIF
            ENDDO

            RF(J,I)=1.0-(6.0/PI2)*SUMKRF
            PI2DT=PI2*DTSUM
            IF(PI2DT.GE.1.0)THEN
                  RFAPPROX(J,I)=1.0-(6.0/PI2)*DEXP(-PI2*DTSUM)
            ELSE
                  RFAPPROX(J,I)=6.0*DSQRT(DTSUM/PI)-3.0*DTSUM
```

```
            ENDIF
            DN(J,I)=DN(J-1,I)*DEXP(-AMBDA*DELT(J))
            DNF(J,I)=DEXP(-AMBDA*3600.0*T(J))
            RLRF(J,I)=FF(J,I)*RF(J,I)*DEXP(-AMBDA*3600.0*T(J))
          ENDIF
         ENDDO
        ENDDO
C       ------------------------------------------------------------------------------
C       LOOP 9A: CALCULATION OF CORE RELEASE FRACTION (CRF)
C       ------------------------------------------------------------------------------

        WRITE (6,*)'FOR CRF ONLY ENTER 1'
        WRITE (6,*)'FOR DIFFERENTIAL CRF, ENTER 2'
        READ (5,*)ICHOICE
        DO I=1,NLAYER
         DO J=1,NTIME-1
            RFNEW (J, I)=RF (J+1,I)-RF (J,I)
            SELECT CASE (ICHOICE)
             CASE (1)
              RL (J,I)=DEXP(-AMBDA*DELT(J))*FF(J,I)*RFNEW(J,I)
             CASE (2)
              RL(J,I)=DEXP(-AMBDA*DELT(J))*FF(J,I)*RFNEW(J,I)/DELT(J+1)
          END SELECT
         ENDDO
        ENDDO

        OPEN(4,FILE='CRF.TXT',STATUS='NEW')
        DO I=1,NTIME
            CRFSUM=0.0
            DO J=1,NLAYER
                CRFSUM=CRFSUM+RL(I,J)
            ENDDO
            IP=I+1
            CRF(IP)=CRFSUM
            CRFAV(IP)=CRFSUM/DFLOAT(NLAYER)
        ENDDO

        WRITE(4,17)
        IF(ICHOICE.EQ.1)THEN
            WRITE(4,*)'CRF'
        ELSE
            WRITE(4,*)'DIFFERENTIAL CRF'
        ENDIF
        WRITE(4,17)
        DO I=1,NTIME
            WRITE(4,18)I,CRF(I)
        ENDDO
        WRITE(4,17)
        WRITE (4,*)'CRFAV'
        WRITE(4,17)
        DO I=1,NTIME
```

```
        WRITE(4,18)I,CRFAV(I)
      ENDDO

      CRF_INT=0.0
      CRFAV_INT=0.0
      WRITE(4,17)
      WRITE(4,*)'INTEGRAL OF  CRF AND CRFAV'
      WRITE(4,17)
      DO I=1,NTIME
            CRF_INT=CRF_INT+CRF(I)
            CRFAV_INT=CRFAV_INT+CRFAV(I)
            WRITE(4,19)T(I),CRF_INT,CRFAV_INT
      ENDDO
      CLOSE(4)
C     ------------------------------------------------------------------------------------------
C     LOOP 9B:     CALCULATION OF CORE RELEASE FRACTION (CRF1)
C     ------------------------------------------------------------------------------------------

      OPEN(4,FILE='CRF1.TXT',STATUS='NEW')
      DO I=1,NTIME
            CRF1SUM=0.0
            DO J=1,NLAYER
                  CRF1SUM=CRF1SUM+RLRF(I,J)
            ENDDO
            CRF1(I)=CRF1SUM
            CRF1AV(I)=CRF1SUM/DFLOAT(NLAYER)
      ENDDO

      WRITE(4,17)
      IF(ICHOICE.EQ.1) THEN
       WRITE(4,*)'CRF1'
      ELSE
            WRITE(4,*)'DIFFERENTIAL CRF1'
      ENDIF
      WRITE(4,17)
      DO I=1,NTIME
            WRITE(4,18)I,CRF1(I)
      ENDDO
      WRITE(4,17)
      WRITE(4,*)'CRF1AV'
      WRITE(4,17)
      DO I=1,NTIME
            WRITE(4,18)I,CRF1AV(I)
      ENDDO

      CRF1_INT=0.0
      CRF1AV_INT=0.0
      WRITE(4,17)
      WRITE(4,*)'INTEGRAL CRF1 AND CRF1AV'
      WRITE(4,17)
      DO I=1,NTIME
```

```
            CRF1_INT=CRF1_INT+CRF1(I)
            CRF1AV_INT=CRF1AV_INT+CRF1AV(I)
            WRITE(4,19)T(I),CRF1_INT,CRF1AV_INT
        ENDDO
        CLOSE(4)
C       ---------------------------------------------------------------
C       LOOP 10 :     CREATE OUTPUT DATA FILES
C       ---------------------------------------------------------------

C       LOOP 10.1 : DATA3.TXT

        OPEN(UNIT=4,FILE='DATA3.TXT',STATUS='NEW')
        WRITE(4,16)
        WRITE(4,*)'KERNEL RELEASE FRACTION (RF)'
        WRITE(4,17)
        DO I=1,NLAYER
            WRITE(4,17)
            WRITE(4,*)'LAYER NUMBER :',I
            WRITE(4,17)
            ISTEP =4
            ISTART=1
            ISTOP =4
            IEND=NTIME
            DO WHILE(ISTART.LE.IEND)
                IF(ISTOP.GT.IEND) THEN
                    ISTOP=IEND
                ENDIF
                IDIFF=ISTOP-ISTART
                IF (IDIFF.GE.4) THEN
                        WRITE(4,13)ISTART,(RF(J,I),J=ISTART,ISTOP)
                ELSE
                    WRITE(4,13)ISTART,(RF(J,I),J=ISTART,ISTOP)
                ENDIF
                ISTART=ISTOP+1
                ISTOP=ISTOP+ISTEP
            ENDDO
            WRITE(4,17)
            WRITE(4,*)'APPROXIMATE KRF (RFAPPROX)'
            WRITE(4,17)
            WRITE(4,*)'LAYER NUMBER :',I
            WRITE(4,17)
            ISTEP =4
            ISTART=1
            ISTOP =4
            IEND=NTIME
            DO WHILE(ISTART.LE.IEND)
                IF(ISTOP.GT.IEND) THEN
                    ISTOP=IEND
                ENDIF
                IDIFF=ISTOP-ISTART
                IF (IDIFF.GE.4) THEN
```

```
                    WRITE(4,13)ISTART,(RFAPPROX(J,I),J=ISTART,ISTOP)
                ELSE
                    WRITE(4,13)ISTART,(RFAPPROX(J,I),J=ISTART,ISTOP)
                ENDIF
                ISTART=ISTOP+1
                ISTOP=ISTOP+ISTEP
            ENDDO
        ENDDO
        CLOSE(4)

C                       LOOP 10.2 : DATA4.TXT

        OPEN(UNIT=4,FILE='DATA4.TXT',STATUS='NEW')
        WRITE(4,*)'DATA4.TXT CONTAINS DATA FOR FF,DN,RLRF'
        WRITE(4,16)
        DO I=1,NLAYER
            WRITE(4,17)
            WRITE(4,*)'TIME,RF,FF,DN & RLRF FOR LAYER : ',I
            WRITE(4,17)
            DO J=1,NTIME
                WRITE(4,11)T(J),RF(J,I),FF(J,I),DN(J,I),RLRF(J,I)
            ENDDO
        ENDDO
        CLOSE(4)
C       ------------------------------ -------------------------
C       OUTPUT FORMATTING STATEMENTS
C       ------------------------------------------------------

1       FORMAT(F7.3,3X,2(1PE12.4,2X))
2       FORMAT(F8.3,2X,2(1PE12.4,3X))
3       FORMAT(F7.3,A5,F7.3,2X,4(1PE15.10,3X))
4       FORMAT(2I5,2X,2(1PE12.4,3X))
5       FORMAT(A20,F8.3,2X,A7,2X,1PE12.5)
6       FORMAT(F8.3,A5,F8.3,3X,1PE12.4)
7       FORMAT(I3,3X,F12.3,3X,F10.2,3X,F15.2)
8       FORMAT(I3,4X,6(F10.3,2X))
9       FORMAT(F8.3,3X,1PE12.4)
10      FORMAT(A25,1PE15.6)
11      FORMAT(F7.3,3X,4(1PE12.4,2X))
13      FORMAT(I3,4X,4(1PE12.4,2X))
14      FORMAT(I2,3X,2(F7.3,2X,1PE10.4,2X,1PE10.4))
15      FORMAT(A25,I4)
16      FORMAT(//)
17      FORMAT(/)
18      FORMAT(I5,4X,1PE12.5)
19      FORMAT(F8.3,3X,2(1PE12.5,3X))
        END
```

APPENDIX 7 : SAMPLE OUTPUT

Table 1: Sample input parameters

CONSTANTS USED IN INPUT FILE:

D01	=	1.4080000E-07
D02	=	9.600000E+06
Q1	=	5.400000E+04
Q2	=	4.800000E+05
A	=	3.511700E-06
B	=	2.027300E-03
FFZERO	=	4.000000E-05
R	=	8.314500E+00
AA	=	2.500000E-04
LAMBDA	=	1.000200E-06
NO OF LAYERS	=	92
NO OF TIME VALUES	=	46

TIME VALUES IN HOURS, SECONDS AND TIME STEPS

1	0.000	000.00	000.00
2	0.100	360.00	360.00
3	0.167	601.20	241.20
4	0.233	838.80	237.60
5	0.300	1080.00	241.20
6	0.533	1918.80	838.80
7	0.767	2761.20	842.40
8	1.000	3600.00	838.80
9	1.500	5400.00	1800.00
10	2.000	7200.00	1800.00
11	2.500	9000.00	1800.00
12	3.000	10800.00	1800.00
13	3.500	12600.00	1800.00
14	4.000	14400.00	1800.00
15	4.500	16200.00	1800.00
16	5.000	18000.00	1800.00
17	5.500	19800.00	1800.00
18	6.000	21600.00	1800.00
19	6.500	23400.00	1800.00
20	7.000	25200.00	1800.00
21	7.500	27000.00	1800.00
22	8.000	28800.00	1800.00
23	8.500	30600.00	1800.00
24	9.000	32400.00	1800.00
25	12.000	43200.00	10800.00
26	15.000	54000.00	10800.00
27	18.000	64800.00	10800.00
28	21.000	75600.00	10800.00

29	24.000	86400.00	10800.00
30	27.000	97200.00	10800.00
31	30.000	108000.00	10800.00
32	33.000	118800.00	10800.00
33	36.000	129600.00	10800.00
34	39.000	140400.00	10800.00
35	42.000	151200.00	10800.00
36	45.000	162000.00	10800.00
37	48.000	172800.00	10800.00
38	61.333	220798.80	47998.80
39	74.667	268801.20	48002.40
40	88.000	316800.00	47998.80
41	101.333	364798.80	47998.80
42	114.667	412801.20	48002.40
43	128.000	460800.00	47998.80
44	141.333	508798.80	47998.80
45	154.667	556801.20	48002.40
46	168.000	604800.00	47998.80

TEMPERATURE HISTORY

LAYER NUMBER: 1

1	571.0	569.0	576.0	583.0	589.0	605.0
7	617.0	627.0	643.0	655.0	665.0	674.0
13	681.0	688.0	693.0	699.0	703.0	708.0
19	712.0	715.0	719.0	722.0	725.0	728.0
25	741.0	751.0	759.0	764.0	768.0	771.0
31	772.0	773.0	773.0	773.0	772.0	770.0
37	769.0	758.0	744.0	729.0	713.0	698.0
43	682.0	666.0	651.0	637.0		

Table 2: Sample temperature averages

TEMPERATURE AVERAGES (CELSIUS)

LAYER NUMBER: 1

1	570.0	572.5	579.5	586.0	597.0	611.0
7	622.0	635.0	649.0	660.0	669.5	677.5
13	684.5	690.5	696.0	701.0	705.5	710.0
19	713.5	717.0	720.5	723.5	726.5	734.5
25	746.0	755.0	761.5	766.0	769.5	771.5
31	772.5	773.0	773.0	772.5	771.0	769.5
37	763.5	751.0	736.5	721.0	705.5	690.0
43	674.0	658.5	644.0			

LAYER NUMBER: 2

1	630.5	611.0	620.5	628.5	643.0	662.5
7	678.0	697.0	718.5	735.5	750.0	763.0
13	774.0	784.0	793.0	801.0	808.0	814.5
19	821.0	826.5	831.5	836.5	841.5	854.5
25	873.0	887.0	897.5	905.0	910.5	914.5
31	917.5	919.5	920.0	919.5	918.5	917.0
37	910.0	895.5	877.5	858.0	837.5	817.0
43	797.0	777.5	759.0			

Table 3: Sample RF and RFapproximation output file

KERNEL RELEASE FRACTION (RF)

LAYER NUMBER: 1

1	0.0000E+00	5.1756E-04	6.7749E-04	8.1142E-04
5	9.3868E-04	1.3239E-03	1.6463E-03	1.9412E-03
9	2.5095E-03	3.0075E-03	3.4628E-03	3.8874E-03
13	4.2886E-03	4.6703E-03	5.0363E-03	5.3889E-03
17	5.7297E-03	6.0609E-03	6.3821E-03	6.6948E-03
21	7.0004E-03	7.2987E-03	7.5909E-03	7.8867E-03
25	9.5773E-03	1.1086E-02	1.2462E-02	1.3732E-02
29	1.4917E-02	1.6025E-02	1.7067E-02	1.8052E-02
33	1.8984E-02	1.9870E-02	2.0709E-02	2.1509E-02

37	2.2252E-02	2.5078E-02	2.7401E-02	2.9340E-02
41	3.0982E-02	3.2386E-02	3.3587E-02	3.4623E-02
45	3.5524E-02	3.5524E-02		

APPROXIMATE KRF (RFAPPROX)

LAYER NUMBER: 1

1	0.0000E+00	5.1756E-04	6.7749E-04	8.1142E-04
5	9.3868E-04	1.3239E-03	1.6463E-03	1.9412E-03
9	2.5095E-03	3.0075E-03	3.4628E-03	3.8874E-03
13	4.2886E-03	4.6703E-03	5.0363E-03	5.3889E-03
17	5.7297E-03	6.0609E-03	6.3821E-03	6.6948E-03
21	7.0004E-03	7.2987E-03	7.5909E-03	7.8867E-03
25	9.5773E-03	1.1086E-02	1.2462E-02	1.3732E-02
29	1.4917E-02	1.6025E-02	1.7067E-02	1.8052E-02
33	1.8984E-02	1.9870E-02	2.0709E-02	2.1509E-02
37	2.2252E-02	2.5078E-02	2.7401E-02	2.9340E-02
41	3.0982E-02	3.2386E-02	3.3587E-02	3.4623E-02
45	3.5524E-02	3.5524E-02		

Table 4: Sample DATA 4.TXT

TIME, RF, FF, DN & RLRF FOR LAYER: 1

0.000	0.0000E+00	3.0000E-05	1.0000E+00	0.0000E+00
0.100	5.1756E-04	3.0000E-05	9.9964E-01	1.5521E-08
0.167	6.7749E-04	3.0000E-05	9.9940E-01	2.0312E-08
0.233	8.1142E-04	3.0000E-05	9.9916E-01	2.4322E-08
0.300	9.3868E-04	3.0000E-05	9.9892E-01	2.8130E-08
0.533	1.3239E-03	3.0000E-05	9.9808E-01	3.9641E-08
0.767	1.6463E-03	3.0000E-05	9.9724E-01	4.9254E-08
1.000	1.9412E-03	3.0000E-05	9.9641E-01	5.8027E-08
1.500	2.5095E-03	3.0000E-05	9.9461E-01	7.4881E-08
2.000	3.0075E-03	3.0000E-05	9.9282E-01	8.9578E-08
2.500	3.4628E-03	3.0000E-05	9.9104E-01	1.0295E-07
3.000	3.8874E-03	3.0000E-05	9.8926E-01	1.1537E-07
3.500	4.2886E-03	3.0000E-05	9.8748E-01	1.2705E-07

4.000	4.6703E-03	3.0000E-05	9.8570E-01	1.3811E-07
4.500	5.0363E-03	3.0000E-05	9.8393E-01	1.4866E-07
5.000	5.3889E-03	3.0000E-05	9.8216E-01	1.5878E-07
5.500	5.7297E-03	3.0000E-05	9.8039E-01	1.6852E-07
6.000	6.0609E-03	3.0000E-05	9.7863E-01	1.7794E-07
6.500	6.3821E-03	3.0000E-05	9.7687E-01	1.8703E-07
7.000	6.6948E-03	3.0000E-05	9.7511E-01	1.9585E-07
7.500	7.0004E-03	3.0000E-05	9.7336E-01	2.0442E-07
8.000	7.2987E-03	3.0000E-05	9.7161E-01	2.1274E-07
8.500	7.5909E-03	3.0000E-05	9.6986E-01	2.2086E-07
9.000	7.8867E-03	3.0000E-05	9.6811E-01	2.2906E-07
12.000	9.5773E-03	3.0000E-05	9.5771E-01	2.7517E-07
15.000	1.1086E-02	3.0000E-05	9.4742E-01	3.1510E-07
18.000	1.2462E-02	3.0000E-05	9.3724E-01	3.5040E-07
21.000	1.3732E-02	3.0000E-05	9.2717E-01	3.8196E-07
24.000	1.4917E-02	3.0000E-05	9.1721E-01	4.1045E-07
27.000	1.6025E-02	3.0000E-05	9.0736E-01	4.3622E-07
30.000	1.7067E-02	3.0000E-05	8.9761E-01	4.5960E-07
33.000	1.8052E-02	3.0000E-05	8.8796E-01	4.8087E-07
36.000	1.8984E-02	3.0000E-05	8.7842E-01	5.0028E-07
39.000	1.9870E-02	3.0000E-05	8.6899E-01	5.1799E-07
42.000	2.0709E-02	3.0000E-05	8.5965E-01	5.3408E-07
45.000	2.1509E-02	3.0000E-05	8.5041E-01	5.4874E-07
48.000	2.2252E-02	3.0000E-05	8.4128E-01	5.6161E-07
61.333	2.5078E-02	3.0000E-05	8.0184E-01	6.0326E-07
74.667	2.7401E-02	3.0000E-05	7.6425E-01	6.2823E-07
88.000	2.9340E-02	3.0000E-05	7.2843E-01	6.4116E-07
101.333	3.0982E-02	3.0000E-05	6.9429E-01	6.4532E-07
114.667	3.2386E-02	3.0000E-05	6.6174E-01	6.4293E-07
128.000	3.3587E-02	3.0000E-05	6.3072E-01	6.3552E-07
141.333	3.4623E-02	3.0000E-05	6.0116E-01	6.2442E-07
154.667	3.5524E-02	3.0000E-05	5.7298E-01	6.1064E-07
168.000	3.5524E-02	3.0000E-05	5.4612E-01	5.8202E-07

Table 5: Sample CRF.TXT output

TIME	CRF
0.0000E+00	0
1.0000E-01	3.90E-06
1.6700E-01	1.18E-06
2.3300E-01	9.73E-07
3.0000E-01	9.04E-07
5.3300E-01	2.69E-06
7.6700E-01	2.22E-06
1.0000E+00	2.01E-06
1.5000E+00	3.83E-06
2.0000E+00	3.33E-06

2.5000E+00	3.01E-06
3.0000E+00	2.80E-06
3.5000E+00	2.64E-06
4.0000E+00	2.52E-06
4.5000E+00	2.43E-06
5.0000E+00	2.36E-06
5.5000E+00	2.31E-06
6.0000E+00	2.27E-06
6.5000E+00	2.24E-06
7.0000E+00	2.21E-06
7.5000E+00	2.19E-06
8.0000E+00	2.18E-06
8.5000E+00	2.17E-06
9.0000E+00	2.34E-06
1.2000E+01	1.51E-05
1.5000E+01	1.52E-05
1.8000E+01	1.59E-05
2.1000E+01	1.67E-05
2.4000E+01	1.75E-05
2.7000E+01	1.82E-05
3.0000E+01	1.87E-05
3.3000E+01	1.88E-05
3.6000E+01	1.87E-05
3.9000E+01	1.84E-05
4.2000E+01	1.79E-05
4.5000E+01	1.71E-05
4.8000E+01	1.58E-05
6.1333E+01	5.34E-05
7.4667E+01	3.39E-05
8.8000E+01	2.27E-05
1.0133E+02	1.59E-05
1.1467E+02	1.18E-05
1.2800E+02	9.35E-06
1.4133E+02	7.73E-06
1.5467E+02	6.62E-06
1.6800E+02	6.41E-14

Table 6: Sample CRF1.TXT output

TIME	CRF1	TIME	CRF1
0.000	0.0000E+00	12.000	9.5114E-05
0.100	5.1953E-06	15.000	1.1562E-04
0.167	6.7682E-06	18.000	1.3651E-04
0.233	8.0635E-06	21.000	1.5797E-04
0.300	9.2662E-06	24.000	1.7982E-04
0.533	1.2835E-05	27.000	2.0179E-04
0.767	1.5786E-05	30.000	2.2358E-04
1.000	1.8441E-05	33.000	2.4475E-04
1.500	2.3490E-05	36.000	2.6487E-04
2.000	2.7861E-05	39.000	2.8372E-04
2.500	3.1819E-05	42.000	3.0110E-04
3.000	3.5538E-05	45.000	3.1683E-04
3.500	3.9077E-05	48.000	3.3023E-04
4.000	4.2514E-05	61.333	3.6758E-04
4.500	4.5865E-05	74.667	3.8376E-04
5.000	4.9151E-05	88.000	3.8727E-04
5.500	5.2365E-05	101.333	3.8361E-04
6.000	5.5505E-05	114.667	3.7601E-04
6.500	5.8584E-05	128.000	3.6624E-04
7.000	6.1617E-05	141.333	3.5529E-04
7.500	6.4619E-05	154.667	3.4372E-04
8.000	6.7614E-05	168.000	3.2761E-04
8.500	7.0595E-05		
9.000	7.4558E-05		

APPENDIX 8
MathCAD CALCULATIONS

Input parameters

$$\theta 1 := \frac{(569 + 571)}{2}$$

$\theta 1 = 570$

$t1 := (0.1 - 0) \cdot 3600$

$t1 = 360$

$t2 := (0.167 - 0.1) \cdot 3600$

$t2 = 241.2$

$$\theta 2 := \frac{(569 + 576)}{2}$$

$\theta 2 = 572.5$

$T1 := \theta 1 + 273$

$T1 = 843$

$T2 := \theta 2 + 273$

$T2 = 845.5$

$$\theta 3 := \frac{(576 + 583)}{2}$$

$\theta 3 = 579.5$

$t3 := (0.233 - 0.167) \cdot 360($

$t3 = 237.6$

$T3 := \theta 3 + 273$

$T3 = 852.5$

$$\theta 4 := \frac{(589 + 583)}{2}$$

$\theta 4 = 586$

$t4 := (0.3 - 0.233) \cdot 360($

$t4 = 241.2$

$T4 := \theta 4 + 273$

$T4 = 859$

$$\theta 5 := \frac{(605 + 583)}{2}$$

$\theta 5 = 594$

$t5 := (0.533 - 0.3) \cdot 360($

$t5 = 838.8$

$T5 := \theta 5 + 273$

$T5 = 867$

$$Dp1 := D \cdot e^{-\left(\frac{Q}{R \cdot T1}\right)}$$

$Dp1 = 6.348803 \times 10^{-11}$

$p1 := Dp1 \cdot t1$

$p1 = 2.285569 \times 10^{-8}$

$$Dp2 := D \cdot e^{-\left(\frac{Q}{R \cdot T2}\right)}$$

$Dp2 = 6.49509 \times 10^{-11}$

$p2 := Dp2 \cdot t2 + p1$

$p2 = 3.852185 \times 10^{-8}$

$$Dp3 := D \cdot e^{-\left(\frac{Q}{R \cdot T3}\right)}$$

$Dp3 = 6.917954 \times 10^{-11}$

$p3 := Dp3 \cdot t3 + p2$

$p3 = 5.495891 \times 10^{-8}$

$k := 100000$

$$Dp4 := D \cdot e^{-\left(\frac{Q}{R \cdot T4}\right)}$$

$Dp4 = 7.328479 \times 10^{-11}$

$p4 := Dp4 \cdot t4 + p3$

$p4 = 7.26352 \times 10^{-8}$

$$Dp5 := D \cdot e^{-\left(\frac{Q}{R \cdot T5}\right)}$$

$$Dp5 = 7.858004 \times 10^{-11}$$

$$p5 := Dp5 \cdot t5 + p4$$

$$p5 = 1.385481 \times 10^{-7}$$

Kernel release fraction calculations

$$j1 := \sum_{n=1}^{k} \frac{1}{n^2} \cdot e^{-n^2 \cdot \pi^2 \cdot p1}$$

$$j1 = 1.644092$$

$$krf1 := 1 - \frac{6}{\pi^2} \cdot j1$$

$$krf1 = 5.116999 \times 10^{-4}$$

$$j2 := \sum_{n=1}^{k} \frac{1}{n^2} \cdot e^{-n^2 \cdot \pi^2 \cdot p2}$$

$$j2 = 1.643841$$

$$krf2 := 1 - \frac{6}{\pi^2} \cdot j2$$

$$krf2 = 6.642848 \times 10^{-4}$$

$$j3 := \sum_{n=1}^{k} \frac{1}{n^2} \cdot e^{-n^2 \cdot \pi^2 \cdot p3}$$

$$j3 = 1.643629$$

$$krf3 := 1 - \frac{6}{\pi^2} \cdot j3$$

$$krf3 = 7.934236 \times 10^{-4}$$

$$j4 := \sum_{n=1}^{k} \frac{1}{n^2} \cdot e^{-n^2 \cdot \pi^2 \cdot p4}$$

$j4 = 1.643434$

$$krf4 := 1 - \frac{6}{\pi^2} \cdot j4$$

$krf4 = 9.121077 \times 10^{-4}$

$$j5 := \sum_{n=1}^{k} \frac{1}{n^2} \cdot e^{-n^2 \cdot \pi^2 \cdot p5}$$

$j5 = 1.642862$

$$krf5 := 1 - \frac{6}{\pi^2} \cdot j5$$

$krf5 = 1.259602 \times 10^{-3}$

$krfnew3 := krf4 - krf3$

$krfnew3 = 1.186841 \times 10^{-4}$

$krfnew4 := krf5 - krf4$

$krfnew4 = 3.474943 \times 10^{-4}$

Iodine decay correction calculations

$I1 := e^{-\lambda \cdot t1}$

$I1 = 0.99964$

$I2 := I1 \cdot e^{-\lambda \cdot t2}$

$I2 = 0.999399$

$I3 := I2 \cdot e^{-\lambda \cdot t3}$

$I3 = 0.999161$

$I4 := I3 \cdot e^{-\lambda \cdot t4}$

$I4 = 0.99892$

$I5 := I4 \cdot e^{-\lambda \cdot t5}$

$I5 = 0.998083$

Layer release calculations

$Lr1 := e^{-\lambda \cdot t1} \cdot krf1 \cdot F$

$Lr1 = 2.046063 \times 10^{-8}$

$Lr2 := e^{-\lambda \cdot t2} \cdot krf2 \cdot F$

$Lr2 = 2.656498 \times 10^{-8}$

$Lr3 := e^{-\lambda \cdot t3} \cdot krf3 \cdot F$

$Lr3 = 3.17294 \times 10^{-8}$

$Lr4 := e^{-\lambda \cdot t4} \cdot krf4 \cdot F$

$Lr4 = 3.647551 \times 10^{-8}$

$Lr5 := e^{-\lambda \cdot t5} \cdot krf5 \cdot F$

$Lr5 = 5.034183 \times 10^{-8}$

Layer release for a (time-step) calculations

$Lr1 := e^{-\lambda \cdot t1} \cdot krfnew1 \cdot F$

$Lr1 = 6.1012 \times 10^{-9}$

$Lr2 := e^{-\lambda \cdot t2} \cdot krfnew2 \cdot F$

$Lr2 = 5.164306 \times 10^{-9}$

$Lr3 := e^{-\lambda \cdot t3} \cdot krfnew3 \cdot F$

$Lr3 = 4.746237 \times 10^{-9}$

$Lr4 := e^{-\lambda \cdot t4} \cdot krfnew4 \cdot F$

$Lr4 = 1.389642 \times 10^{-8}$

APPENDIX 9: EXAMPLE OF VSOP CALCULATIONS

Time (h)	0	0.1	0.167	0.233	0.3	0.533	0.767	1.0	1.5
Layer	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
1	571	569	576	583	589	605	617	627	643
2	655	606	616	625	632	654	671	685	709
3	743	656	669	680	691	720	743	763	797
4	863	743	759	773	786	822	850	874	917
5	919	783	799	814	827	864	894	919	964
6	990	846	862	877	890	929	960	986	1033
7	1032	891	907	921	933	969	998	1023	1068
8	1042	916	931	944	955	989	1017	1041	1084
9	1068	953	966	977	987	1016	1040	1060	1098
10	1068	970	981	990	999	1025	1046	1064	1097
11	1060	982	992	1000	1008	1031	1050	1067	1097
12	1073	1000	1007	1014	1020	1037	1052	1065	1088
13	1062	1005	1011	1017	1022	1038	1051	1063	1084
14	1058	1011	1017	1021	1026	1039	1050	1060	1078
15	1058	1017	1021	1025	1028	1038	1047	1054	1068
16	1047	1018	1021	1025	1028	1037	1044	1051	1063
17	1042	1017	1020	1023	1025	1032	1038	1043	1052
18	1032	1012	1014	1016	1018	1024	1030	1034	1041
19	1011	995	997	999	1001	1005	1009	1011	1012
20	557	568	579	587	595	617	633	647	668
21	627	603	616	627	638	668	691	710	742
22	705	649	666	681	695	735	768	795	842
23	813	734	755	774	791	841	882	916	972
24	866	772	794	814	832	885	927	962	1021
25	932	832	854	875	893	948	992	1028	1088
26	975	876	897	916	934	985	1026	1060	1117
27	989	900	920	938	954	1003	1042	1075	1129
28	1017	935	952	968	982	1024	1058	1086	1133
29	1023	951	966	980	992	1030	1060	1085	1126

30	1018	962	976	989	1000	1034	1061	1083	1121
31	1035	980	991	1000	1009	1035	1056	1074	1103
32	1027	985	995	1003	1011	1035	1053	1069	1094
33	1026	992	1000	1007	1014	1034	1050	1063	1084
34	1029	999	1005	1010	1016	1031	1043	1053	1069
35	1022	1000	1005	1010	1015	1028	1039	1048	1061
36	1016	1000	1005	1008	1012	1023	1032	1038	1048
37	1001	988	991	993	995	1000	1004	1006	1005
38	546	558	567	576	583	604	620	632	653
39	608	590	602	613	623	652	674	692	723
40	684	633	648	662	675	714	745	771	815
41	786	714	734	752	769	817	856	887	940
42	837	751	772	791	808	859	899	932	987
43	898	808	830	849	867	920	961	994	1050
44	940	851	872	890	907	956	994	1025	1076
45	954	874	893	911	927	973	1009	1038	1086
46	981	907	924	939	953	993	1024	1048	1088
47	988	924	939	952	964	999	1025	1047	1080
48	986	936	949	961	972	1003	1027	1045	1075
49	1003	954	964	974	982	1005	1023	1036	1057
50	997	960	969	977	985	1005	1020	1032	1049
51	997	967	975	982	988	1005	1017	1026	1040
52	1002	975	981	986	991	1003	1012	1018	1025
53	997	978	983	987	991	1002	1009	1013	1018
54	995	981	985	989	992	1000	1004	1007	1008
55	991	979	981	983	985	988	989	988	982
56	542	555	563	570	576	594	608	618	635
57	603	587	598	607	616	640	658	673	698
58	683	630	644	656	668	700	726	747	782
59	787	710	729	744	758	799	830	855	897
60	837	747	766	782	797	839	871	897	940
61	899	804	823	840	855	898	930	956	999
62	939	845	863	879	893	932	961	985	1024
63	951	867	884	899	912	948	976	997	1034
64	978	901	915	928	938	968	990	1008	1037

65	983	917	929	940	949	974	993	1007	1031
66	980	928	939	949	957	978	994	1006	1026
67	997	946	954	961	967	982	992	999	1010
68	991	952	959	965	969	982	990	995	1003
69	990	959	964	969	973	982	987	991	995
70	994	966	970	974	976	981	984	984	984
71	990	970	973	976	978	983	984	984	981
72	989	975	978	981	983	987	987	986	982
73	986	971	973	973	973	971	966	960	946
74	539	542	546	551	554	565	573	580	591
75	600	571	577	582	587	601	611	620	636
76	688	610	618	624	630	647	661	673	695
77	796	685	694	702	708	728	745	759	786
78	846	720	728	736	743	763	779	794	821
79	906	773	781	788	794	813	829	843	870
80	945	814	820	825	830	845	858	870	893
81	955	836	840	845	849	861	872	882	903
82	978	868	871	873	875	882	889	896	910
83	983	885	886	887	887	890	894	898	908
84	978	897	896	896	896	896	897	900	906
85	992	915	912	910	908	903	900	899	898
86	985	921	918	915	912	905	900	897	894
87	983	929	924	920	917	907	901	896	890
88	987	937	932	927	923	910	901	894	883
89	981	941	935	930	926	913	903	896	884
90	982	946	940	935	930	916	905	896	881
91	979	948	944	939	935	921	910	901	885
92	984	964	963	962	960	952	943	935	918

Time (h)	2	2.5	3	3.5	4	4.5	5	5.5	6
Layer	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
1	655	665	674	681	688	693	699	703	708
2	728	743	757	769	779	789	797	805	811
3	825	848	869	886	902	916	929	941	951
4	952	981	1006	1028	1048	1065	1080	1094	1107
5	1001	1032	1058	1081	1102	1119	1135	1150	1163
6	1072	1104	1132	1155	1176	1195	1212	1227	1240
7	1104	1135	1161	1184	1204	1222	1238	1252	1265
8	1119	1148	1174	1196	1215	1232	1247	1261	1273
9	1129	1154	1176	1195	1212	1227	1240	1252	1262
10	1125	1148	1167	1184	1198	1211	1223	1233	1242
11	1122	1143	1160	1175	1188	1200	1210	1219	1227
12	1108	1123	1137	1148	1157	1166	1173	1180	1185
13	1101	1115	1126	1136	1144	1152	1158	1163	1168
14	1092	1103	1113	1121	1128	1133	1138	1142	1146
15	1079	1087	1094	1099	1104	1107	1110	1113	1115
16	1072	1079	1085	1089	1092	1095	1097	1099	1100
17	1059	1064	1067	1069	1071	1072	1072	1072	1072
18	1046	1050	1052	1052	1053	1052	1051	1050	1049
19	1011	1009	1005	1001	996	991	987	982	978
20	683	694	704	711	717	722	727	731	734
21	766	785	799	811	821	830	837	844	849
22	877	904	927	945	960	973	984	994	1002
23	1014	1047	1073	1094	1112	1127	1139	1151	1161
24	1064	1098	1125	1147	1165	1181	1194	1206	1216
25	1133	1167	1194	1217	1235	1251	1265	1277	1288
26	1159	1191	1217	1238	1255	1270	1283	1295	1305
27	1168	1199	1223	1243	1260	1275	1287	1298	1308
28	1167	1194	1215	1232	1247	1259	1270	1279	1288
29	1156	1179	1197	1212	1225	1236	1245	1253	1260
30	1148	1169	1185	1198	1209	1219	1227	1234	1241
31	1123	1139	1151	1160	1168	1175	1180	1185	1189
32	1113	1126	1136	1144	1151	1156	1160	1164	1168

33	1099	1110	1118	1124	1129	1133	1136	1139	1141
34	1080	1087	1092	1096	1099	1100	1102	1103	1103
35	1070	1075	1079	1081	1082	1083	1083	1083	1083
36	1053	1056	1057	1057	1056	1055	1054	1053	1051
37	1002	997	991	985	979	974	968	963	958
38	667	678	687	693	699	703	707	710	713
39	745	763	776	788	797	804	811	816	821
40	848	873	894	911	925	936	946	955	962
41	979	1009	1033	1052	1068	1081	1092	1102	1111
42	1027	1057	1081	1101	1117	1131	1143	1153	1162
43	1090	1120	1144	1164	1181	1195	1207	1217	1227
44	1112	1141	1163	1181	1197	1210	1221	1231	1241
45	1120	1146	1167	1184	1199	1211	1222	1232	1241
46	1117	1139	1156	1171	1183	1193	1203	1211	1219
47	1105	1123	1138	1150	1160	1169	1177	1184	1190
48	1096	1112	1124	1135	1144	1151	1158	1164	1169
49	1072	1082	1090	1097	1103	1107	1112	1115	1119
50	1061	1069	1075	1080	1084	1088	1091	1094	1096
51	1048	1054	1058	1061	1064	1066	1068	1069	1071
52	1029	1031	1032	1033	1033	1033	1033	1033	1033
53	1020	1020	1020	1019	1018	1017	1016	1015	1014
54	1008	1005	1003	1000	998	995	992	990	988
55	974	966	958	951	944	937	932	927	922
56	647	656	664	669	674	678	681	684	686
57	717	731	743	753	761	768	773	778	783
58	809	831	848	863	876	887	896	904	911
59	929	954	975	992	1007	1020	1031	1040	1049
60	973	999	1020	1038	1053	1066	1077	1087	1096
61	1032	1058	1080	1097	1113	1126	1138	1148	1158
62	1053	1077	1096	1113	1127	1140	1151	1161	1170
63	1061	1083	1101	1117	1130	1142	1153	1162	1171
64	1059	1076	1091	1104	1115	1125	1134	1142	1149
65	1048	1063	1075	1085	1095	1103	1110	1117	1123
66	1041	1053	1063	1072	1079	1086	1093	1099	1104
67	1019	1025	1031	1036	1041	1045	1049	1052	1056

68	1009	1014	1018	1022	1025	1028	1031	1033	1036
69	998	1000	1002	1004	1005	1007	1008	1010	1011
70	983	981	980	980	979	978	978	978	978
71	979	976	974	972	970	968	967	966	965
72	978	973	969	965	961	958	955	952	950
73	933	922	912	903	895	888	882	877	872
74	600	606	612	616	620	623	626	628	630
75	649	660	669	677	683	689	695	699	703
76	713	729	743	755	766	776	785	792	799
77	808	828	845	860	874	886	897	907	916
78	844	864	883	899	913	926	937	948	958
79	893	914	932	949	964	977	990	1001	1011
80	914	932	949	964	978	991	1003	1014	1024
81	922	939	954	968	981	993	1005	1015	1024
82	924	937	949	961	971	981	991	1000	1008
83	918	928	938	947	955	964	971	979	986
84	913	921	929	936	944	950	957	963	969
85	900	903	907	911	915	919	923	927	931
86	894	895	897	899	902	904	907	910	913
87	887	886	886	886	888	889	891	893	895
88	877	872	870	868	867	866	866	866	866
89	876	870	866	864	862	860	859	859	859
90	871	863	857	852	849	846	843	841	840
91	873	865	858	852	847	844	841	838	836
92	903	891	880	872	864	858	852	848	843

Time (h)	6.5	7	7.5	8	8.5	9	12	15	18
Layer	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
1	712	715	719	722	725	728	741	751	759
2	818	824	829	834	839	844	865	881	893
3	961	969	978	985	992	999	1032	1055	1073
4	1118	1129	1139	1148	1157	1165	1204	1234	1256
5	1175	1186	1197	1206	1215	1224	1265	1297	1321
6	1253	1265	1275	1285	1295	1303	1347	1381	1407

7	1277	1288	1298	1308	1317	1326	1368	1402	1428
8	1285	1295	1305	1314	1323	1331	1373	1405	1432
9	1272	1281	1290	1298	1306	1313	1349	1379	1403
10	1251	1259	1266	1273	1280	1286	1318	1344	1365
11	1235	1242	1249	1255	1260	1266	1294	1318	1338
12	1191	1196	1200	1205	1209	1212	1232	1249	1263
13	1173	1177	1181	1184	1187	1191	1207	1221	1233
14	1149	1152	1155	1158	1160	1162	1174	1184	1193
15	1117	1118	1120	1121	1122	1123	1128	1133	1137
16	1101	1102	1102	1103	1103	1104	1106	1107	1108
17	1072	1071	1070	1070	1069	1068	1064	1060	1056
18	1047	1046	1044	1043	1041	1040	1031	1023	1016
19	974	970	966	963	959	956	938	924	911
20	737	739	741	743	745	747	754	759	762
21	854	858	862	866	869	872	885	894	900
22	1010	1017	1023	1028	1033	1038	1059	1073	1084
23	1169	1177	1185	1191	1197	1203	1229	1249	1263
24	1225	1233	1241	1248	1254	1260	1289	1310	1326
25	1297	1306	1314	1321	1328	1335	1366	1389	1408
26	1315	1323	1331	1338	1345	1351	1382	1406	1426
27	1317	1325	1333	1340	1346	1352	1383	1407	1426
28	1296	1303	1309	1315	1321	1326	1354	1376	1394
29	1267	1273	1279	1284	1289	1293	1317	1336	1353
30	1246	1252	1257	1261	1266	1270	1291	1308	1323
31	1193	1197	1200	1203	1206	1208	1222	1235	1245
32	1171	1174	1176	1178	1181	1183	1194	1203	1212
33	1143	1145	1146	1148	1149	1151	1158	1165	1171
34	1104	1104	1105	1105	1105	1106	1107	1109	1111
35	1083	1082	1082	1082	1081	1081	1079	1079	1078
36	1050	1048	1047	1045	1044	1042	1036	1031	1027
37	954	950	946	942	939	935	919	905	894
38	715	717	718	720	721	722	726	728	729
39	825	828	832	834	837	839	849	855	859
40	969	975	980	984	989	992	1009	1020	1028
41	1119	1126	1132	1137	1143	1147	1170	1185	1197

42	1170	1177	1184	1190	1195	1201	1225	1243	1257
43	1235	1243	1250	1257	1263	1268	1295	1316	1333
44	1249	1256	1263	1270	1275	1281	1309	1331	1349
45	1249	1256	1263	1269	1275	1280	1308	1329	1348
46	1225	1232	1238	1243	1248	1253	1278	1298	1316
47	1196	1201	1206	1210	1215	1219	1241	1259	1274
48	1174	1179	1183	1187	1191	1195	1214	1230	1245
49	1122	1125	1128	1130	1133	1135	1148	1160	1170
50	1099	1101	1103	1105	1107	1108	1118	1128	1136
51	1072	1073	1075	1076	1077	1078	1085	1091	1098
52	1033	1033	1033	1033	1033	1033	1034	1036	1039
53	1013	1012	1011	1011	1010	1010	1008	1008	1008
54	986	984	983	981	980	978	972	968	965
55	917	913	910	906	903	900	886	875	865
56	688	690	691	692	693	694	698	700	701
57	786	790	793	795	798	800	809	815	819
58	917	923	928	932	936	940	957	968	976
59	1056	1063	1069	1075	1080	1085	1108	1124	1137
60	1104	1111	1118	1124	1130	1135	1160	1179	1193
61	1166	1174	1181	1188	1194	1200	1228	1250	1268
62	1178	1186	1193	1200	1206	1211	1241	1264	1283
63	1179	1186	1193	1199	1205	1211	1240	1264	1283
64	1156	1163	1169	1174	1180	1185	1211	1233	1252
65	1129	1135	1140	1145	1149	1154	1177	1196	1213
66	1109	1114	1118	1123	1127	1131	1151	1169	1185
67	1059	1062	1065	1067	1070	1073	1087	1100	1111
68	1038	1040	1043	1045	1047	1049	1061	1071	1081
69	1013	1014	1015	1017	1018	1019	1028	1035	1043
70	978	978	978	978	978	979	981	985	989
71	964	963	963	962	962	961	961	962	963
72	948	946	944	943	942	940	935	931	929
73	867	864	860	857	854	851	838	828	819
74	631	633	634	635	636	637	641	644	645
75	707	710	713	716	719	721	731	739	744
76	806	811	817	822	826	830	849	863	873

77	925	932	939	946	952	958	985	1006	1021
78	967	975	982	989	996	1002	1033	1056	1074
79	1021	1030	1038	1046	1053	1060	1094	1121	1143
80	1033	1042	1050	1057	1065	1072	1107	1135	1158
81	1033	1042	1050	1057	1064	1071	1106	1134	1158
82	1016	1023	1030	1037	1043	1049	1081	1108	1130
83	992	999	1005	1010	1016	1021	1049	1073	1094
84	975	981	986	991	996	1001	1026	1048	1067
85	935	938	942	946	949	953	971	988	1003
86	916	919	922	925	928	931	946	960	972
87	897	899	901	903	905	907	919	930	940
88	867	868	869	869	870	871	878	884	890
89	859	859	859	859	860	860	865	869	873
90	839	838	837	837	836	836	835	836	836
91	835	833	832	831	830	830	827	826	825
92	840	836	833	831	828	826	816	808	801

Time (h)	21	24	27	30	33	36	39	42	45
Layer	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
1	764	768	771	772	773	773	773	772	770
2	902	908	913	916	919	920	920	919	918
3	1087	1097	1105	1110	1114	1116	1117	1117	1116
4	1274	1288	1299	1307	1313	1317	1320	1321	1321
5	1340	1356	1368	1378	1385	1390	1393	1395	1396
6	1429	1446	1461	1472	1481	1488	1492	1496	1497
7	1450	1469	1484	1497	1507	1515	1521	1525	1528
8	1454	1473	1488	1501	1512	1521	1527	1532	1536
9	1424	1442	1457	1470	1481	1490	1498	1504	1508
10	1384	1401	1415	1427	1437	1446	1453	1459	1464
11	1355	1370	1383	1395	1405	1413	1420	1426	1430
12	1276	1287	1297	1306	1314	1320	1325	1330	1334
13	1243	1253	1261	1268	1275	1280	1284	1288	1291
14	1201	1208	1214	1219	1224	1227	1230	1233	1234
15	1140	1143	1145	1147	1148	1149	1149	1149	1148

16	1109	1110	1110	1110	1109	1108	1107	1105	1103
17	1052	1049	1045	1041	1037	1032	1028	1024	1019
18	1010	1003	997	991	985	979	973	967	962
19	899	888	878	869	859	851	842	834	826
20	764	765	766	766	765	764	763	761	759
21	904	908	910	911	911	911	910	908	906
22	1092	1097	1101	1104	1106	1106	1105	1104	1102
23	1275	1284	1291	1296	1299	1301	1302	1302	1301
24	1339	1350	1358	1364	1369	1372	1373	1374	1373
25	1423	1436	1446	1454	1461	1465	1468	1470	1470
26	1442	1456	1468	1478	1485	1491	1496	1498	1500
27	1443	1458	1470	1480	1489	1495	1500	1504	1506
28	1411	1425	1437	1448	1457	1464	1470	1475	1478
29	1368	1381	1392	1402	1411	1418	1423	1428	1432
30	1337	1349	1360	1369	1377	1384	1390	1394	1398
31	1255	1265	1273	1280	1286	1292	1296	1300	1303
32	1220	1228	1235	1241	1246	1250	1254	1256	1259
33	1177	1182	1187	1192	1195	1198	1201	1202	1204
34	1114	1116	1117	1119	1119	1120	1120	1119	1118
35	1078	1078	1078	1077	1076	1075	1073	1071	1069
36	1023	1019	1016	1012	1008	1004	1000	996	992
37	883	873	864	855	847	839	831	823	816
38	730	730	730	730	729	727	726	724	722
39	861	863	865	865	865	864	863	861	859
40	1033	1037	1040	1042	1043	1043	1042	1040	1038
41	1207	1215	1220	1225	1228	1229	1230	1229	1228
42	1268	1277	1284	1290	1294	1296	1298	1298	1297
43	1347	1358	1368	1375	1381	1385	1388	1389	1390
44	1364	1377	1388	1397	1405	1410	1415	1417	1419
45	1364	1377	1389	1399	1407	1413	1418	1421	1424
46	1332	1345	1357	1367	1376	1383	1389	1393	1397
47	1288	1301	1312	1322	1330	1337	1342	1347	1350
48	1258	1269	1280	1289	1297	1303	1309	1313	1317
49	1180	1189	1197	1204	1210	1216	1220	1224	1227
50	1144	1152	1158	1164	1169	1174	1177	1180	1182

51	1104	1109	1114	1119	1123	1126	1128	1130	1132
52	1041	1044	1046	1047	1048	1049	1049	1049	1048
53	1008	1009	1009	1009	1008	1007	1006	1004	1002
54	963	960	958	955	952	949	945	942	938
55	857	849	841	833	826	818	811	805	798
56	701	702	701	701	700	699	698	696	694
57	822	824	825	825	825	825	824	822	820
58	981	986	989	991	992	992	992	990	989
59	1147	1155	1161	1166	1169	1171	1172	1172	1171
60	1205	1215	1223	1229	1233	1236	1238	1239	1238
61	1283	1295	1305	1313	1320	1324	1327	1329	1330
62	1299	1313	1325	1335	1343	1349	1353	1357	1358
63	1300	1315	1327	1337	1346	1353	1358	1362	1364
64	1268	1283	1295	1306	1315	1323	1329	1334	1338
65	1228	1242	1253	1264	1272	1280	1286	1291	1294
66	1199	1211	1222	1232	1241	1248	1254	1258	1262
67	1122	1132	1140	1148	1155	1160	1165	1169	1172
68	1090	1098	1105	1112	1117	1122	1126	1129	1132
69	1049	1056	1061	1066	1070	1074	1077	1079	1081
70	992	995	998	1000	1001	1003	1003	1003	1003
71	964	965	966	966	966	966	965	964	962
72	926	924	922	919	916	913	909	906	902
73	811	803	796	788	781	774	767	760	753
74	646	647	647	647	647	646	645	644	643
75	748	751	753	754	755	755	755	754	753
76	880	886	891	894	896	897	898	897	896
77	1034	1045	1053	1059	1064	1067	1069	1070	1070
78	1089	1101	1111	1119	1125	1129	1132	1134	1135
79	1161	1176	1188	1198	1206	1213	1217	1220	1222
80	1178	1195	1209	1220	1230	1237	1243	1248	1251
81	1178	1195	1210	1222	1232	1241	1247	1252	1256
82	1150	1167	1182	1194	1205	1214	1221	1227	1232
83	1112	1127	1141	1153	1163	1172	1179	1184	1189
84	1084	1099	1111	1123	1132	1141	1148	1153	1158
85	1016	1027	1038	1047	1055	1061	1067	1072	1076

86	984	993	1002	1010	1017	1022	1027	1031	1034
87	949	957	965	971	976	981	984	987	990
88	896	900	904	907	910	912	913	914	914
89	877	880	882	884	885	886	886	886	885
90	837	837	836	835	834	832	830	827	824
91	824	823	821	819	816	813	810	807	804
92	795	788	782	776	769	763	757	750	744

Time (h)	48	61.333	74.667	88	101.333	114.667	128	141.333	154.667	168
Layer	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
1	769	758	744	729	713	698	682	666	651	637
2	916	904	887	868	848	827	807	787	768	750
3	1114	1100	1078	1054	1028	1001	975	950	925	902
4	1320	1306	1282	1253	1221	1189	1157	1126	1096	1067
5	1395	1382	1358	1328	1295	1261	1228	1195	1163	1133
6	1498	1488	1466	1435	1401	1366	1330	1295	1260	1228
7	1530	1525	1506	1479	1447	1412	1377	1342	1308	1276
8	1538	1536	1519	1494	1463	1430	1396	1362	1328	1296
9	1511	1514	1503	1482	1455	1426	1395	1363	1332	1301
10	1467	1471	1462	1444	1420	1394	1365	1336	1307	1279
11	1434	1439	1432	1416	1394	1370	1343	1316	1288	1261
12	1336	1341	1335	1321	1303	1283	1260	1237	1213	1190
13	1293	1295	1288	1275	1257	1237	1216	1194	1171	1149
14	1236	1235	1227	1214	1197	1178	1158	1138	1117	1097
15	1147	1139	1127	1111	1094	1076	1057	1038	1019	1001
16	1101	1089	1074	1057	1039	1021	1002	984	966	949
17	1015	995	975	955	936	917	899	882	865	849
18	956	933	910	889	869	850	832	815	799	784
19	819	789	764	741	721	702	685	669	655	641
20	757	745	731	716	700	685	669	654	640	626
21	904	890	872	853	833	812	793	773	755	737
22	1099	1082	1060	1035	1008	982	957	932	908	886
23	1298	1281	1256	1226	1194	1162	1131	1100	1071	1043
24	1371	1355	1330	1299	1266	1232	1199	1166	1135	1106

25	1470	1456	1432	1401	1366	1331	1295	1261	1227	1195
26	1501	1492	1471	1443	1410	1376	1341	1307	1274	1242
27	1507	1502	1483	1457	1425	1392	1358	1325	1292	1260
28	1480	1480	1466	1444	1417	1387	1356	1325	1294	1265
29	1434	1435	1424	1405	1381	1354	1326	1297	1269	1241
30	1401	1403	1394	1377	1355	1330	1304	1277	1250	1224
31	1305	1307	1299	1285	1267	1246	1224	1201	1178	1155
32	1260	1260	1252	1238	1221	1201	1180	1158	1136	1115
33	1204	1202	1194	1180	1163	1145	1125	1105	1085	1065
34	1117	1109	1096	1081	1064	1046	1027	1009	991	974
35	1067	1054	1039	1022	1005	987	969	951	934	918
36	988	969	950	931	913	895	877	861	845	829
37	809	780	756	734	714	696	679	664	650	637
38	720	708	695	680	665	650	636	621	608	594
39	857	843	826	807	788	769	750	732	714	697
40	1036	1019	997	973	948	924	899	876	853	832
41	1226	1209	1184	1155	1125	1094	1064	1034	1006	980
42	1295	1280	1255	1225	1193	1160	1128	1097	1068	1039
43	1389	1376	1352	1321	1288	1253	1219	1186	1154	1123
44	1419	1411	1390	1363	1331	1298	1264	1231	1199	1168
45	1425	1419	1401	1375	1345	1312	1280	1247	1216	1185
46	1399	1398	1385	1363	1337	1308	1278	1248	1218	1190
47	1353	1354	1343	1325	1301	1275	1248	1220	1193	1167
48	1320	1322	1313	1297	1275	1251	1226	1200	1174	1149
49	1229	1231	1224	1210	1192	1172	1151	1128	1106	1085
50	1184	1184	1176	1163	1146	1127	1107	1086	1065	1045
51	1132	1131	1122	1109	1093	1075	1057	1037	1018	999
52	1047	1040	1028	1013	997	979	962	945	927	911
53	1000	989	974	958	941	924	907	890	874	859
54	934	917	899	881	863	846	830	814	799	784
55	792	765	742	721	701	684	668	653	639	626
56	692	681	668	654	640	625	611	597	584	571
57	818	805	789	772	753	735	716	699	682	666
58	986	971	950	927	904	880	856	834	812	791
59	1169	1154	1130	1102	1073	1043	1014	986	959	933

60	1237	1222	1198	1170	1139	1107	1076	1046	1017	990
61	1330	1318	1295	1265	1233	1200	1166	1134	1103	1073
62	1359	1352	1332	1306	1275	1242	1210	1177	1146	1116
63	1366	1361	1344	1319	1289	1258	1226	1194	1163	1134
64	1340	1341	1328	1307	1281	1253	1224	1195	1166	1138
65	1297	1299	1289	1271	1248	1223	1196	1169	1143	1117
66	1265	1269	1261	1245	1224	1200	1176	1150	1125	1101
67	1175	1178	1171	1158	1141	1122	1101	1079	1058	1037
68	1133	1135	1128	1115	1099	1080	1060	1040	1020	1000
69	1082	1081	1073	1061	1045	1028	1010	991	973	954
70	1002	996	984	970	955	938	921	904	887	871
71	960	950	936	920	904	887	871	855	839	823
72	899	881	864	846	828	812	795	780	765	751
73	747	720	697	676	658	640	625	610	597	585
74	641	632	620	607	594	580	567	554	541	529
75	751	740	726	710	693	675	658	642	626	610
76	895	882	864	844	821	799	777	756	736	717
77	1069	1057	1036	1010	983	955	927	901	875	851
78	1134	1123	1102	1076	1047	1017	988	959	932	905
79	1222	1214	1194	1166	1136	1104	1073	1042	1012	984
80	1252	1249	1231	1207	1178	1147	1116	1085	1055	1027
81	1258	1257	1242	1219	1191	1161	1131	1101	1071	1043
82	1235	1238	1228	1209	1185	1158	1130	1102	1075	1048
83	1193	1198	1190	1173	1152	1128	1103	1077	1052	1027
84	1162	1168	1161	1147	1128	1106	1083	1059	1035	1011
85	1079	1084	1079	1068	1052	1033	1013	993	972	952
86	1036	1040	1034	1023	1008	990	972	952	933	914
87	991	993	986	975	960	944	927	909	891	874
88	914	909	899	886	871	855	839	823	807	792
89	884	876	864	850	835	819	803	788	773	758
90	821	807	791	775	759	743	727	713	698	685
91	800	783	766	749	732	716	701	686	672	659
92	738	714	691	671	653	636	621	607	594	581

P B M R

niversity of
North-West