THE DEVELOPMENT OF A HIGH COUNT RATE NEUTRON FLUX MONITORING CHANNEL USING SILICON CARBIDE SEMICONDUCTOR RADIATION DETECTORS

DISSERTATION

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ABSTRACT

In this dissertation, a fast neutron flux-monitoring channel, which is based on the use of SiC semiconductor detectors is designed, modeled and experimentally evaluated as a power monitor for the Gas Turbine Modular Helium Reactors. A detailed mathematical model of the SiC diode detector and the electronic processing channel is developed using TRIM, MATLAB and PSpice simulation codes. The flux monitoring channel is tested at the OSU Research Reactor. The response of the SiC neutron-monitoring channel to neutrons is in close agreement to simulation results. Linearity of the channel response to thermal and fast neutron fluxes, pulse height spectrum of the channel, energy calibration of the channel and the detector degradation in a fast neutron flux are presented.

Along with the model of the neutron monitoring channel, a Simulink model of the GT-MHR core has been developed to evaluate the power monitoring requirements for the GT-MHR that are most demanding for the SiC diode power monitoring system. The Simulink model is validated against a RELAP5 model of the GT-MHR. This dynamic model is used to simulate reactor transients at the full power and at the start up, in order to identify the response time requirements of the GT-MHR.

Based on the response time requirements that have been identified by the Simulink model and properties of the monitoring channel, several locations in the central...
reflector and the reactor cavity are identified to place the detector. The detector lifetime and dynamic range of the monitoring channel at the detector locations are calculated. The channel dynamic range in the GT-MHR central reflector covers four decades of the reactor power. However, the detector does not survive for a reactor refueling cycle in the central reflector. In the reactor cavity, the detector operates sufficiently long; however, the dynamic range of the channel is smaller than the dynamic range of the channel in the central reflector.
Dedicated to My Beloved Parents
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CHAPTER 1

INTRODUCTION

In this dissertation, SiC semiconductor detectors have been investigated as power monitors for Generation IV power reactors. The SiC semiconductor detector and a fast neutron flux-monitoring channel, which operates in the pulse mode, will be designed, modeled and experimentally evaluated at the OSU Research Reactor. Use of the designed flux-monitoring channel in the Gas Turbine Modular Helium Reactor (GT-MHR) will be analyzed, by modeling the GT-MHR transients and evaluating the monitoring channel response at various locations of the GT-MHR.

A number of characteristics of SiC detectors make them well suited as power monitors for reactors. Among these characteristics are: small size, small mass, small power consumption, radiation hardness, capability for high temperature operation, and the potential for pulse mode operation at high count rates. Due to the SiC detector superior properties, the SiC semiconductor detector can be used for in-core monitoring of the neutron flux. Furthermore, the pulse mode operation of the channel makes it possible to monitor the reactor power with high precision over a wide dynamic range, which reduces the complexity of the monitoring instruments. In-core monitoring of the neutron
flux and operation of the monitoring channel in the pulse mode at the power range are unique features of the proposed monitoring channel.

As the first step, a mathematical model was developed to simulate the SiC detector and the electronic processing channel required for high count rate applications. The model, which is presented in Chapters 2, 3, and 4 is based on our prior publications [1,2,3].

In Chapter 2, a mathematical model of the SiC diode detector is developed. The detector model includes a description of the formation of electron-hole pairs in SiC using the computer code TRIM. The TRIM results are used as input to a MATLAB simulation of detector current output pulse formation, the results of which are intended for use as the input to a model of the detector channel as a whole.

In Chapter 3, a fast electronic processing channel is introduced and simulated by a MATLAB code. The detector output current which was calculated in Chapter 2 is processed by a simulated voltage sensitive preamplifier and a simulated discriminator to count the number of neutrons incident on the detector. In this Chapter, the preamplifier and discriminator models are presented and results of the simulations are discussed. The effects of the cable in transmitting the detector output current to the preamplifier is not considered in this Chapter.

In Chapter 4, the model developed in Chapter 3 is completed by considering the detector capacitance and cable characteristics in the channel model. In this Chapter, the effects of the detector capacitance on the output signal of a SiC detector, and the frequency response of the current-to-voltage transfer function for the detector-cable system with detector diameter and thickness as parameters, is described. The effects of
cable type and cable length are also examined. The cable analysis is presented both in the time and frequency domains and the sensitivity of the overall detector-cable system performance to cable characteristics such as resistance, capacitance, length and characteristic impedance are discussed.

In Chapters 5 and 6, experiments without radiation, using the SiC detector channel, are described. To begin with, a discussion is presented about the number of preamplifiers needed to amplify the detector output current. Based on this discussion, the channel setup is justified and the response of the channel to the fast neutrons is presented by evaluating the preamplifier output voltage. Also, the effect of the Mineral Insulated cable, modeled in Chapter 4, is studied. Finally, the noise introduced by the preamplifier is measured in order to define an appropriate discrimination level for future experiments.

In Chapter 7, the experimental setup of the monitoring channel is presented in detail. The SiC detector response to fast and thermal neutron fluxes is studied. The linearity of the monitoring system, the energy calibration of the channel, and the detector degradation in a fast neutron field are discussed.

In Chapters 8, 9 and 10, a mathematical model of the GT-MHR core, which is based on the Simulink simulation program, is presented. Two types of reactor transients, namely the Full Power Reactivity Insertion Transient and the Start-Up Reactivity Insertion Transient, which are considered as the limiting accident scenarios in terms of specifying the dynamic range of the monitoring channel, are discussed.
In Chapter 11, the implications of the results of the previous Chapters are discussed as they relate to the potential of SiC semiconductor detectors as power monitors for Generation IV power reactors in general, and the GT-MHR in particular.

Finally, in Chapter 12 an overall conclusion of the dissertation is presented.
CHAPTER 2

A MATHEMATICAL MODEL OF A SiC DIODE DETECTOR

CHAPTER SUMMARY

This dissertation is a theoretical and experimental analysis of SiC semiconductor detectors as power monitors for Generation IV power reactors. In this Chapter, a mathematical model of a SiC detector is presented. The model includes a description of the formation of electron-hole pairs in a SiC diode detector, using the computer code TRIM. The TRIM results are used as input to a MATLAB simulation of detector current output pulse formation, the results of which are intended for use as the input to a model of the detector channel processing electronics.

2.1 INTRODUCTION

As a part of a research program within the Ohio State University Nuclear Engineering Program, SiC semiconductor detectors are being analyzed as power monitors for Generation IV power reactors. A number of characteristics of SiC detectors make them well-suited as power monitors for reactors. Among these characteristics are: small size (allowing for multiple detectors for reliability), small mass, small power consumption, mechanical ruggedness (in comparison to gas-filled detectors, which in
conventional proportional counters and ion chambers have a thin anode wire that is susceptible to mechanical damage), radiation hardness, capability for high temperature operation, and the potential for pulse mode operation at high count rates (which may allow for a reduction in the complexity of the reactor instrumentation and control system, verification of detector sensitivity, verification of channel operability, channel self-repair, and the use of digital electronics in the power monitoring system.)

Pulse mode operation at high count rates is desirable, because it may allow for a reduction of the complexity of the reactor instrumentation and control system over instrumentation and control systems that are presently in use in commercial land-based nuclear plants. For example, the instrumentation and control system of a typical pressurized water reactor (PWR) is complex from the perspective of power monitoring, because three different instrumentation chains are required for measurement of neutron flux over a wide dynamic range. Consequently, different instrument chains are used in the start-up, intermediate and power ranges. In the start-up range proportional counters, which operate in pulse mode are used to monitor reactor power. In the intermediate range, reactor power is monitored using ion chamber pairs operating in current mode, one sensitive to gamma rays only and one sensitive to gamma rays and neutrons. The current that is produced by the gamma sensitive ion chamber is subtracted from the current that is produced by the neutron plus gamma sensitive ion chamber, to form a gamma-ray “compensated” signal. For operation in the power range, uncompensated ion chambers are operated in the current mode. For SiC detectors operated in the pulse mode, gamma-ray events can be discriminated from neutron induced events on the basis of peak pulse height, as is the case for the operation of proportional counters in the start-up range for
PWRs. However, unlike proportional counters, SiC detectors can operate at such high count rates that it may be possible to monitor reactor power, by operation in the pulse mode, over the full range of reactor powers. Instrumentation for current mode operation would be unnecessary, thus reducing the power monitoring system complexity from 12 safety-related channels (assuming 2 of 4 trip logic) to 4 safety-related channels. Besides allowing for discrimination of gamma-ray events from neutron induced events, pulse mode operation with SiC detectors is advantageous, because SiC pulse height spectra can be monitored. Also, the lower level discriminator setting for pulse height can be adjusted to account for the pulse height distribution changing, in the event that it evolves in time, as a consequence of radiation damage. Finally, abrupt changes in the monitored pulse height spectra can be recognized as corresponding to component failure, and replacement components can be switched into the detector channel circuit, as a means of detector channel self-repair.

In this Chapter, a mathematical model of a SiC detector is presented. The detector model includes a description of the formation of electron-hole pairs in SiC using the computer code TRIM (Transport of Ion in Matter). The TRIM results are used as input to a MATLAB simulation of detector current output pulse formation, the results of which are intended for use as the input to a model of the detector channel processing electronics. The model of the detector channel processing electronics includes a detector, cable, preamplifier, amplifier and discriminator. Our intent in creating the detector channel model is to use the model to design the detector channel to maximize the rate at which counts can be recorded, while discriminating gamma-ray events from neutron events, in order to maximize the dynamic range of the detector channel.
2.2 METHODS AND RESULTS

In this Section, we discuss the methods that we have used to model detector current output pulse formation in SiC diode detectors, which are to be designed for use in high-speed SiC neutron monitoring channels for Generation IV power reactors. Westinghouse Electric Corporation (WEC) has developed designs for the SiC diode detectors, which will be used in the neutron monitoring channel [5,6,7]. A four-layer configuration of a diode detector, consisting of LiF, Al, Au and SiC, has been simulated with TRIM to find the response of the SiC detector to radiation from the reactor core.

In Section 2.2.1, we describe how we have used TRIM output files to calculate the energy deposited in the detector active volume by the charged particles that are produced when thermal neutrons interact with Li, in the LiF radiator. In Section 2.2.2, we present the results of the TRIM calculations. In Section 2.2.3, we describe how the results, that are obtained using the methods described in Section 2.2.1, are used to develop MATLAB simulation models of the detector output current signal. In Section 2.2.4, we present the results of the MATLAB simulation models.

2.2.1 SiC Detector Diode TRIM Simulations

The SRIM code package is a group of programs which calculate the stopping and range of ions (10 eV - 2 GeV/amu) in matter using a full quantum mechanical treatment of ion-atom collisions. TRIM (the Transport of Ions in Matter) is the most comprehensive program included in the SRIM package. TRIM will accept complex targets and will calculate kinetic phenomena associated with ion energy loss in the target, such as target ionization and target damage [4]. Although the TRIM code was generated
mainly for accelerator applications, it is very appropriate for use in this project. In this project, the target is the SiC diode detector, and the bombarding particles are the charged particles that are produced when thermal neutrons interact with Li, in the SiC diode detector’s LiF radiator.

A TRIM model of the SiC diode detector structure has been made with four layers. In this four-layer structure, neutrons from the reactor core are absorbed in the LiF layer and tritons and alpha particles are emitted [5]. The tritons produce ionizations in the active regions of the SiC detector, and the corresponding electrical signal that is generated is processed by the detector electronics to produce a pulse that is counted. The main purpose of the TRIM model is to predict the number of electron-hole pairs that are produced, as a function of position in the SiC diode detector. A secondary purpose of the TRIM calculations is to predict the radiation damage that will occur in the SiC active volume, as a consequence of radiation damage induced by the products of the $^6\text{Li}(n,^3\text{H})^4\text{He}$ reaction.

The LiF radiator has a density of 2.635 g/cm$^3$. The sensitivity of the SiC diode detector to thermal neutrons can be adjusted by changing the LiF thickness. For operation in the power range, the LiF radiator has been considered by the WEC to be from 0.632 µm to 1.21 µm thick [6]. We have assumed that the LiF layer is 1 µm thick in our analysis. The tritons and alpha particles, which are emitted in the $^6\text{Li}(n,^3\text{H})^4\text{He}$ reaction are assumed to be emitted uniformly as a function of depth in the LiF radiator. We have also assumed that their emission is isotropic, although this may not be apparent.
in Figure 2.1, which presents a schematic diagram of the SiC diode detector and includes in the diagram the initial energies of the $^6$Li(n,$^3$H)$^4$He reaction products.

An Al layer with density of 2.702 g/cm$^3$ and thickness of 8 µm is placed beside the LiF layer. The purpose of the Al layer is to stop all alpha particles that are produced in the LiF layer. The Al layer also affects the tritons’ spatial energy deposition distribution. This effect will be discussed later. In the WEC detector design, a thin Au layer (1 µm) is placed between the Al and the SiC to protect the detector contact [7]. We have included this Au layer in our model.
The final layer of the SiC diode detector is SiC. This layer absorbs the tritons’ energy to produce an output signal. We have used 4H-SiC, with a density of 3.21 g/cm$^3$ [8], in our simulation. Consistent with the WEC design, we have modeled the SiC active volume as being 10 µm thick [7]. The reader should note that this thickness arises in the mathematical modeling of the energy deposition in the detector active volume, and in the modeling of the detector current pulse, but is not obvious in Figure 2.2 and Figure 2.3, because a portion of the SiC substrate adjacent to the active volume is included in these figures. With a 10 µm thick active volume, the collection time for the electrons and holes, which are generated in the SiC by the tritons is very short. In addition to resulting in a short collection time, the small thickness of the SiC active volume causes less damage in the active volume layer. The SiC thicknesses is greater than 10 µm in Figure 2.2 and Figure 2.3, because, in addition to modeling the creation of electron-hole pairs in the SiC active volume, we were interested in observing the damage events that occur in the SiC substrate, which supports the SiC active volume. The effects of changing the SiC thickness will be discussed later.

2.2.2 TRIM Simulation Results

In Sections 2.2.2.1 and 2.2.2.2, the results of TRIM simulations are presented for the two charged reaction products of $^6$Li(n,$^3$H)$^4$He reaction; namely, alpha particles and tritons.

2.2.2.1 Alpha Particles

We have run TRIM simulations for alpha particles and tritons separately. Simulations show that for the configuration of the SiC detector, which were described
above in the Section 2.2.1, the alpha particles are absorbed completely in the Al layer. Figure 2.2 shows the tracks of alpha particles in LiF, Al and Au layers. No alpha particles passed through the Al layer and entered the SiC layer. Thus we are assured that 8 µm of Al is thick enough to stop all alpha particles.

**Figure 2.2** Alpha Particles Penetration into the Four Layers of the SiC Diode Detector (Regions are from Left to Right LiF, Al, Au, and SiC).
2.2.2.2 Tritons

In our TRIM simulations, we have assumed that 20000 tritons with an initial energy of 2.73 MeV, were emitted spatially uniformly from within the LiF layer, in random directions and that the diameter of the detector is be 200 µm [9]. In Figure 2.3, the tritons’ path through the four detector layers is shown. 43% of all emitted tritons enter the SiC layer, and many of the tritons pass through the SiC active layer, completely.

**Figure 2.3** Tritons Penetration into the Four Layers of the SiC Diode Detector (Regions are from Left to Right LiF, Al, Au, and SiC).
Figure 2.4 shows the average energy given up to electrons per angstrom within the four material regions of the SiC detector, as a function depth within the detector. The energy loss within the active region of the SiC is especially important, because the average energy loss is proportional to the detector output signal.

Figure 2.4 Average Energy Transferred to Electron-Hole Pairs Per Angstrom of Target Material.
Damage events in the SiC detector are shown in Figure 2.5. As one can see, the peak, of the distribution of damage events per unit target depth, is beyond the detector’s active volume. This feature of the detectors design increases the detector lifetime.

TRIM simulations also provide the history of each particle from the point where it is emitted to the point where it stops. The information that is provided includes each
interaction between the ion and the target atoms, including the amount of energy lost in each interaction and the point where interaction takes place. This data is useful to us in calculating the energy transferred from tritons to SiC atoms, and consequently to finding the electrical current pulse coming out of the detector. For this purpose, from the TRIM output files, the interactions between tritons and SiC atoms were selected. As a next step, the amount of energy loss in each interaction of the tritons with SiC atoms was calculated. Finally, by summing these energy losses for each triton, the total energy loss for each triton entering the SiC detector was calculated. We wrote a MATLAB code to perform these calculations. The results of these calculations are presented in the following Section.

As we stated previously, tritons are emitted uniformly with depth in the LiF radiator and isotropically in direction. Consequently, the tritons have different path lengths in the SiC active volume, and so they deposit various amounts of energy in the SiC active layer, which is assumed to be 10 µm thick. In order to see this effect, an energy deposition spectrum was created, with 50 keV energy bins. It should be emphasized that we considered only the tritons, which pass through the gold layer and enter the SiC layer in forming the energy deposition spectrum.

The energy, which is lost by the tritons in the SiC active region, creates electron-hole pair carriers in the detector. A significant fraction of tritons contribute to the small energy deposition region of the spectrum. The presence of low energy tritons may make discrimination between gamma rays events and triton events difficult. A discrimination
level can be set using Figure 2.6, if we are able to determine a similar spectrum for gamma rays.

The effect on the energy deposition spectrum due to increasing the active volume thickness can be seen in Figure 2.6. Figure 2.6 shows that as the active volume thickness increases, tritons deposit more energy in the SiC active layer. The effect on the average energy deposition, due to increasing the active volume thickness, can be seen in Figure 2.7. This figure shows that the average energy transferred to the SiC active layer increases as the SiC active layer becomes thicker. It also shows that, with the maximum SiC active layer thickness, on average, only half of the initial triton energy is transferred to this layer. That means that, on average, half of the tritons energy is lost in the preceding layers.

![Figure 2.6 Comparison Among Energy Deposition Spectra for Various Thicknesses of SiC Active Volumes.](image)
From Figure 2.7, we conclude that increasing the SiC active layer’s thickness up to approximately 15 µm has the beneficial effect of causing, on average, more of the triton’s energy to be absorbed. Also, the detector’s capacitance decreases when the SiC active layer’s thickness is increased; and decreasing the detector’s capacitance makes the detector channel faster. Besides these advantages, increasing the SiC layer’s thickness has two disadvantages. As one can see in Figure 2.5, the number of collisions with SiC target atoms is relatively high for depths in the SiC active region (relative to its front surface), between 7 and 13 µm. Thus using a thicker detector has the disadvantage of increasing the radiation damage from triton induced displacements within the SiC active
volume. Also, increasing the detector’s active volume requires a higher bias voltage, which increases the risk of electrostatic breakdown within the detector.

### 2.2.3 MATLAB Simulation-Detector Channel Model

We have developed a MATLAB simulation model to examine the whole process of measurement, from the detector, where tritons interact with the SiC, to the output of a single channel analyzer. This simulation model includes a detector, pre-amplifier, pulse shaping amplifier and a single channel analyzer. Only the generation of the current pulse from the detector is presented here. It is calculated with the detector model, which is presented below.

As we discussed earlier, with the TRIM simulation, we can find the amount of energy transferred to incremental sub-volumes within the SiC active volume, for each triton which is incident upon the SiC. By dividing the energy that is deposited by the tritons in the various sub-volumes, by the energy (W) which is required to create an electron-hole pair, we can calculate the number of electron-hole pairs, which are liberated for each detector sub-volume. In our calculations we assumed that the W-value for SiC is 8.1 eV [9].
Figure 2.8 presents a schematic drawing of the creation of an electron-hole pair, and of the movement of the electron and the hole, in opposite directions in response to the electrostatic potential (-V) that is applied to the detector. The current that is produced by the formation of electron–hole pairs within the various sub-volumes is calculated by modeling the movement of the electrons and holes within the detector and summing the contribution to the total current in the detector, arising from the movement of the electrons and holes that are liberated in each sub-volume. The mathematical expressions which were used to calculate the current arising from the passage of a triton through the detector’s active volume are presented below.

The electric field a distance x from the front face (i.e., the gold/SiC interface) of the SiC active volume, is assumed to be given by the expression [10]

\[
E(x) = \left[ -\frac{2}{d^2} \frac{d}{d} \frac{x}{V_{dep}} + \frac{V - V_{dep}}{d} \right] = \left[ \frac{V + V_{dep}}{d} - 2 \frac{x V_{dep}}{d^2} \right],
\]

Equation 2.1
where $V$ is the applied voltage and $d$ is the detector thickness. In the simulation, we applied 100 V to the detector. When the applied voltage is increased, the depletion region may be made to extend all the way to the back surface of the wafer. The minimum voltage that is required to achieve this condition is called the “depletion voltage” ($V_{dep}$). The depletion voltage can be obtained from the following expression [11]

$$V_{dep} = \frac{qnd^2}{2\varepsilon}$$

\textbf{Equation 2.2}

where $q$ is the absolute value of the electron charge, $n$ is the doping concentration, $\varepsilon$ is dielectric constant, and, as defined previously, $d$ is the detector thickness. Assuming $d=10 \mu m$ and $n=10^{15}$ cm$^{-3}$,

$$V_{dep} = \frac{(1.6 \times 10^{-19}) \times (10^{15}) \times (10 \mu m)^2}{2 \times (10 \times 8.85 \times 10^{-14})}$$

\textbf{Equation 2.3}

Integrating an ordinary differential equation for the time rate of change of the electron position as a consequence of its drift in the applied electric field, subject to the initial conditions $x_e(t=0)=x_0$, yields the following equation for the position of the electron as a function of time [10]

$$x_e(t) = d \frac{V + V_{dep}}{2V_{dep}} + [x_0 - d \frac{V + V_{dep}}{2V_{dep}}]e^{-2\mu \frac{V_{dep}}{d^2}}$$

\textbf{Equation 2.4}

Differentiating this expression with respect to time yields the following expression for the electron velocity as a function of time
\[ v_e(t) = \mu_n \left[ \frac{2V_{dep}}{d^2} x_0 - \frac{V + V_{dep}}{d} \right] e^{-2\mu_n \frac{V_{dep}}{d^2} t} \]  \hspace{1cm} \text{Equation 2.5}\]

**Figure 2.9** Collection Time for Electrons and Holes for a 10\(\mu\)m Detector Thickness.

Equations 2.4 and 2.5 hold for holes with the replacement of \(\mu_n\) with \(-\mu_p\). The electron’s movement ends when it reaches the bottom electrode’s surface, i.e. when \((x_e(t_e)=d)\). Similarly, the hole stops moving when it reaches the top electrode’s surface, i.e. when \((x_h(t_h)=0)\).
2.2.4 MATLAB Simulation Results

Figure 2.9 show the collection time for electrons and holes, as a function of the depth within the detector ($x_0$), where the electrons and holes are assumed to be liberated. It can be observed in the figure that the nearer $x_0$ is to the anode, the shorter the collection time for electrons and the longer the collection time for holes. The limiting collection time is, of course, for holes that are liberated near to the anode. For the parameters that we have assumed in our calculations, as given above, this time is approximately 0.16 ns. Consequently, event rates on the order of $6 \times 10^9$ events/s should be achievable, without significant dead time effects due to charge transit time within the detector. This event rate sets a goal for pulse processing times in the remainder of the detector channel. Modeling of the remainder of the detector channel in MATLAB will indicate if such large pulse processing rates can be achieved and the fraction of events that are lost as a function of event rate.

The current induced by the movement of the electrons and holes liberated at position $x$ is given as the sum of the electron current and the hole current

$$i(t) = \frac{q}{d^2} (2V_{dep} \frac{x_0}{d} - (V + V_{dep})) \ast [\mu_n e^{-2\mu_n V_{gap}} d u(t_e - t) + \mu_h e^{-2\mu_h V_{gap}} d u(t_h - t)]$$

Equation 2.6

Equation 2.6 was evaluated assuming $V=100$ V, $\mu_n=900$ cm$^2$/V.s, $\mu_h=100$ cm$^2$/V.s, $d=10$ $\mu$m, and $n=10^{15}$ cm$^{-3}$, with the input for $q$ as a function of $x_0$ coming from the ionization track calculations from the TRIM code. The slowing down time of the tritons in SiC was neglected in the calculation of the current time history. That is to say, the
charge, which is liberated along the entire length of the triton’s track was assumed to be liberated instantaneously.

**Figure 2.10** Output Current of the Detector in Time Domain
Figure 2.10 and Figure 2.11 show the detector output current for tritons that enter the SiC active volume. The time intervals between the pulses were sampled using Monte Carlo methods assuming an event rate of $10^8$ events/s.

2.3 CHAPTER CONCLUSION

Simulation techniques using TRIM and MATLAB can be useful tools for designing detector channels. Thus far we have used TRIM and MATLAB to model the detector current output pulse for SiC semiconductor detectors as power monitors for Generation IV power reactors. In the subsequent Chapters, we will develop a model of
the rest of the detector channels; and pulses, which are created in the same manner as those that are shown in Figure 2.10 and Figure 2.11. These pulses will be propagated through the detector channels in order to optimize their characteristics with respect to speed and resolution for application to the GT-MHR reactors.
CHAPTER 3

A MATHEMATICAL MODEL OF SiC DETECTOR AS POWER MONITORS

CHAPTER SUMMARY

The mathematical model of the SiC diode detector that is described in Chapter 2 was augmented to include preamplifier, amplifier, and discriminator models.

As described in Chapter 2, the four-layer diode detector has been simulated with TRIM, and its output current has been calculated as a function of time using the TRIM results and a MATLAB code. Chapter 3 describes the following model augmentation: 1) the detector output current was modeled as being applied directly to a voltage sensitive preamplifier by including its transfer function in s-space in the MATLAB code, 2) an SCA was modeled in MATLAB as the last component in the channel. Using the augmented model, in Chapter 3 the overall performance of the system is assessed by comparing curves of the fraction of counts that are lost versus the true count rate, for the modeled voltage sensitive preamplifier with a similar curve for a perfect voltage sensitive preamplifier. We conclude that the discriminator restricts the system count rate and that
by using a discriminator with a shorter dead time, one can count pulses with rates higher than $10^8$ cps.

3.1 INTRODUCTION

As noted above, the mathematical model of the SiC diode detector that is described in Chapter 2 was augmented to create a mathematical model of the SiC detector as a whole. This augmented model was developed to study the use of SiC semiconductor detectors as power monitors for Generation IV power reactors. It is a useful tool for optimizing the detector and the channel characteristics with respect to speed and resolution for application to neutron monitoring in Generation IV power reactors. The augmented model is described in Chapter 3. The channel model includes a SiC detector, preamplifier, and discriminator models.

As described in Chapter 2, simulations are based on a SiC diode detector design, which has been developed by WEC, for use in a neutron monitoring channel of Generation IV reactors. A four-layer configuration of such a diode detector, consisting of LiF, Al, Au and SiC, has been simulated with TRIM to find the response of the four-layer SiC detector head to neutrons. The output current of the detector as a function of time has been calculated using TRIM results and a MATLAB code [1]. In Chapter 3 the detector output current is modeled as being applied directly to a voltage sensitive preamplifier disregarding the detector capacitance and cable effects on the channel. These effects, which may become significant in some cases, are described in the Chapter 4.
3.2 METHODS

In Section 3.2.1, we describe how we have developed the voltage preamplifier model. In brief, a voltage sensitive preamplifier was modeled as the second component of the detector channel, by including its transfer functions in s-space in the MATLAB code. The preamplifier transfer function was calculated based on its bandwidth characteristics and gain, as specified by the manufacturer’s published information. In Section 3.2.2, we describe the discriminator model. A single channel threshold discriminator is required to distinguish the pulses induced by neutrons from those arising from gamma-ray interactions. The discriminator was modeled in MATLAB as the final component in the channel. A MATLAB model was developed to record the number of times that the input voltage of the discriminator passes a specific threshold. Using this model, one can count the number of pulses in the voltage preamplifier output (input of the discriminator), which are above the discrimination level. The discriminator dead time is an important parameter and is a limiting factor establishing the system count rate. Both paralyzable and nonparalyzable models of the discriminator are described. Finally in Section 3.3, we present the results of simulations based on the model, which are described in Sections 3.2 and the equipments’ characteristics. The overall performance of the system was assessed by examining the output of the discriminator model.

3.2.1 Preamplifier model

The detector produces a charge, which is collected on its electrodes in response to incident radiation. The purpose of the pre-amplifier is to convert the small output signals into voltage pulses large enough to be analyzed by subsequent pulse analysis circuits. To
model a preamplifier, two kinds of preamplifiers were considered: a voltage sensitive preamplifier and a charge sensitive preamplifier. In this Chapter, the methods employed to simulate a voltage sensitive preamplifier are presented.

The action of the preamplifier is most simply described in terms of Laplace transform variables. Namely, the Laplace transform of the input voltage of the preamplifier is proportional to the Laplace transform of the detector current multiplied by a transfer function that represents the parallel impedance of the preamplifier input resistance and the sum of the cable and detector capacitance in s-space. Effects of the detector and cable capacitance, on the voltage at the input to the preamplifier, are described in the Chapter 4. There are two generic concerns regarding the use of voltage sensitive preamplifiers. Firstly, since the cable length and the detector characteristics during operation are not constant, the input voltage of the preamplifier varies when they vary. Secondly, even with a constant cable length and constant detector capacitance, this capacitance can be high enough to attenuate the input voltage to the noise level. With respect to these concerns, we developed a cable model [3].

In this Chapter, we assumed that the detector and cable capacitance has no effect on the input voltage of the preamplifier and that the output current of the detector is directly fed into the preamplifier (The effect of the cable capacitance will be discussed in Chapter 4). So the next step was to define a transfer function for the preamplifier to find the output voltage from the preamplifier given a voltage pulse as its input.

Initially, we calculated the input voltage to the preamplifier considering the loading effect of the voltage sensitive preamplifier on the detector-cable system. We
simply modeled the input impedance of the preamplifier as a 50 \, \Omega \, \text{resistor to ground.}

This model is explained in Chapter 4 [3]. After calculating the input voltage of the preamplifier, we developed the transfer function of the voltage sensitive preamplifier, which relates the output voltage of the preamplifier to the input voltage of preamplifier. This transfer function has been modeled based on the preamplifier’s bandwidth characteristics. An operational transfer function, \( G(s) \) for the preamplifier is:

\[
G(s) = \frac{A \frac{s}{\omega_1}}{(\frac{s}{\omega_1} + 1)(\frac{s}{\omega_2} + 1)}
\]

Equation 3.1

where \( A \) is the preamplifier gain, and \( \omega_1 \) and \( \omega_2 \) are lower and upper cut off frequencies, respectively. This transfer function simply models the voltage sensitive preamplifier as a band pass filter, which amplifies the incoming signal by \( A \) in the bandwidth region.

### 3.2.2 Discriminator model

As discussed in the previous Section, in the case of using a voltage sensitive preamplifier, we intend to have the output of the voltage sensitive preamplifier feed directly into the discriminator without an intervening pulse shaping amplifier such as those that are used after a charge sensitive preamplifier. A block has been designed in MATLAB for modeling the discriminator. This block distinguishes the pulses coming from neutrons from those arising from gamma-rays. This model has an adjustable discrimination level, dead time and delay time. The output of this block is an on/off signal. When the input signal passes a specific threshold (discrimination level), the
output signal turns into one. The output remains high for a dead time period of the discriminator. After passing the dead time period, the output signal turns off (zero level).

By dead time, we mean the minimum amount of time that must separate two events, in order that they are recorded as two separate pulses. Dead time losses can become severe when high counting rates are encountered, and accurate counting measurements made under these conditions must include some correction for these losses. Since the dead time of the discriminator is the principle parameter, which limits the pulse processing rate of an electronic channel, selecting a fast discriminator with a small dead time is an important issue.

Two common models of dead time behavior, paralyzable and nonparalyzable, are simulated in this study. They represent, respectively, models of maximum and minimum count loss due to the discriminator dead time and as such bound count losses. A real system may not behave like either extreme. The behavior of a specific counting system depends on the physical processes taking place in the detector and on delays introduced by the pulse processing and recording electronics [11].

With the nonparalyzable model, one obtains the minimum counts lost due to the discriminator dead time. In this model, a new signal, coming within the dead time period, is not counted. In the paralyzable model, if a pulse comes within the dead time period, in addition to the loss of that signal, the dead time period is extended by another dead time period. Therefore, additional counts are lost.
Equations 3.2 and 3.3 express the relationship between the true count rate ($r_t$), the recorded count rate ($r_c$), and the discriminator dead time ($\tau$) for paralyzable and nonparalyzable discriminator models respectively [11].

$$r_c = r_t e^{-r_c \tau} \quad \text{Equation 3.2}$$

$$r_t = \frac{r_c}{1 - r_c \tau} \quad \text{Equation 3.3}$$

The equations do not include the effect of the rest of the channel on the count loss. In Section 3.3.2, by comparing the recorded count rate obtained from the simulation with the recorded count rate calculated using Equations 3.2 and 3.3, we identify the degree to which the detector contributes to dead time loss.

3.3 SIMULATION RESULTS

3.3.1 Preamplifier Selection and Simulation

We have modeled the Phillips Scientific 774 quad voltage sensitive preamplifiers. The preamplifier bandwidth is 100 kHz to 1.8 GHz. It also has 180 ps rise time [12]. With these specified performance parameters, the transfer function of this preamplifier is:

$$\text{Transfer Function} = \frac{1.592 \times 10^{-5}s}{1.305 \times 10^{-16}s^2 + 1.529 \times 10^{-6}s + 1} \quad \text{Equation 3.4}$$

The Bode plot of the preamplifier’s transfer function is shown in Figure 3.1.
The output voltage trace of the voltage sensitive preamplifier is calculated in MATLAB from the input voltage trace of the preamplifier and the preamplifier’s transfer function. The voltage sensitive preamplifier output is shown for an example input pulse in Figure 3.2.
3.3.2 Discriminator Selection and Simulation

We have chosen to examine the performance of the Philips Scientific 6904 discriminator to separate gamma-ray spectra from neutron spectra. The dead time of the selected discriminator is 3.3 ns and it has an input to output propagation delay of 1.5 ns. Since propagation delay has no effect on the system count rate, in our simulation the propagation delay was set to zero. The MATLAB model, as described in Section 3.2.2, counts the number of pulses passing an adjustable threshold employing either a paralyzable or nonparalyzable dead time loss model.

To find the percentage of counts lost, the simulation was made at different count rates. Since our design is focused on evaluation of a fast counting system, count rates...
above $3 \times 10^7$ cps were selected to be examined. The highest evaluated count rate is $1.5 \times 10^8$ cps, a count rate for which the percentage of counts lost is relatively large.

Figure 3.3 shows the percentage of counts lost as a function of true count rate with the assumption of nonparalyzable performance of the discriminator. The same analysis was made for the paralyzable discriminator and the result is shown in Figure 3.4. At the highest true count rate, we can see a 6% difference between the fractions of counts lost obtained from nonparalyzable and paralyzable models.

The count loss can be improved to an acceptable value by considering an appropriate dead time correction factor, which is one purpose for the detailed modeling that we have presented in this Chapter.

Figure 3.3 Fraction of counts lost as a parameter of count rate; nonparalyzable model
To evaluate the importance of the discriminator dead time on the percentage of counts lost, we considered the fraction lost in two situations. In the first case, we used an ideal preamplifier in the system and in the second case, we used the selected voltage sensitive preamplifier. In Figure 3.5, we compare these two cases. In this figure, the difference in the fraction of the counts that are lost, as calculated using the simulation, or as calculated using either Equation 3.2 or Equation 3.3 is presented as a function of the count rate. A positive difference means that the percent of counts that are lost is greater for the simulation than as calculated using either Equation 3.2 or Equation 3.3.
shown, the count loss for these cases is very nearly equal especially for high count rates. This means that the voltage preamplifier contributes only slightly to the count loss and that the count loss is mostly caused by the discriminator. According to Figure 3.5 this argument is true for both paralyzable and nonparalyzable models.

**Figure 3.5** Difference between the fraction of count loss when an ideal preamplifier is modeled and when the selected voltage sensitive preamplifier is modeled.
In conclusion, the proposed electronic channel is able to monitor the neutron flux with count rates on the order $10^8$ counts/s with less than 25% count loss. With a voltage sensitive preamplifier of the type that we have specified, the speed of the channel is limited by the discriminator dead time. Similar simulations show that with a charge sensitive preamplifier, the fractions of the counts that are lost increases drastically. Thus, to design a fast counting system, we described a counting system based on the use of a voltage sensitive preamplifier. Consequently, we have focused our attention on finding a faster discriminator as a way of speeding up the system, since it is mainly the discriminator, and not the amplifier, that limits the count rate for the system that we have analyzed. To date we have not found a faster discriminator.
CHAPTER 4

EFFECT OF DETECTOR CAPACITANCE AND CABLE ON SiC DETECTOR-CABLE SYSTEM PERFORMANCE

CHAPTER SUMMERY

Using the codes TRIM and MATLAB, a mathematical model of the detector channel has been developed to study the use of SiC semiconductor detectors as power monitors for Generation IV power reactors and to optimize the SiC detector channel. In Generation IV reactors, cables may be required to operate in high temperature and high radiation environments, and consequently, it may be necessary to use a cable type that may not have the most favorable electronic characteristics for pulse propagation. This Chapter describes the effects of the detector capacitance on the output signal of a SiC detector and the frequency response of the current-to-voltage transfer function for the detector-cable system with detector diameter and thickness as parameters.

The effects of cable type and cable length are also examined. Specifically with a constant detector capacitance, changes in the output current of the detector are reported with cable characteristics as parameters for three cable lengths. The cable analysis is
presented both in the time and frequency domains and the sensitivity of the overall detector-cable system performance to cable characteristics such as resistance, capacitance, length and characteristic impedance are discussed.

A Mineral Insulated cable was selected for use in high temperature and high radiation environments. Although its capacitance and resistance per unit length are large, simulations show that it performs acceptably well, in the terms of attenuation and distortion, based on the frequency response of the detector-cable system. In the time domain, we show that for the selected SiC diode detector channel configuration and the specified cable and cable length, the cable satisfactorily transmits the calculated output current of the detector to the preamplifier.

4.1 INTRODUCTION

As the next step, in the development of a mathematical model of the detector channel, we have included models of the detector capacitance and the cable connecting the detector to its preamplifier. The effect of the cable degrading the output signal of the detector as it transmits the signal to the preamplifier is usually negligible. However, in some special circumstances the effect of the cable is not trivial. This is the case for our application for the following reasons: Firstly, a long cable may be necessary to transmit the detector output current to the preamplifier. Secondly, the detectors may be used in-core, in which case they must operate in high temperature and high radiation environments. Consequently, the type of cable, which is chosen for this application, may not have the most favorable electronic characteristics for pulse propagation. Finally, it may be necessary for pulses to be processed at high count rates, in which case distortions
of the pulses by the cable may be most noticeable, due to the presence of high frequency Fourier components in the Fourier representations of the pulses. To evaluate the effect of cable degrading the detector output signal, we used PSpice to model the detector-cable system.

4.2 METHODS

In this Chapter, we used a PSpice model of the detector-cable to evaluate the effect of cabling degrading the output current pulse of the detector, which is transmitted to the preamplifier. We considered three cable lengths (9, 11 and 13 meters), corresponding to detector placement in the top-third, middle, and bottom-third of the Gas Turbine Modular Helium Reactor (GT-MHR) core. In Section 4.3, we introduce the detector-cable system model. Based on this model, in Section 4.3 we estimate the effect of detector capacitance, assuming a nominal cable type (mineral insulated (MI)) and a nominal cable length (11 m) (See Table 4.1 for nominal values). The effects of the detector capacitance on the output signal of a SiC detector and the frequency response of the current-to-voltage transfer function for the detector-cable system, as a parameter of detector diameter and thickness are described.

In Section 4.4, we examine the effects of off-nominal cable characteristics and cable lengths assuming a nominal detector capacitance (See Table 4.1 for nominal values). Specifically, with a nominal detector capacitance, changes in the output current of the detector are investigated as the cable lengths and characteristics are varied parametrically. The cable analysis is presented both in the time and frequency domains. This analysis helps us to evaluate the sensitivity of the overall detector-cable system.
performance to cable characteristics such as resistance, capacitance, length and characteristic impedance. Finally, we have simulated the detector-cable system response considering nominal characteristics for all system components. The simulation results are discussed in Section 4.5.

<table>
<thead>
<tr>
<th>Detector parameters: thickness, diameter</th>
<th>10 µm, 500 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable parameters: resistance, capacitance, length</td>
<td>1 Ω/m, 110 pF/m, 11 m</td>
</tr>
<tr>
<td>Preamplifier input impedance</td>
<td>50 Ω</td>
</tr>
</tbody>
</table>

**Table 4.1.** The nominal detector-cable system parameters

4.3 DETECTOR CAPACITANCE AND THE DETECTOR MODEL

The depletion region of a biased SiC detector exhibits some properties of a charged capacitor [11]. The detector capacitance slows down the detector channel and distorts the signals that are propagated through the cable to the preamplifier. The capacitance of the detector depends on the detector reverse bias voltage. If the reverse bias is increased, the depletion region in the detector grows thicker and the capacitance decreases. Conversely, the detector capacitance increases if the detector bias is decreased.
Our model of the detector consists of a current source in parallel with the detector capacitance. Figure 4.1 presents a schematic model of the detector (including its capacitance) and the cable that connects the detector to the preamplifier.

The current source model was developed in the preceding studies and was reported in Chapter 2 [1]. Figure 2.10 and Figure 2.11 show the current source output in the time domain, disregarding the effect of detector capacitance. In this Section, the effect of the detector capacitance and cable on the output of the current source will be discussed. For this Section and the remainder of this Chapter, a pulse with unit amplitude (1 A) and a decay time constant of $10^{-10}$ seconds has been chosen as the reference input current to the cable. Since the current source output is a train of pulses with different amplitudes, prediction of voltages in the remainder of the Chapter for a unit amplitude pulse would have to be scaled according to the current source amplitude (i.e. by a factor...
on the order of $10^{-3}$) in order to predict the voltage pulses corresponding to current pulses in Figure 2.10.

The detector capacitance per unit area is expressed by the following equation as:

$$c = \frac{\varepsilon}{d}$$

Equation 4.1

where $c$ is the detector capacitance per unit area, $\varepsilon$ is the permittivity of the SiC and $d$ is the detector thickness [11]. As mentioned above, $d$ is a function of the applied voltage to the detector and the doping concentration. This relationship is revealed by the expression [11]:

$$d \equiv \left(\frac{2eV}{eN}\right)^{1/2}$$

Equation 4.2

Combining the above two equations, results in the following equation for the detector capacitance per unit area:

$$c = \frac{\varepsilon}{d} \equiv \left(\frac{e\varepsilon N}{2V}\right)^{1/2}$$

Equation 4.3

To have a high-speed channel, the capacitance of the channel should be made as small as possible. Since the detector capacitance contributes significantly to the channel capacitance, we wish to make it small. From Equation 4.3, it can be concluded that considering a single material (for example, one polytype of SiC), the only way to reduce the capacitance per unit area is to increase the detector thickness. Although increasing the active volume thickness is beneficial with respect to the detector capacitance, it has the disadvantage of increasing the radiation damage from triton induced displacements.
within the SiC active volume, because more triton paths then end in the SiC active volume. Also, increasing the detector’s active volume demands that a higher bias voltage be applied, which increases the risk of electrostatic breakdown within the detector.

4.3.1 Sensitivity to Detector Thickness

Figure 4.2 shows the change of the system frequency response as the bias voltage, the thickness of the detector active volume, and subsequently, the detector capacitance is changed. In the definition of the transfer function, the output current of the detector (or input current of the cable) is assumed to be the input and the input voltage at the preamplifier (or output voltage of the cable) is assumed to be the output. To calculate the frequency bandwidth of the system, a −3db line shows the cut off frequency of the cable. One would expect to see a transfer function with a gain of 50 (34db), since a 1A detector current creates a voltage across the preamplifier input impedance of 50 V. As Figure 4.2 shows, this only happens at low frequencies. For frequencies higher than 5 MHz (the exact frequency depends on the cable length), the transfer function amplitude decreases, and this is the reason for the attenuation that is observed for the pulses (Figure 4.3), since the pulses contain significant Fourier components with frequencies larger than 5 MHz. A nitrogen doping concentration of $N=10^{15}$ cm$^{-3}$ [9] and a bias voltage of 100V were used in Equation 4.3. The SiC relative permittivity was assumed to be $\varepsilon=10$ [10, 13].

Obviously, the upper cut off frequency for the cable for the detector-cable system depends on the detector capacitance. As bias voltage increases, the active volume thickness and detector capacitance decreases, so the upper cut off frequency shifts to the
higher frequencies. Figure 4.3 shows the effect of changes in the thickness of the detector active volume on the output signal of the cable.

Higher capacitance attenuates and slows down the signal. On the basis of the discussion above regarding bias voltage and detector thickness, and based on the results of Figure 4.2 and Figure 4.3, a detector thickness of 10 µm was selected as the nominal detector thickness for subsequent modeling.

**Figure 4.2** Frequency response of the system with detector active volume thickness as a parameter. All other system components and specifications are nominal.
4.3.2 Sensitivity to Detector Diameter

The detector sensitivity can be adjusted by varying the detector area. However, as the detector area is increased to increase the detector sensitivity, the capacitance of the detector is correspondingly increased. Figure 4.5 shows the effect of detector diameter on the detector voltage pulse shape when the detector thickness is 10 µm. The frequency response of the system is shown in this case in Figure 4.4.
**Figure 4.4** Frequency response of the detector-cable system with detector diameter as a parameter. All other system components and specifications are nominal.

**Figure 4.5** Response of the detector-cable system to the input current pulse with detector diameter as a parameter. All other system components and specifications are nominal.
4.4 CABLE MODEL

Although the detector capacitance is an important parameter in the calculation of the channel capacitance, in this particular channel design the cable is the main source of capacitance. Because we desire to accurately transmit fast signals through the cable, we chose a distributed parameter model of the cable so as to accurately model the high frequency response of the cable. The distributed model is based on the schematic of the cable shown in Figure 4.6. Its analysis results in two coupled linear first order constant coefficient partial differential Equations. Although the solution of this pair of differential equations provides a very accurate description of their behavior, the solution of the differential equations is somewhat difficult. Consequently, although the mathematical model for the channel as a whole is based on Laplace transform analysis and MATLAB, this approach was not adopted for the analysis of the cable, because Laplace transforms of the form that arises when the differential equation pair is transformed in the time-domain and solved in space, cannot presently (to the best of our knowledge) be inverted by the MATLAB code. Thus, a PSpice program was used to simulate the cable response and results of that simulation were used in the MATLAB code.
The differential equation pair describing the cable is given in Equations 4.4 and 4.5:

\[
\frac{\partial v(z,t)}{\partial z} = -R i(z,t) - L \frac{\partial i(z,t)}{\partial t} \quad \text{Equation 4.4}
\]

\[
\frac{\partial i(z,t)}{\partial z} = -G v(z,t) - C \frac{\partial v(z,t)}{\partial t} \quad \text{Equation 4.5}
\]

where \(v\) is the voltage, \(i\) is current, \(R\), \(L\), \(G\), and \(C\) are respectively the resistance, inductance, admittance, and capacitance per unit length of the cable at some position \(Z\) along the cable length at some time \(t\).

### 4.4.1 Sensitivity to Impedance Matching

One of the important issues is impedance matching in the channel. To eliminate reflection, the cable characteristic impedance and the load impedance, which is the
preamplifier input impedance, should be matched. The preamplifier input impedance for nuclear pulse processing, which is modeled by a resistor in Figure 4.1, is typically $50 \ \Omega$.

Figure 4.7 shows the effect of mismatched impedance in the system response by displaying $V_{\text{out}}/I_{\text{in}}$ in the frequency domain for loads of 30, 50 and 100 $\Omega$. Although 30 and 100 $\Omega$ loads are not much different than the 50 $\Omega$ matched impedance, the system response is greatly changed.

The frequency response of the magnitude of the system transfer function at low frequencies is as expected, a constant number which is equal to the load impedance. But at high frequencies a lot of oscillations are observed in the graph of $V_{\text{out}}/I_{\text{in}}$. For the case of 50 $\Omega$ impedance, the oscillation of the transfer function amplitude at high frequencies becomes just a relatively small diminution of its amplitude. This diminution in the magnitude of the 50 $\Omega$ transfer function is due to line resistance. As discussed previously, the cable characteristic and load impedances should be equal in order to eliminate reflections. The characteristic impedance of a transmission line is given by Equation 4.6:

$$Z_0 = \sqrt{\frac{R + j \omega L}{G + j \omega C}}$$  \hspace{1cm} \text{Equation 4.6}

When a lossless transmission line is considered, Equation 4.6 becomes

$$Z_0 = \sqrt{\frac{L}{C}}$$ \hspace{1cm} \text{Equation 4.7}
Because of the relatively high cable resistance, the lossless transmission line assumption is not valid. As the cable characteristic impedance is specified for a cable using Equation 4.7 (i.e., neglecting the contribution of the resistance of the cable), the true (calculated using Equation 4.6)) characteristic impedance is slightly different from the specified impedance. This difference is the cause of the diminution of the amplitude of the 50 Ω transfer function at high frequencies that is shown in Figure 4.7.

4.4.2 Sensitivity to Cable Capacitance

Figure 4.8 shows the system transfer function relating $V_{out}$ to $I_{in}$ with the cable capacitance as a parameter. In simulating, the cable inductance was changed as the capacitance was changed to maintain a 50 Ω characteristic impedance. The cable length is 11 m and the detector capacitance is 1.73 pF, corresponding to a detector with a 10 μm active volume thickness and a 500 μm diameter.

As we can see in Figure 4.8, there are two drops in the cable transfer functions. As shown earlier in Figure 4.4, the point at which the higher frequency drop occurs depends on the detector capacitance. Figure 4.8 shows the lower frequency drop occurs at lower frequency when the cable capacitance increases.
Figure 4.7 Frequency response of the cable for detector-cable system with different loads. All other system components and specifications are nominal.

Figure 4.8 Frequency response of the cable for the detector-cable system with cable capacitance as a parameter. All other system components and specifications are nominal.
4.4.3 Sensitivity to Cable Resistance

Typically, coaxial cable resistance is negligible. Since it may be necessary to use a special type of cable with a large resistance, cable resistance may become significant. The nominal cable resistance per unit length is assumed in our calculations to be 1 Ω/m. As one would expect, increasing the cable resistance increases the voltage drop along the cable for the detector-cable system. Figure 4.9 shows the voltage drop across an 11 m cable with cable resistance per unit length of 0.1 Ω/m, 1 Ω/m and 10 Ω/m.

![Graph showing voltage drop across 11 m with cable resistance per unit length as a parameter.](image)

Figure 4.9 Voltage drop across 11 m with cable resistance per unit length as a parameter.

All other system components and specifications are nominal.
Figure 4.10 Frequency response of the cable for the detector-cable system with cable resistance as a parameter. All other system components and specifications are nominal.

Figure 4.10 shows the frequency response of the transfer function of the cable \((V_{\text{out}}/I_{\text{in}})\) for the detector-cable system. For high cable resistance, a big drop is seen in the transfer function at high frequencies.

As a conclusion for this Section, PSpice provides us a suitable method to model the cable response. The frequency response of the cable was shown for the detector-cable system in several figures. If the cable bandwidth is greater than that of the
subsequent electronic devices, we can say that the cable can be used in our system without degrading the pulse. With a $1 \ \Omega/m$ cable resistance per unit length, since the attenuation due to the low frequency is less than -3db, it is not a significant attenuation. However, the high frequency drop point is mainly determined by the detector capacitance. In addition, the transfer function continues to decrease after it starts to drop, unlike the transfer function following the first drop where the transfer function remains at a constant level after an initial decrease. So special attention should be paid to the detector capacitance selection, since it determines the upper cut off frequency of the system.

The big drop at high frequencies can be explained by looking at the schematic diagram of the circuit in Figure 4.6. For an element of cable, as the ratio between the series impedance of the cable (includes cable resistance and inductance) and the parallel impedance of the cable (includes cable capacitance and conductance) goes up, more current will flow to the parallel branch, and the output current (which is the difference of input current and the current of parallel branch) decreases. As shown in Figure 4.10, this occurs for frequencies higher than 1 MHz.

4.5 RESULTS OF MODEL ANALYSIS

As stated before, in-core cables have to be able to operate in high temperatures and in a harsh radiation environment. Mineral insulated cables are usually used for these purposes and employed in the nuclear reactors. Their conductors are insulated with a highly compressed mineral, normally magnesium oxide, and sealed in a liquid-tight, gas-tight metallic tube, normally made of seamless copper. Other than where copper can
become corroded, this cable is usable in wet, dry, hazardous, and explosive locations. We have evaluated mineral insulated cables from THERMOCOAX Company. These cables are designed to be used at very high temperature (600°C) and very aggressive media. They are specifically suitable for the transmission of hyperfrequency signals up to 20 GHz. The line capacity of this cable is \( \sim 110 \, \text{pF/m} \pm 5\% \), with a characteristic impedance of \( 50 \, \Omega \pm 6\% \) [14]. The resistance of the cable is about \( 1 \, \Omega /\text{m} \). With this information and the information about the cable length and the detector capacitance, the PSpice program was run and the following results were obtained.

**Figure 4.11** Transfer function of the cable, \( V_{\text{out}} / I_{\text{in}} \), for detector-cable system with cable length as a parameter for nominal cable characteristics. All other system components and specifications are nominal.
Figure 4.11 shows the frequency response for detector-cable system. As shown, the upper cut off frequency of the system is about 4 GHz. Thus, the upper cut off frequency of the system is higher than the upper cut off frequency of the fast preamplifiers, which is 1 GHz to 2 GHz. This means that the selected cable matches the subsequent device in term of having a larger bandwidth. Figure 4.12 shows the output voltage of the cable for detector-cable system for 11 m cable. All system components and specifications are nominal.
voltage of the cable for the detector-cable system in a real case and in an ideal case (zero cable resistance and zero cable capacitance). The effect of the selected cable can be gauged by comparing the two traces.

4.6 CHAPTER CONCLUSION

The detector-cable model was introduced to investigate the effect of the detector and cable electrical and physical characteristics on the output signal of the detector at the preamplifier input. The system response was presented both in the time and frequency domains. As discussed, although the very high frequency components of the detector output signal are attenuated and distorted for the detector-cable system, the overall system performance is acceptable. Since the simulated system bandwidth is broader than that of the subsequent component in the channel, which is the preamplifier, the detector-cable system does not contribute significantly to signal distortion compared to the preamplifier.
CHAPTER 5

MODELING CASCADING AMPLIFIERS

CHAPTER SUMMARY

In this Chapter, an argument is provided to justify the use of more than one preamplifier in the counting channel.

It is concluded that the gain is too small with only one preamplifier, that it is too large if three amplifiers are cascaded, but that it is acceptable if two amplifiers are cascaded.

5.1 INTRODUCTION

As a possible design, we propose to use the channel set up presented in Figure 5.1. In this design, we have two separate channels, which allows us to look at the detector and pulser outputs at the same time. More explanations about the channel set up will be provided later in this Chapter.
In Section 5.2, using more than one preamplifier is considered by cascading the preamplifiers. We simulated the pulse height distribution of the preamplifier output voltage as more preamplifiers are added to the system. In addition, we used simulation to investigate the effects of adding more preamplifiers on the overall system bandwidth and preamplifier output pulse shape, as was done in Chapter 3.
5.2 MODELING CASCADING PREAMPLIFIERS

The output voltage of the preamplifier is not large enough to be handled by the discriminator. The minimum discrimination threshold is 20 mV and the manufacturer has recommended not setting it close to this threshold [14]. Thus, we consider using more than one preamplifier in order to amplify the voltage to a satisfactory level.

5.2.1 Pulse Height Distribution

To evaluate the output voltage of the preamplifier using different stages of amplification, the pulse height distribution of the preamplifier was simulated mathematically using the TRIM, PSpice and MATLAB models that we presented in previous Chapters using one, two and three preamplifiers. Figure 5.2 shows the preamplifier pulse height distribution when one preamplifier is used. Obviously, if the discrimination level is set to 20 mV a large fraction of counts are lost (more than 80%). Therefore, according to the pulse height distribution of the preamplifier output voltage, using one preamplifier is not a good choice.
Figure 5.2 Preamplifier output pulse height distribution using one preamplifier

Figure 5.3 shows the preamplifier pulse height distribution when two preamplifiers are cascaded. According to this distribution, more than 10% of counts are lost when the discrimination level is 20 mV. In this case, we cannot increase the discrimination level to higher voltages, like 100 mV, because the discrimination level would be set at a point, which is sensitive to change in the discrimination level. For a discriminator setting of 100 mV, a slight change in the discrimination level changes the count rate significantly.
Figure 5.3 Preamplifier output pulse height distribution using two preamplifiers

Figure 5.4 shows the pulse height distribution, when three stages of amplification are used. A 100 mV discrimination level causes less than 4% count loss. Although using three preamplifiers reduces the fraction of lost counts considerably, it produces large pulses, which cannot be processed by the discriminator, because the discriminator input voltage has to be kept less than 1 V. Major portions of pulses are larger than 1 V according to the distribution shown in Figure 5.4.
On the basis of this analysis, we conclude that the gain is too small with only one preamplifier, that it is too large if three amplifiers are cascaded, but that it is acceptable if two amplifiers are cascaded.

In our experiment, as will be discussed in Chapter 7, the monitoring channel set up is slightly different from the set up that we modeled with MATLAB. In the experimental set up a 50 Ω signal splitter is used in the output of the preamplifier, which reduces the input signal to the discriminator by one half. Besides the spiller, we usually use bias voltages less than the fully depletion voltage, which makes the detector active volume thinner. Reducing the detector active volume decreases the amount of energy transfer to the detector. Because of these reasons, we have used three cascaded preamplifiers in our
experiments. However, if we remove the signal splitter and if we operate the detector at higher bias voltages, using two preamplifiers will be more effective.

5.2.2 Pulse Shape

Besides the changes in the pulse height distribution, using more preamplifiers changes the preamplifier output voltage pulse shape. These changes were simulated mathematically using the TRIM, PSpice and MATLAB models, which can be seen in Figure 5.5. The output voltage of the preamplifier is shown in Figure 5.5 when one, two and three preamplifiers are used. To show these three pulses in one graph, the preamplifier output voltage is divided by 10 and 100 for the case of using two and three preamplifiers, respectively. As shown in Figure 5.5, the pulse rise time and pulse width are increased as more preamplifiers are added to the system. The increase in the pulse width may lead to more pile up when high count rates are encountered.
Figure 5.5 Amplifier output voltage with one, two and three preamplifiers (Time base is 1ns/div).

5.2.3 System bandwidth

The change in the preamplifier output voltage pulse shape is explained by looking at the preamplifier bandwidth. This change was calculated using MATLAB and the published transfer function for a single preamplifier making assumptions regarding the dependence of the transfer function on frequency for frequencies falling outside of the bandwidth of the preamplifier. Figure 5.6 shows that the preamplifier bandwidth changes
when more preamplifiers are added. The preamplifier passband extends from 100 kHz to 1.8 GHz when we use one preamplifier, as we know from the manufacturer’s published information. By adding another preamplifier, the system passband extends from 157 kHz to 1.16 GHz. Therefore, the total system bandwidth is narrowed when this preamplifier is added. The system bandwidth will be narrowed once more, when the third preamplifier is inserted. With the third preamplifier, the overall system passband begins at 197 kHz and goes up to 904 MHz. Although the lower cut off frequency is changed slightly, the upper cut off frequency is reduced by 50% when compared to one amplifier. This change in the upper cut off frequency filters out high frequency portion of the signal, which causes slower rise time and larger pulse width, as was shown in Figure 5.5.
5.3 CHAPTER CONCLUSION

In this Chapter, we simulated the detector channel with the cascaded preamplifiers. Based on the simulated pulse height spectrum of the amplifier output voltage it was concluded that, using two cascaded preamplifiers suits the discriminator requirements with respect to the discriminator input voltage. In addition, with more than two stages of amplification the pulse rise time and pulse width are less than the discriminator dead time, which would reduce the channel high count rate performance.
CHAPTER 6

EXPERIMENTS WITHOUT RADIATION

CHAPTER SUMMARY

To develop a fast electronic counting channel for SiC diode detector and check the validity of our simulations regarding the SiC detector and the electronic channel, we tested the detector channel. The testing without radiation is described in this Chapter.

6.1 INTRODUCTION

This Chapter covers two topics regarding the channel performance: 1) evaluation of MI cable performance, and 2) analyzing noise in the preamplifier output voltage.

In Section 6.2, we compared the performance of a short length of RG 58 cable with an 8 meter length of Mineral Insulated (MI) cable, which was modeled in Chapter 4. The RG 58 cable was employed because of its nearly-ideal electrical characteristics. So practically, in this experiment, we are comparing the MI cable with an ideal cable. The procedure of the experiment and the analysis of its results are explained in Section 6.2.

In Section 6.3, the preamplifier-cable-oscilloscope system bandwidth was measured and compared to simulation results.
6.2 EFFECT OF MINERAL INSULATED CABLE ON THE COUNTING SYSTEM

This experiment was performed to evaluate the effect of THERMOCOAX Mineral Insulated cable introduced in Chapter 4. A comprehensive study was made to simulate this cable in the fast counting channel, which was reported in Chapter 4 [3]. In this Section, we explain our experiments and compare them with some of the simulation results.

To evaluate the effect of the MI cable on the system, we performed an experiment to compare the response of the system using this cable with the response of the system using a near-ideal cable, like RG 58. As shown in Table 6.1, the electronic characteristics of RG 58 is more suitable than those of the MI cable for transmitting a fast pulse. Thus, compared to the MI cable, we can consider the RG 58 as being an ideal cable, which doesn't change the signal shape as the signal goes through the cable.

<table>
<thead>
<tr>
<th></th>
<th>Impedance (Ω)</th>
<th>Outer Diameter (mm)</th>
<th>Capacitance (pF/m)</th>
<th>Resistance (Ω/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG-58C/U</td>
<td>53.5</td>
<td>4.95</td>
<td>93.5</td>
<td>0.039</td>
</tr>
<tr>
<td>MI Cable</td>
<td>50</td>
<td>3</td>
<td>110</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6.1 Comparison between RG 58 and MI cable characteristics [10-11]
As shown, the major difference between RG 58 and MI cable is the cable resistance. Simulations have shown that this difference in the cable resistance makes a significant difference in the detector-cable transfer function. Although the change in the transfer function of the detector-cable system may affect a number of features in the cable output signal, we only studied the effect of the MI cable on two parameters, which characterize the cable output signal; the rise time and the amplitude.

Since we are developing a fast counting channel, we are interested in identifying parameters that slow down the system. Assuming a constant count rate, the fraction of counts lost increases when the input signals to the discriminator are broadened. One way to broaden a signal is to increase its rise time or fall time. In addition, the rise time of a pulse may increase when it passes through a system with a limited bandwidth. This would likely happen when a fast pulse goes through the MI cable. Thus, one of our goals in this Section is to evaluate the increase in the rise time and width of the signal as it is transferred through the cable and the preamplifier. We then experimentally determined the cable bandwidth based on the increase in rise time and width.

Another important characteristic of a signal is its amplitude. Particularly in this study, the signal amplitude is an essential parameter, because we want to set a threshold above which the input signals of the discriminator are counted. So we should be able to predict the amplitude of the cable output signals (more accurately the pulse height spectrum) in order to define an appropriate discrimination level. We will show that the cable output signal amplitude not only depends on the preamplifier gain and bandwidth, but also depends on the type of cable we are using in the system.
To achieve the above goals, four types of analysis were made based on the gathered data. Firstly, we looked at the pulser output signal in case of having either RG 58 cable or the MI cable. This analysis was the most direct way to compare the effect of the MI cable with the effect of the RG 58. In the second step, the preamplifier was placed after the pulser and the output voltage of the preamplifier was considered once with RG 58 as the connector between the pulser and the preamplifier and the other time with MI cable. In the third analysis, we compared the output voltage of the pulser and the output voltage of the preamplifier when there was RG 58 in the system; and then compared the output voltage of the pulser and the output voltage of the preamplifier when there was MI cable between the pulser and the preamplifier.

In Sections 6.2.1 and 6.2.2 we will look at the increase in the rise time of the pulser output voltage when the pulse goes through the channel. In Sections 6.2.3 and 6.2.4, the change in the pulse amplitude is discussed.

### 6.2.1 Pulser Output Voltage

As stated, in this Section the pulser output voltage was measured when we placed RG 58 and MI cable between the pulser and the oscilloscope. The oscilloscope input impedance is set to 50 Ω because the pulse generator is supposed to provide the voltage over a 50 Ω load. Also the preamplifier input impedance, which will be placed in the system, is 50 Ω.
Figure 6.1 Evaluate the effect of MI cable on the pulser output voltage.

Results are shown in Figure 6.2 and Figure 6.3 with two time scales of 500 ps/div and 2 ns/div. Also in Table 6.2 the pulse characteristics are shown.
Figure 6.2 The pulser output voltage with the time scale of 500ps/div

Figure 6.3 The pulser output voltage with the time scale of 2ns/div

<table>
<thead>
<tr>
<th></th>
<th>$V_{max}$ (V)</th>
<th>$V_{pp}$ (V)</th>
<th>Frequency (MHz)</th>
<th>Rise time (ps)</th>
<th>Fall time (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG 58 (4 ft)</td>
<td>2.1296</td>
<td>2.5305</td>
<td>151.3</td>
<td>386</td>
<td>746</td>
</tr>
<tr>
<td>MI Cable (8 m)</td>
<td>1.1181</td>
<td>1.3863</td>
<td>150.5</td>
<td>475</td>
<td>1180</td>
</tr>
</tbody>
</table>

Table 6.2 Characteristics of the pulser output voltage using RG 58 and MI cable

Firstly, based on Table 6.2, we determined the actual rise time of the signal. The oscilloscope has a bandwidth of 1 GHz [16]. So it does not perfectly follow the input signal and it makes the observed rise time longer. To calculate the total rise time of a signal which passes through the various components, the following equation is used [17].
\[ t_s = \left( t_{r1}^2 + t_{r2}^2 + t_{r3}^2 + \ldots \right)^{\frac{1}{2}} \]  \hspace{1cm} \text{Equation 6.1}

where \( t_s \) is the total system rise time and \( t_{r1}, t_{r2}, \ldots \) are the rise times associated with the various components.

From Table 6.2, the oscilloscope shows 386 ps rise time for the pulser output voltage when RG 58 is used. So by applying Equation 6.1, the actual pulser rise time when we use RG 58 can be found without the oscilloscope contribution.

\[
\begin{align*}
 t^2 &= t_{pulser\_RG\ 58}^2 + t_{scope}^2 \\
 (386\ ps)^2 &= t_{pulser\_RG\ 58}^2 + (350\ ps)^2 \\
 \Rightarrow t_{pulser\_RG\ 58} &= 163\ ps
\end{align*}
\]

This rise time is close to the minimum published rise time of the AVTECH pulse generator, which we tried to achieve [18]. With the same analysis, we can find the pulser output voltage rise time when we use the MI cable.

\[ t_{pulser\_MI\ Cable} = 321 \text{ps} \]

Now by using the pulser output voltage rise times for the cases of using RG 58 and the MI cable, the effect of the MI cable can be evaluated. We assume that the MI cable is a device with a rise time of \( t_{MI} \), so

\[
\begin{align*}
 t_{pulser\_MI}^2 &= t_{pulser\_RG\ 58}^2 + t_{MI}^2 \\
 (475\ ps)^2 &= (386\ ps)^2 + t_{MI}^2 \\
 \Rightarrow t_{MI} &= 277\ ps
\end{align*}
\]

Based on the MI rise time, the cable bandwidth can be determined:
\[ \text{Bandwidth} = \frac{0.35}{t_{MI}} = \frac{0.35}{277 \text{ps}} = 1.26 \text{GHz} \]

This is the bandwidth for a comparison of the output voltage of the cable to the input voltage of the cable. This bandwidth is less than the bandwidth, which we have found from simulations. As stated by the manufacturer, these cables are specifically suitable for the transmission of hyperfrequency signals up to 20 GHz. Therefore, the bandwidth of 1.26 GHz includes the effects of other parameters in addition to those of the MI cable on the system bandwidth like the loading effect of the pulse generator.

6.2.2 Preamplifier Output Voltage

In this Section, we considered the output voltage of the preamplifier when we use RG 58 and the MI cable as the cable between the pulse generator and the preamplifier. Figure 6.4 shows the set up, which is used for this experiment. The effect of the preamplifier on the pulse rise time is discussed in this Section. In the previous experiment, the effect of the preamplifier was not taken into account and we only looked at the pulser output voltage.
**Figure 6.4** Equipment setup to evaluate the effect of MI cable on the preamplifier output voltage

Figure 6.5 and Figure 6.6 show the output voltage of the preamplifier with 500 ps/div and 2 ns/div time scales, respectively.
Figure 6.5 The preamplifier output voltage with a time scale of 500 ps/div. (not in the same scale)

Figure 6.6 The preamplifier output voltage with a time scale of 2 ns/div. (not in the same scale)

Table 6.3 shows the properties of the preamplifier output voltages using RG 58 and the MI cable. From the following table we can evaluate the effect of the preamplifier.

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{max}}$ (V)</th>
<th>$V_{\text{pp}}$ (V)</th>
<th>Frequency (MHz)</th>
<th>Rise time (ps)</th>
<th>Fall time (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG 58</td>
<td>16.915</td>
<td>20.62</td>
<td>151.6</td>
<td>442</td>
<td>769</td>
</tr>
<tr>
<td>MI Cable</td>
<td>8.92</td>
<td>11.16</td>
<td>151.2</td>
<td>540</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table 6.3 Characteristics of the preamplifier output voltage using RG 58 and MI cable
To evaluate the validation of our data, we predict the preamplifier output voltage rise time and compare it to what was found from the experiment. From vendor publication, the preamplifier rise time is 180 ps. From Equation 6.1 for RG 58 cable

\[
\tau_r = \tau_{\text{pulser}}^2 + \tau_{\text{scope}}^2 + \tau_{\text{preamplifier}}^2
\]

\[
\tau_r^2 = (163)^2 + (350\, ps)^2 + (180\, ps)^2
\]

\[\Rightarrow \tau_r = 426\, ps\]

This rise time (426 ps) is very close to the corresponding value in Table 6.3, which is 442 ps. We can do the same analysis and calculate the expected rise time when we use the MI cable according to the information obtained in Section 6.2.1.

\[
\tau_r = \tau_{\text{pulser-MI}}^2 + \tau_{\text{scope}}^2 + \tau_{\text{preamplifier}}^2
\]

\[
\tau_r^2 = (321)^2 + (350\, ps)^2 + (180\, ps)^2
\]

\[\Rightarrow \tau_r = 508\, ps\]

Again, this rise time is consistent with its corresponding value in Table 6.3, which is 540 ps. We conclude that the preamplifier rise time may be slightly larger than the published value.

6.2.3 Pulser Output Voltage and Preamplifier Output Voltage Using RG 58

In this Section, we analyze the output voltages of the pulser and the preamplifier when the cable between the pulser and the preamplifier is RG 58. Issues regarding the effect of the MI cable and the preamplifier on slowing down the pulser output voltage are
presented in Sections 6.2.1 and 6.2.2. In this Section, we will focus our attention on the amplification performance of the preamplifier. Figure 6.7 shows the setup that was used for this experiment.

**Figure 6.7** Pulser and preamplifier output voltages (using RG 58)

Figure 6.8 and Figure 6.9 show the preamplifier input and output voltages with 500 ps/div and 2 ns/div time scales. Table 6.4 also provides the information about these signals.
Figure 6.8 The pulser and preamplifier output voltages using RG 58 with a time scale of 500ps/div. (not in the same scale)

Figure 6.9 The pulser and preamplifier output voltages using RG 58 with a time scale of 2ns/div. (not in the same scale)

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{max}}$ (V)</th>
<th>$V_{\text{pp}}$ (V)</th>
<th>Frequency (MHz)</th>
<th>Rise time (ps)</th>
<th>Fall time (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulser</td>
<td>2.04</td>
<td>2.42</td>
<td>151.3</td>
<td>386</td>
<td>746</td>
</tr>
<tr>
<td>Preamplifier</td>
<td>16.91</td>
<td>20.62</td>
<td>151.6</td>
<td>442</td>
<td>768</td>
</tr>
</tbody>
</table>

Table 6.4 Characteristics of the pulser and preamplifier output voltages using RG 58

We expect the input voltage of the preamplifier to be amplified by a factor of 10 over the preamplifier bandwidth, but this doesn't happen because of the very high frequency components in the pulser output voltage.
To set the discrimination level, we need to know the peak output voltage of the preamplifier. Therefore, we measure the peak voltage of the preamplifier output and calculate the amplification knowing the peak voltage of the pulser output.

\[
Gain_{\text{max}} = \frac{V_{\text{max-out}}}{V_{\text{max-in}}} = \frac{16.91}{2.04} = 8.29
\]

The amplification of the peak is 17% less than the nominal amplification of the preamplifier. Therefore, when the input voltage of the preamplifier is a very fast pulse (rise time on the order of 200 ps), in the case of using RG 58, we can assume that the preamplifier's gain is about 8.3 instead of 10 (since we are concerned about the pulse peak).

### 6.2.4 Pulser Output Voltage and Preamplifier Output Voltage Using MI cable

In this Section, we compare the input voltage of the preamplifier (the output voltage of the pulser) and the output voltage of the preamplifier when the cable between the pulser and the preamplifier is the MI cable. By measuring the output voltage of the preamplifier and comparing it with the output voltage of the pulser, we specify the total effect of the MI cable-preamplifier on the peak output voltage of the pulser. Figure 6.10 shows the set up for this experiment. Figure 6.11 and Figure 6.12 present the input and output voltages of the preamplifier when the pulser is connected to the preamplifier with MI cable.
**Figure 6.10** Pulser and preamplifier output voltages (using MI cable)

**Figure 6.11** The pulser and preamplifier output voltages using MI cable with a time scale of 500 ps/div. (not in the same scale)

**Figure 6.12** The pulser and preamplifier output voltages using MI cable with a time scale of 2 ns/div. (not in the same scale)
Using the output voltage of the preamplifier from Table 6.5 and output voltages of the pulser from Table 6.4 and using the output voltage of the preamplifier from Table 6.5 and output voltage of the pulser from Table 6.4, the gain is found as

\[ Gain_{\text{max}} = \frac{V_{\text{max-out-preamp}}}{V_{\text{max-out-pulser}}} = \frac{8.92}{2.04} = 4.37 \]

This shows that when the MI cable is used (instead of RG 58) the total gain of the system is reduced from 8.29 (Section 6.2.3) to 4.37. Thus, the preamplifier yields a gain of 8.29 instead of 10 because of high frequency components in the pulser output voltage (see Section 6.2.3 and discussion immediately before), and the MI cable adds an extra attenuation and changes the total gain to 4.37.

The preamplifier gain is also calculated from Table 6.5 as it was calculated from Table 6.4.
\[
Gain_{\text{max}} = \frac{V_{\text{max-out-preamp}}}{V_{\text{max-in-preamp}}} = \frac{8.92}{1.08} = 8.26
\]

This gain is very close to the gain found in Section 6.2.3. That means the cable type has not influenced the preamplifier gain, because the output voltage of the MI cable is still a very sharp pulse, like the output voltage with RG 58.

6.3 MEASUREMENT OF SYSTEM BANDWIDTH

The observed overall system bandwidth is not only affected by the number of preamplifiers, but also the cable bandwidth and the oscilloscope bandwidth. These effects are not easily modeled, and can be a cause of discrepancies between simulated and measured results. In this Section, the results of these experiments are presented.

As discussed in the Chapter 4, the bandwidth of the cable that connects the detector to the preamplifier depends on the cable type and length and the detector capacitance. We have shown that with a nominal detector capacitance, the cable bandwidth is sufficiently large for our applications. However, the detector used in our simulation has a different thickness than the detector thickness used in the experiments. Because of this difference in the detector thickness, the detector capacitance is different. The detector capacitance as reported by WEC is 9 pF which is about 5 times greater than what was used in the simulations. This difference in the detector capacitance changes the detector-cable system bandwidth. Hence, the effect of the cable is not negligible and should be considered on the overall system performance.
Another issue which should be taken into account is the effect of the oscilloscope on the waveform that is observed on the oscilloscope. Because the oscilloscope itself has a limited bandwidth, the waveform we see on the screen may not be identical to the oscilloscope input voltage.

Figure 6.13 shows the way that the channel is setup. This setup is nearly identical to Figure 5.1 in that it is similar to the way the channel will be setup in practice, but also allows for the channel to be tested using an alpha source. In this design, we have two separate channels, which allows us to simultaneously look at the detector and the pulser outputs. In practice, we have not yet used the alpha source. Figure 6.11 is different from Figure 5.1 in that it is indicated on Figure 6.11 where the cable was disconnected in order to perform system bandwidth measurements.
Figure 6.13 Schematic of the electronic counting channel for SiC neutron sensors

The overall system bandwidth including the cable, preamplifiers and oscilloscope bandwidths is shown in the following figures. To obtain the system bandwidth experimentally, the input of the preamplifier is disconnected and a pulse height spectrum analysis is performed to the preamplifier output voltage. Since the input is not connected to any source, the output voltage of the preamplifier is the response of the system to the white noise. The response of the system to the white noise determines the bandwidth characteristics of the system. Figure 6.14 shows the system bandwidth with two
preamplifiers. In addition, Figure 6.15 shows the system bandwidth calculated from simulation. As seen, the simulation result is consistent with the experimental result. Figure 6.16 and Figure 6.17 present the system bandwidth when three preamplifiers are used in the system.

**Figure 6.14** Cable-preamplifier-oscilloscope system bandwidth measured experimentally, where two preamplifiers are cascaded.
Figure 6.15 Cable-preamplifier-oscilloscope system bandwidth calculated from simulation (Like Bode amplitude diagram with linear abscissa for cascaded transfer functions), where two preamplifiers are cascaded.

Figure 6.16 Cable-preamplifier-oscilloscope system bandwidth measured experimentally, where three preamplifiers are cascaded.
The system bandwidth was presented in Figure 5.6 when the cable and the oscilloscope bandwidths were not included in the system. Figure 6.18 and Figure 6.19 show the frequency response of the system considering the effect of the RG 58 cable and oscilloscope with two and three preamplifiers, respectively. The upper cut off frequency is shifted to less than 400 MHz, which makes the observed system bandwidth much narrower than a single preamplifier.
Figure 6.18 The observed system bandwidth with two preamplifiers.

Figure 6.19 The observed system bandwidth with three preamplifiers.
6.4 CHAPTER CONCLUSION

In this Chapter, testing without radiation was described. Firstly, the performance of the MI cable was observed. Although the MI cable has a relatively large resistance and capacitance, it does not attenuate and distort the fast pulses drastically. Finally, in the Chapter, the bandwidth of the system is measured. The upper cut off frequency of the system is shifted towards frequencies close to 400 MHz, when we include the effect of the cable and the oscilloscope.
CHAPTER 7

EXPERIMENTAL VERIFICATION WITH NEUTRON-SiC OUTPUT SIGNAL

7.1 INTRODUCTION

As explained earlier, this dissertation is directed towards development of a fast neutron counting system based on the use of SiC semiconductor detectors. Thus far, the power-monitoring system has been designed and the mathematical model of the channel has been presented. In this Chapter, we present our experiments to evaluate the performance of the counting system. We direct our experiments towards five goals: 1) Evaluation of the detector response to incident neutrons, 2) Calibration of the monitoring system, 3) Finding the pulse height spectrum of the channel in response to neutrons, 4) Evaluation of the detector degradation, and 5) Evaluation of the detector linearity. To accomplish these goals, we use both the voltage sensitive system and the charge sensitive system, since the voltage sensitive system is the best system for certain applications, while the charge sensitive system is the best system for other applications.

In Section 7.2, the response of the neutron monitoring channel to fast neutrons is presented by monitoring the voltage sensitive preamplifier output. In Section 7.3, the fast power monitoring system, which is based on the use of a voltage sensitive preamplifier, is
presented. In Section 7.4, the pulse height spectrum of the detector channel, in response to fast and thermal neutrons comprising various neutron flux spectrums, is studied using the voltage sensitive system. In Section 7.5, degradation of the SiC detector in a fast neutron flux is shown using the voltage sensitive system. Finally, in Section 7.6, the linearity of the detector is discussed using the voltage sensitive system.

7.2 SiC CHANNEL PULSE SHAPE MEASUREMENTS

In this Section, we present the response of the SiC detector to fast neutrons. Figure 7.1 shows the arrangement that was used for monitoring the output pulses of the detector responding to neutrons.
A more detailed description of the equipment setup is as follows: A four-diode package (Package 2) SiC detector is placed in the Ohio State Research Reactor beam port BP1. A five meter length of RG 58 is connected to the second detector of the four-diode package (Package 2). The bias voltage for the detector is provided by an ORTEC 210 power supply. One meter of RG 58 is used to connect the power supply to the
preamplifier input. The SiC detector is also connected to the preamplifier input, so the bias voltage is provided to the detector by connecting both power supply and the detector to the preamplifier input. Since the lower cut off frequency of the preamplifier is 100 kHz, the DC voltage coming from the power supply will not appear in the preamplifier output. A bias voltage of 25 V is used in this experiment. Three preamplifiers are used by cascading amplifiers in the 774 Phillips preamplifier. The output voltage of the preamplifier is connected to the oscilloscope to observe the output pulse of the preamplifier. The input impedance of the oscilloscope was set to 50 Ω, because the input impedance of the discriminator is 50 Ω and we are interested in knowing the characteristics of the discriminator input voltage.

All connections in Figure 7.1 are made by RG 58 cables to avoid reflection. The following figures show the response of the channel to neutrons for different time scales. The oscilloscope trigger level was set to see the big preamplifier output pulses. If we lower the oscilloscope trigger level, we could see lots of pulses with smaller amplitudes.

The experiment setup was flawed in two ways. Firstly, three preamplifiers were used, instead of two, which was later shown to be the optimum number. Secondly, we realized during the course of the experiments that the experimental setup was flawed, because of an impedance mismatch that allowed pulses to travel through the Tee on the input of the ganged preamplifiers and reflect off the high input impedance of the Power Supply. This flaw was fixed by adding an impedance matching circuit to equipment circuit. The design of the impedance matching circuit is discussed in the following sub-
Section. Despite the flaws mentioned above, the results of the experiment were still valuable, regarding their conclusions regarding pulse rise and fall times.

Figure 7.2 and Figure 7.3 show two pulses with a time scale of 1 ns/div. As we expect, the amplitude of pulses out of the preamplifier varies significantly depending on how much energy has been transferred to the detector. However, this large variation cannot be seen in these figures, because the trigger level is set to only catch the big pulses.

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>$V_{p-p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>508 ps</td>
<td>676 ps</td>
<td>683 mV</td>
</tr>
</tbody>
</table>

**Table 7.1** Properties of the preamplifier output voltage shown in Figure 7.2.

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>$V_{p-p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>784 ps</td>
<td>961 ps</td>
<td>609 mV</td>
</tr>
</tbody>
</table>

**Table 7.2** Properties of the preamplifier output voltage shown in Figure 7.3.
The rise time of these pulses varies between 500 ps to 700 ps. Accounting for the pulses passing through three preamplifiers and the oscilloscope, the rise time of the detector signal is calculated to be as indicated below:

\[ t_{\text{preamplifier-output}}^2 = 3 \times t_{\text{preamplifier}}^2 + t_{\text{oscilloscope}}^2 + t_{\text{detector}}^2 + t_{\text{cable}}^2 \]

Specially for the pulses displayed in Figure 7.2 and Figure 7.3, respectively:

Fast rise: \((500\,\text{ps})^2 = 3 \times (180\,\text{ps})^2 + (350\,\text{ps})^2 + t_{\text{detector}}^2 + t_{\text{cable}}^2\)

Slow rise: \((700\,\text{ps})^2 = 3 \times (180\,\text{ps})^2 + (350\,\text{ps})^2 + t_{\text{detector}}^2 + t_{\text{cable}}^2\)

If we assume that the cable doesn't have a large contribution to the pulse rise time (which might not be a good assumption), the rise time of the detector is calculated as

Detector fast rise time (corresponds to 500 ps on the oscilloscope): 174 ps

Detector slow rise time (corresponds to 700 ps on the oscilloscope): 520 ps

The rise time of 520 ps for a 5 µm detector thickness seems slightly slow (Package 2). Therefore, the effect of the 5 meter of RG 58 separating the detector and the preamplifier may not be negligible.

Figure 7.4 and Figure 7.5 present two other pulses with a time scale of 500 ps/div. Although the rise times of these pulses are consistent with the rise times of the two pulses analyzed immediately above, the faster time-base in these figures allows us to observe a flat–top in these pulses.
Figure 7.4 Preamplifier output voltage with a time scale of 500 ps/div. Scale of the Y-axis is 200 mV/div.

Table 7.3 Properties of the preamplifier output voltage shown in Figure 7.4.

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>V_{pp}</th>
</tr>
</thead>
<tbody>
<tr>
<td>674.8 ps</td>
<td>681.6 ps</td>
<td>720 mV</td>
</tr>
</tbody>
</table>

Figure 7.5 Preamplifier output voltage with a time scale of 500 ps/div. Scale of the Y-axis is 200 mV/div.

Table 7.4 Properties of the preamplifier output voltage shown in Figure 7.5.

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>V_{pp}</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 ps</td>
<td>923 ps</td>
<td>611 mV</td>
</tr>
</tbody>
</table>

The pulse width of the preamplifier output voltage is about 1.5 ns. This pulse width is larger than the pulse width calculated from the simulations shown in Figure 4.12. There can be several reasons for this behavior: As an example, the oscilloscope is not included in the simulations of the pulse shape. The oscilloscope bandwidth causes an
increase in the observed rise time of the preamplifier output voltage. Similarly, the
oscilloscope increases the observed pulse width. However, discounting the effects of the
oscilloscope, and considering the pulse shape to be an accurate representation of the
properties of the preamplifier output voltage, the channel speed is still limited by the
discriminator.

7.2.1 IMPEDANCE MATCHING CIRCUIT

During the course of the experiments, we realized that the bias voltage cannot be
applied directly to the detector through the preamplifier input, because the output
impedance of the power supply does not match the cable characteristic impedance. When
we looked at the preamplifier output voltage with a bigger time scale, some oscillations
and a relatively big undershoot could be seen after the pulse decays. The big undershoot
always occurred at the same time, which is about 15 ns after the original signal appears.
This big undershoot is about as big as the original pulse. The source of the big
undershoot that occurs at 15 ns after the main pulse is the reflection in the cable, because
of the mismatched impedance of the cable and the power supply output impedance. As
shown in Figure 7.1, the detector is connected to both preamplifier and the power supply
through 50 Ω cables. The preamplifier input impedance is 50 Ω which is matched to the
cable characteristic impedance, but the power supply output impedance is much higher
than 50 Ω and is not matched to the cable impedance. Since the power supply output
impedance is much larger than the cable impedance, the reflection is as big as the main
pulse. Figure 7.5 and Figure 7.6 show the output voltage of the preamplifier with a time
scale of 5ns/div. The big reflection can be seen in both cases. Figure 7.8 and Figure 7.9 show two other pulses with a time scale of 10ns/div. The reflection can also be seen in these two figures too.

**Table 7.5** Properties of the preamplifier output voltage shown in Figure 7.6

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>$V_{p-p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>753 ps</td>
<td>812 ps</td>
<td>920 mV</td>
</tr>
</tbody>
</table>

**Table 7.6** Properties of the preamplifier output voltage shown in Figure 7.7

<table>
<thead>
<tr>
<th>Rise time</th>
<th>Fall time</th>
<th>$V_{p-p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.87 ns</td>
<td>790 ps</td>
<td>1.4 V</td>
</tr>
</tbody>
</table>
Figure 7.8 Preamplifier output voltage with a time scale of 10 ns/div. Scale of the Y-axis is 200 mV/div.

Figure 7.9 Preamplifier output voltage with a time scale of 10 ns/div. Scale of the Y-axis is 200 mV/div.

Figure 7.10 shows the modified circuit diagram of the counting system including the detector, power supply, "impedance matching circuit", and the preamplifier. The impedance matching circuit provides the DC voltage to the detector and transfers the detector output pulse to the preamplifier. Thus, to evaluate the function of this circuit, we perform two types of analysis; DC analysis and AC analysis.
An impedance matching circuit was designed to change the input impedance of the power supply to match the cable characteristic impedance. Therefore, a circuit was built by modifying an Ortec 109 charge sensitive preamplifier to provide the bias voltage to the detector. The specifications of this circuit are described in this Section. In addition, we present simulations of the circuit with the program PSpice.

Charge sensitive preamplifiers have been designed in such a way that they can provide the bias voltage to the detector through the same cable that is used to transfer the detector signal to the preamplifier. However, the voltage sensitive preamplifier that is being used does not have this feature. This preamplifier only provides an input for the
detector output signal and no circuit has been included to provide the bias voltage to the detector through the preamplifier.

To design a proper circuit to eliminate the reflection, we used the idea employed in the charge sensitive preamplifiers. The following figure shows the simplified block diagram of the circuitry in an ORTEC 109 preamplifier. This circuit helps us to specify the key points that we need to consider, when we design a similar circuit for the voltage sensitive preamplifier. The part of the circuit that we are interested in is specified in the figure. This part of the circuit provides the bias voltage to the detector and transfers the detector output pulse into the preamplifier. The bias accepted into the preamplifier through the SHV bias connector is furnished through R2 and R4 (approximately 100 MΩ) to the input BNC connector of the preamplifier. If the detector leakage current is large, a significant voltage drop will occur across the series load resistor in the preamplifier. This leakage current is determined by the diode I-V curve. In the ideal case, when the detector is reverse-biased, the output current of the detector is zero. This means that the detector shows infinite impedance. However, in the real case, a small current flows in the detector and the impedance the detector is not infinite anymore. Although the detector impedance is very large, it drops the bias voltage at the detector input. When a high-leakage detector is to be used and its drop across the load resistor would be excessive, the load resistance can be decreased by installing R3, the 10 MΩ resistor in parallel with R4 as indicated in Figure 7.11.

To understand the circuit shown in Figure 7.11, we need to perform two kinds of analysis; AC and DC. In the DC analysis, the DC performance of the system is studied.
For example, capacitors will be treated as open-circuit elements in this analysis. In the AC analysis, we assume that the frequencies in the system are high enough to treat capacitors as the short-circuit elements.

![Figure 7.11 Ortec 109 charge sensitive preamplifier circuit diagram](image)

**Figure 7.11** Ortec 109 charge sensitive preamplifier circuit diagram

We perform the AC and DC analysis to specify the important points needed to be considered in design of the circuit used to connect the power supply to the detector and the voltage preamplifier. These points can be listed as follows.
1. The input impedance of the circuit connected to the power supply should be high to make the output current of the power supply as low as possible.

2. The power supply and the detector should be separated in terms of AC signal.

3. The output impedance of the circuit should match the cable impedance.

4. The bias voltage should remain constant at the detector input.

The PSpice model of the circuit is shown below in Figure 7.12.
Figure 7.12 The schematic diagram of the system includes detector, cable, impedance matching circuit and preamplifier
Figure 7.12 shows the DC analysis of the system including the detector, power supply, impedance matching circuit and the preamplifier. The detector is modeled by a current source in parallel with a capacitor and a resistor. The current source models the output current of the detector. The capacitor shows the detector capacitance, which is 1.73 pF for a 10 μ thickness, 500 μ diameter diode. The resistor models the diode resistance when the detector is reverse-biased. Usually, the bias voltage of -20 Volts is applied to the detector. At this voltage, the diode resistance is 40 GΩ.

DC voltages and currents in different parts of the circuit are shown in Figure 7.12. As we expect, the bias voltage at the detector input is very close to the power supply output voltage. However, we see a small voltage drop because of the detector resistance. This resistance is much bigger than R1 and R2 in the matching impedance circuit, so the voltage drop is insignificant. If the detector resistance is not significantly larger than R1 and R2, R2 should be replaced by a smaller resistance. The coupling capacitor, C1, prevents the DC current from the power supply from going through the preamplifier and blocks the DC voltage at the preamplifier input. So having this capacitor is crucial in order to maintain the power supply output voltage.

The AC performance of the circuit is determined by C1 and C2. For high frequency signals, C2 isolates the detector from the power supply and the detector output current goes directly to the preamplifier. In addition, C1 should be large enough to have low impedance for high frequency signals, otherwise a reflection will be observed in the system.
This matching impedance circuit is used in our experiments to evaluate its performance. The detector output is connected to the impedance matching circuit input with 5 m of RG 58. The four-diode package (Package 2) is connected to the same length of RG 173, which has similar electrical characteristics as RG 58. This cable carries the detector signal out of the beam port. The signal at the impedance matching circuit output is carried by a 1 m length of RG 58 to the preamplifier input.

Figure 7.13 shows the preamplifier output voltage after three stages of amplification. By comparing this result with the previous results, we see that the reflection is eliminated.

![Graph of Figure 7.13 showing preamplifier output voltage. The y-axis has a scale of 50mV/div, and the time scale is 5 ns/div.](image)

**Figure 7.13** The preamplifier output voltage when the matching impedance circuit is used in the system with a the time scale of 5 ns/div
7.3 VOLTAGE SENSITIVE CHANNEL SETTING

The fast neutron monitoring channel system is presented as a photograph in Figure 7.14. The channel is shown more closely by dividing the system into sections. Figure 7.17 to Figure 7.20 present each section in more detail. As shown, the channel consists of the following components: Power supply Ortec 210, PRM-400 rate meter, matching impedance circuit, Avtech AVN-1-C pulser, 774 Phillips Scientific preamplifier, Phillips Scientific 6904 discriminator, discriminator power supply, MT050 signal splitter, IT100 inverting transformer, and Agilent 54832B oscilloscope. A detailed description of the channel components along with their mathematical models was provided earlier.

In addition to the components shown in previous Chapters, we have added two more components to the system: the signal splitter and the cable shielding. The signal splitter is used to split the preamplifier output signal between the discriminator and the oscilloscope. The signal splitter is necessary to avoid reflections of the preamplifier output. If the preamplifier is connected to the oscilloscope and the discriminator though a simple tee connection, the input impedance of the circuit downstream of the preamplifier is 25 Ω instead of 50 Ω. Therefore, MT050 50-Ω Matched Tee Signal Splitter from ORTEC is used to avoid the reflection. The signal splitter inputs the preamplifier output signal and provides two equal half-amplitude outputs and still preserves 50 Ω termination. According to the splitter manual, reflection is typically 10% (dc to over 500 MHz equivalent bandwidth) and the output signal rise time is less than 1 ns, which is sufficient for our applications. The cable shielding will be discussed in Section 7.3.1.
As presented in Figure 7.14, the channel is divided into five divisions:

1. Neutrons interact with the SiC detector and detector pulses are transferred by 15 feet of RG-58 to the matching impedance circuit (in Figure 7.15).

2. Figure 7.17: The matching circuit impedance provides the bias voltage to the detector and transmits the detector signal to the 774 Phillips-Scientific voltage sensitive preamplifier. The detector signal is amplified through three cascaded preamplifiers; each has a gain of 10.

3. Figure 7.18: The preamplifier output voltage is connected to the 6904 Phillips Scientific discriminator. Since the output of the preamplifier is connected to the 50-ohm splitter, the signal at the discriminator input is half of the signal at the preamplifier output. A NIM module is used to provide the power to the discriminator.

4. Figure 7.19: MT050 Matched Tee Signal Splitter from ORTEC is placed to split the preamplifier output voltage between the discriminator and the oscilloscope. The oscilloscope shows the preamplifier output voltage, the discrimination level and the discriminator output voltage.

5. Figure 7.20: The discriminator output voltage pulse goes to the rate meter and the rate meter shows the count rate. The detector power supply is also presented.
Figure 7.14 SiC neutron-counting channel
Figure 7.15 The SiC detector housing and holder
Figure 7.16 The SiC detector housing
Figure 7.17 Impedance matching circuit and preamplifier
Figure 7.18 Discriminator and discriminator power supply
Figure 7.19 Signal splitter and the oscilloscope
7.3.1 Cable Shielding

The voltage sensitive system is connected to the SiC detector through an RG 58 or an MI cable. Since the detector is located in the reactor, 15-25 feet (depending on the voltage amplifier location) of cable is required to carry the detector signal. The effect of the cable length in the detector channel has been discussed earlier by evaluating the cable bandwidth as the cable length is increased. In addition to changing the system bandwidth, increasing the cable length affects the amount of high-frequency noise, which the cable
picks up from external sources. In this Section, we describe the radio-frequency (RF) shielding method that we used to eliminate the high frequency noise.

Instrumentation often must operate in the presence of high frequency disturbances. High frequency interference is often called EMI or electromagnetic interference. In our counting system, without appropriate RF shielding, the EMI noise greatly dominates the detector pulse. The noise itself is dominated by a 100 MHz signal. There are two methods to eliminate the noise: 1) filtering the noise (since a major part of the noise signal has a nearly single frequency) and 2) shielding the cable. In our system, the noise can be filtered by placing a high pass filter with a cut off frequency of 100 MHz at the preamplifier input. Although in general this method can be useful, we have not adopted this solution due to the addition of complexity to the system in terms of mismatched impedance. An effective filter in the frequency range of interest is a passive filter, which introduces mismatched impedances, and, consequently, reflections over the frequency ranges for which the impedances are not matched. To use the second solution, the transmitting cable needs to be shielded in order to eliminate the EMI. In our system, we have used the Braided Tinned Copper from Belden to shield the cable. Braid consists of many strands of copper wire which are interwoven in the process of fabrication. Braid provides the mechanical flexibility needed in most applications. The weaving of these small filaments takes current from the inner surface to the outer surface, and vice versa [19]. This flow of current allows some field energy to cross through the sheath. The flow of signal current to the outer surface adds no noise, but reduces the quality of the cable. The flow of external noise current to the inner surface adds field to the cable and this is undesirable. The conversion of the external sheath current to internal signal voltage is a
measurable parameter for all cables. This parameter is termed transfer impedance and is
given in terms of ohms per meter. Curves of transfer impedance as a function of
frequency are published for many standard cables.

The sheath is connected to the ground of the NIM bin as shown in Figure 7.21.
Since all the other equipment components in the NIM bin are connected to the ground of
the NIM bin, by connecting the braided shielding to the same ground, we avoid making
multiple grounds in the system. The configuration shown in

reduces the noise level from more than a volt peak-to-peak to less then 40 mV.
The 40 mV of noise is mostly generated by the preamplifier.
To achieve a linear response of the monitoring system to the reactor power, we need to discriminate noise and gamma ray pulses against pulses induced by neutrons, by setting the discrimination level above the noise level and the level of the largest gamma ray pulses. To set the appropriate discrimination level, the preamplifier output voltage is monitored when the reactor is at zero power. The discrimination level is increased until it is greater than the noise and gamma rays peaks. This level can be identified by either looking at the oscilloscope or monitoring the rate meter output. The oscilloscope screen
shows the discrimination level and the noise pulses simultaneously, so that one can easily
adjust the discrimination level so that it is above the noise. In addition, the rate meter
output shows zero counts, when the discrimination level is greater than the noise. By
setting the discrimination level at 40 mV, gamma ray pulses and noise will not be
counted.

7.4 PULSE HEIGHT SPECTRUM

The pulse height spectrum of the SiC detector in the thermal column was obtained
with a charge sensitive system in earlier experiments that were performed by Viji
Krishnan. Those experiments are not discussed in detail in this thesis. However, the
results the spectrum measurements are compared with the results of spectrum
measurements for the voltage sensitive system. In this Section, we present the pulse
height spectrum of the detector, when the voltage sensitive system is used.

The SiC detector was placed in the OSURR thermal column (Package 1). Figure
7.22, Figure 7.23 and Figure 7.24 show three typical preamplifier output pulses. As
discussed, we are able to monitor the preamplifier output, the discrimination level and the
discriminator output simultaneously on the oscilloscope screen. Figure 7.22, shows a
preamplifier output pulse with a peak that is larger than the discrimination level.
Therefore, the discriminator generates a pulse to show that the incoming pulse is
detected. Figure 7.23 shows another pulse, which is not detected, because its height is
smaller than the discrimination level. The third situation occurs when the pulse height is
larger than the discrimination level; however, it is not detected by the discriminator, as
shown in Figure 7.24. In this case, the preamplifier output pulse is not larger than the discrimination level for a sufficient amount of time, so that the discriminator is able to detect the pulse.

**Figure 7.22** Preamplifier output voltage, discrimination level and discriminator output on 100 mV/div voltage and 5 ns/div time scales with the discrimination level at 120 mV
Figure 7.23 Preamplifier output voltage, discrimination level and discriminator output on 100 mV/div voltage and 5 ns/div time scales with the discrimination level at 120 mV.

Figure 7.24 Preamplifier output voltage, discrimination level and discriminator output on 100 mV/div voltage and 5 ns/div time scales with the discrimination level at 120 mV.
The count rate of alpha particles and tritons was measured in the reactor thermal column, after the discrimination level was set to the minimum value that eliminates noise pulses. The cumulative pulse height spectrum at different power levels was obtained by increasing the discrimination level in steps and recording the number of counts for each discrimination level. The following figure shows the normalized cumulative spectrum at different power levels.

![Cumulative distribution function of the voltage sensitive system](image)

**Figure 7.25** Cumulative distribution function of the voltage sensitive system
In this experiment, we started from 100 kW and we measured the spectrum, which is shown by “100 kW Up” in the above figure. In the next steps, we changed the power to 450 kW, 300 kW and 200 kW and we obtained the spectrum at each power level. Finally, we decreased the power to 100 kW and we measured the spectrum, which is presented as “100 kW Down”. As shown in Figure 7.25, the channel exhibits a linear response to variations of power, except at “100 kW Up”. The difference between the “100 kW Up” spectrum and the other spectra is a consequence of radiation damage, which will be discussed in later Sections. Figure 7.26 shows the maximum deviation of counts/kW.s from its average, for different discrimination levels. The error is largely dominated by the statistical error, due to the lack in the number of counts at each discrimination level, since the detector count rate in the thermal column is relatively small.
Figure 7.26 Maximum deviation of counts/kW.s from its average at different discrimination levels

To obtain the differential pulse height spectrum, the curve presented in Figure 7.25 is differentiated. The differential pulse height spectrum is presented in the Figure 7.27.
The charge sensitive system is more efficient for obtaining the pulse height spectrum, because of the existing built-in MCA of this system. In the voltage sensitive system, we have an SCA, which makes the spectroscopy tedious. However, once we find the appropriate discrimination level, the voltage sensitive system is able to operate at much higher count rates. Charge sensitive and voltage sensitive systems will be compared in more detail later.
7.4.1 Channel Calibration

The goal of this Section is to calibrate the neutron monitoring systems. To calibrate the neutron monitoring systems, we use two sets of data: 1) the pulse height spectrum of the SiC detector in response to thermal neutrons, obtained by both monitoring systems and 2) the pulse height spectrum of the SiC detector in response to the Am 241 alpha source. Once the relation between the charge sensitive system and the voltage sensitive system is established, the energy calibration of the voltage sensitive system is obtained by the energy calibration of the charge sensitive system, which is known.

The pulse height spectrum of the SiC detector in response to the thermal neutrons was shown previously for the charge sensitive system. As discussed earlier, there are two distinct peaks in the spectrum, which correspond to the alpha and triton particles. For the charge sensitive system, these peaks are located at channels 532 and 1190, when the DSA gain is 120. To compare the voltage sensitive system against the charge sensitive system, the thermal neutron spectrum has been measured in the OSURR thermal column, using the voltage sensitive system. The voltage sensitive system spectrum is presented in Figure 7.27. The resolution in this system is not as good as the resolution in the charge sensitive system, because the spectrum is obtained manually, by increasing the discrimination level in 1 mV or 5 mV steps. The best discrimination resolution of the voltage sensitive system is 0.1 mV, which is the discriminator resolution. Although the resolution of this voltage sensitive system spectrum is not as good as the charge sensitive system resolution, the voltage sensitive system recognizes both distinct peaks. Table 7.7
shows the correspondence between the channel numbers of the charge sensitive system and the discrimination level of the voltage sensitive system at the peak locations.

<table>
<thead>
<tr>
<th>Channel Number (Gain of 120)</th>
<th>Discrimination Level (mV)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>532</td>
<td>46.5</td>
<td>Alpha peak in thermal neutron spectrum</td>
</tr>
<tr>
<td>1190</td>
<td>100</td>
<td>Triton peak in thermal neutron spectrum</td>
</tr>
<tr>
<td>2796</td>
<td>243</td>
<td>Am 241 lower energy cutoff</td>
</tr>
<tr>
<td>4041</td>
<td>349</td>
<td>Am 241 higher energy cutoff</td>
</tr>
</tbody>
</table>

Table 7.7 Correspondance between the channel numbers of the charge sensitive system and the discrimination level of the voltage sensitive system

The spectrum of Am 241 was also used to calibrate the monitoring systems. An Am 241 source with a diameter of \(\frac{3}{4}\) of an inch was placed at a distance of \(\frac{5}{8}\) of an inch from a 250-micron diameter detector. Figure 7.28 shows the spectrum of the alpha source, when we used the charge sensitive system at the gain of 40. As shown, the spectrum extends from channel 932 (channel 2796 with the gain of 120) to channel 1347 (channel 4041 with the gain of 120). These points are shown in Figure 7.28.
Figure 7.28 Pulse height spectrum of $^{241}$Am obtained by the charge sensitive system with a gain of 40

The voltage sensitive system was used to make the same measurement. Using the voltage sensitive system, the spectrum extends from 243 mV to 349 mV, as shown in Table 7.7. Based on the features of the detector spectra in the reactor thermal column and for the Am 241 source, the relation between the charge sensitive system channel numbers and the voltage sensitive system discrimination voltage was established. Figure 7.29 shows the relation between the two monitoring systems.
Figure 7.29 Relation between the charge sensitive system channel number at the gain of 120 and the voltage sensitive system output voltage

The next step is to determine the relation between the pulse height observed with the monitoring systems and the energy deposited within the detector. Based on other set of experiments that have been conducted the charge sensitive system has a sensitivity of 0.3963 keV/ch. Therefore, the energy to discrimination level correspondence for the voltage sensitive system is calculated as 4.585 keV/mV.
7.5 DETECTOR DEGRADATION

As an important step in the development of the SiC detector monitoring system, we studied the lifetime of the detector by monitoring the detector degradation. Degradation of the detector in a thermal neutron flux is being studied. In this Section, we study the detector lifetime, when the detector is located in a fast neutron field. The detector lifetime was expressed in terms of the 1 MeV equivalent fluence, which is the fluence of 1 MeV neutrons which creates in a specified material (in this case SiC) an amount of displacement damage that is equivalent to the displacement damage that is created by a fluence with a distributed neutron energy spectrum. The ultimate goal of our experiments is to relate the degradation of the SiC fast neutron monitoring system performance to the 1 MeV equivalent fluence and flux (there are rate effects) to which the detector is exposed. In this Section, we present the effect of radiation on the detector. To expose the SiC detector to a fast neutron flux, a SiC power diode was located in the OSURR’s Auxiliary Irradiation Facility (AIF). Characteristics of these diodes are very similar to characteristics of the WEC diodes that we used in our previous experiments. The main difference is the detector active volume, which is about 10 micron for the SiC power diodes. The larger detector thickness makes the detector output signal slower. As shown in Figure 7.30, the tail of a SiC power diode output signal is longer than that of a WEC detector. This effect may become noticeable at high count rates.
We have used two methods to monitor the degradation of the SiC detector, as the detector is exposed to the fast neutron flux. In the first degradation measurement method, we studied the degradation of the detector using a voltage sensitive monitoring system. Based on the recorded pulse height distribution shown in Figure 7.31, a lower level discriminator was set to a sufficiently large voltage to discriminate gamma-ray events from neutron-induced events, in order to minimize the sensitivity of the detector to interfering gamma-ray events. According to the spectrum, if the lower level discriminator is set above channel 400 on the charge sensitive system, the sensitivity of the monitoring channel to gamma-ray events is insignificant. Based on the calibration curve that was shown before, channel 400 on the charge sensitive system corresponds to about 35 mV.
on the voltage sensitive system. Therefore, a lower level discriminator of 40 mV was chosen.

![Graph of Pulse Height Spectrum]

**Figure 7.31** Pulse height spectrum of the SiC power diode at different power levels using the charge sensitive system

With the lower level discriminator set as described above, the total count rate of the monitoring system, above the discrimination level, was monitored as the detector was irradiated in the AIF. The SiC power diode was placed in the AIF and the detector count rate was measured with the voltage sensitive system at different power levels of 50
kW, 100 kW and 450 kW. The detector was biased at -110 V during the experiment. Figure 7.32 shows the variation of the monitoring system count rate as a function of time at different power levels. The detector count rate is expressed as a fraction, with the numerator of the fraction being the detector count rate at the indicated time and the denominator of the fraction being the detector count rate at the beginning of the experiment. As expected, the count rate ratio decreases more rapidly at higher fluxes. Figure 7.32 shows count rate fraction for the first 100 minutes of irradiation of the detectors. The detector that was operating at 450 kW failed completely after about 35 minutes.

![Graph showing count rate fraction for different power levels](image)

**Figure 7.32** Detector count rate fraction (i.e. ratio of the detector count rate, at the indicated time, to the detector initial count rate) as a function of time
Figure 7.33 shows the detector count rate for a longer irradiation of 6 hours at 50 kW. The blue curve in Figure 7.33 shows the detector count rate for the first 3 hours of irradiation of a fresh detector. The detector did not receive more radiation for a week and then it was exposed to the neutron flux at 50 kW for another 3 hours. The red curve in Figure 7.33 shows the detector count rate for the second 3 hours of irradiation of the detector. The detector count rate at the beginning of the second experiment was equal to the detector count rate at the end of the first experiment.

![Graph showing detector count rate fraction as a function of time.](image)

**Figure 7.33** Detector count rate fraction (i.e. ratio of the detector count rate, at the indicated time, to the detector initial count rate) as a function of time when the reactor operates at 50 kW
Besides the fluence dependence of the detector degradation, the detector degradation also depends on the fast neutron flux. Figure 7.34 shows the variation of the monitoring system count rate as a function of the fluence, with reactor power as a parameter. The fluence is specified in units of flux at 50 kW for 1000 seconds. For example, the observed degradation for operation at a power of 100 kW for 1000 seconds is plotted in Figure 7.34 at $2\phi$ (50 kW), which is the same value of the abscissa for which the observed degradation for operation at a power of 50 kW for 2000 seconds is plotted. It can be seen from Figure 7.34, that in terms of the neutron fluence, the detector is degraded at a higher rate, in a higher neutron flux.
This method of assessing the detector degradation does not reveal all of the consequences of the detector degradation, such as shifting of the detector pulse height spectrum to lower voltages. However, it is a very operationally significant measurement method, since the channel configuration for this measurement method matches the configuration of the monitoring system, if it were deployed.

In the second degradation measurement method, we studied the degradation of the detectors by measuring changes in their I-V curves, with the goal of better understanding
the mechanisms by which the detectors are degraded. Since monitoring the I-V curves of the diodes is difficult during irradiation of the detectors in the AIF, the I-V curves were measured for discreet increments of fluence, after we removed the detectors from the AIF.

Figure 7.35 presents the SiC detector I-V curve for a power diode when it is reverse biased, before irradiation, after 3 hours of irradiation at 50 kW and after 6 hours of irradiation at 50 kW. As the detector was irradiated, the detector leakage current decreased and the detector breakdown voltage increased. Therefore, the detector characteristics in terms of the leakage current and the breakdown voltage were improved.

![Figure 7.35 The SiC diode I-V curve when it is reverse biased.](image-url)
Figure 7.36 and Figure 7.37 show, respectively, the forward characteristic before irradiation, and after irradiation for 3 and 6 hours. The detector does not operate as a diode in the forward direction after 3 hours of radiation. However, the detector is still able to detect the fast neutrons.

Figure 7.36 The SiC diode I-V curve before radiation, when it is forward biased
Figure 7.37 The SiC diode I-V curve after 3 and 6 hours of radiation, when it is forward biased

In future studies, variations of the monitoring system count rate can be related to the 1 MeV equivalent flux and the exposure time.

7.6 LINEARITY IN RESPONSE TO POWER

The linearity of the detector response to thermal neutrons with a LiF radiator was shown in Section 7.4, as we showed integral pulse height distributions with counts per kW.s as the ordinate and with Lower Level Discriminator Channel Number as the
To examine the linearity of the detector response, a start up transient was considered. The count rate of the neutron counting system, and the reactor power, were monitored during the start up. Using this method, every second, the relation between the reactor power and the monitoring channel count rate was calculated. Figure 7.38 shows the variation of the reactor power and the detector count rate during the start up.

**Figure 7.38** The reactor power and the SiC detector count rate during the start up
Figure 7.39 presents the detector count rate to the reactor power ratio as a function of the reactor power. At low power, the detector count rate is small, which makes a relatively large uncertainty on the count rate. When the reactor power is less than 1 kW, the detector count rate is less than 500 cps, which introduces about 5% uncertainty. As shown in Figure 7.39, the detector degradation begins when the reactor power passes 20 kW, where the counts/kW.s slightly decreases.

Figure 7.39 The counts/kW.s as a function of reactor power
7.7 CHAPTER CONCLUSION

In this Chapter, characteristics of the preamplifier output voltage were studied. A circuit was designed and evaluated to remove the reflection due to the mismatched impedance between the cable impedance and the power supply output impedance. The preamplifier output voltage has typically a rise time between 500 ps to 700 ps and the pulse width is close to 1.5 ns.

The voltage sensitive system setup was presented. The pulse height spectrum of the thermal neutrons was shown. The linearity of the detector count rate with reactor power in both thermal (0.92 counts/kW.s) and fast neutron fluxes (500 counts/kW.s) was presented. It should be noted that the locations where the measurements were made for the thermal and the fast neutron fluxes were different and consequently, no conclusions should be drawn from these measurements regarding the relative sensitivity of the detector to thermal and fast neutrons. An example of the degradation of the detector in a fast neutron field was presented and discussed.
CHAPTER 8

SIMULINK MODEL OF THE GT-MHR CORE

8.1 INTRODUCTION

As discussed, this dissertation is directed toward the design, development, and assessment of a power monitoring system for a Generation IV reactor, namely the Gas Turbine Modular Helium Reactor (GT-MHR). The power monitoring system is based on the use of Silicon Carbide (SiC) semiconductor diode detectors [5], [6], [7], [9], [20], [21]. The SiC diode detector and the electronic processing channel have been studied, developed and modeled in previous Chapters. As an essential step in the development of the power monitoring system, we are investigating the power monitoring requirements for the GT-MHR. To evaluate the power monitoring requirements for the GT-MHR that are most demanding for a SiC diode power monitor, we have developed a Simulink model to study the transient behavior of the GT-MHR. In this Chapter, the Simulink dynamic model of the GT-MHR core is presented.
8.2 BACKGROUND

8.2.1 Rationale for model development

For the GT-MHR, rapid increases in the reactor power can potentially lead to fuel failure in two ways: 1) by exceeding the maximum allowable fuel temperature within individual microspheres and 2) by exceeding the maximum allowable rate of change of fuel temperature within individual microspheres. A number of reactor parameters are monitored during reactor operation to detect increases of reactor power in case of accidents and consequently to trip the reactor before fuel failure occurs. Safety trips of the GT-MHR are based on the neutron flux to He mass flow ratio, the primary coolant pressure, the core inlet and outlet temperatures, and the turbomachine speed [22]. Among the safety trip signals, the neutron flux to He mass flow ratio trip signal is relied upon to protect the reactor against fast up-power transients. Therefore, the neutron flux measurement and the response time associated with the neutron flux measurement are especially important.

Due to the significance of the neutron monitoring instrumentation response time, the adequacy of a SiC neutron power monitoring channel to respond to fast up-power transients should be examined. Furthermore, as a consequence of the proportional relationship between count rate and power, identifying the largest acceptable response time of the power monitoring channel, which can provide protection of the reactor for the most rapidly increasing credible reactor power transient, is a major step in specifying the dynamic range of the power monitoring system. Therefore, accident scenarios that can cause reactor power to increase rapidly have to be studied. Accident scenarios such as
accidental withdrawal of control rods, loss of poison material from the core, insertion of reactive material into the core, changes in geometrical core configuration, loss of coolant and blower failure, and start-up accidents have been qualitatively studied [23,24] for HTRs. Among those accidents, the Start up Reactivity Insertion Transient (SURIT), which is an accident within the category “accidental withdrawal of control rods”, where the transient is initiated with the reactor initially operating below the power range, is considered the most limiting protectable accident (an accident where the concern is damage to the reactor plant) in terms of establishing the dynamic range of the SiC power monitoring system [25].

Analysis of the reactivity insertion accident (RIA) is a main category of the design basis accident (DBA) analyses [26,27]. In the analysis of the accidents occurring during power operation, such as the RIA, it is important to find the worst conditions for which the accident can occur [27]. The maximum temperatures reached during an accident, and the rate of power increase, vary considerably according to initial power. Therefore, we developed a computational tool with which to study control rod withdrawal accidents that are initiated from various power levels, such as the two power level extremes (full power and start up powers).

### 8.2.2 Work of others and scope of our model

In order to study and model GT-MHR RIA transients such as the SURIT and the Full Power Reactivity Insertion Transient (FPRIT), two dynamic reactor models have been developed. One is based on the RELAP5 [28] program and the other is based on the
Simulink [29] program. The RELAP5 model of the GT-MHR was developed previously by General Atomics [30], [31]. The Simulink model was developed recently by the author of this dissertation. It is the subject of this Chapter.

The Simulink program is widely used in variety of fields due to its superior capabilities in modeling and analyzing dynamic systems. Recently, the Simulink program has been used by others to model the dynamics of nuclear reactors [32], [33], [34]. In general, reactor dynamics simulations are concerned with the analysis of the time-dependent behavior of the reactor in normal operation and during accidents [23]. Numerous reactor dynamic simulation codes have been developed to study various aspects of reactor dynamics for different types of nuclear power plants. Depending on the application of the simulation, computer codes are focused on different parts of the reactor, such as the reactor core and the power conversion system. Since our Simulink model of the GT-MHR was written to evaluate the response of detectors to fast reactor transients, we have included in our model a detailed model of the GT-MHR reactor core that includes the main short time constant phenomena. On the other hand, we did not include the power conversion system, which introduces long-term transients, in our model.

Similarly, the GT-MHR reactor core model does not account for fuel burn-up and fission product decay. Xe and Sm transients have time constants that vary between 9 and 48 hours. The time constants for burn-up transients are even longer. For the transients that are of concern to us in our analysis of response time requirements for SiC diode power monitors, i.e. transients with fast time dynamics (transients with time constants
that vary from fractions of seconds to a few minutes), the number of Xe and Sm and fuel atoms within the core hardly changes.

8.3 MODEL AND CHAPTER OVERVIEW

The Simulink GT-MHR model consists of the core model and a subsystem that has been created to model the control instrumentation. The core model consists of two major subsystems: a neutronics subsystem and a thermal hydraulics subsystem. The GT-MHR model offers a number of new features in terms of modeling methods and interfacing schemes in the simulation of the reactor core and control systems. The control instrumentation modeling scheme provides a fully interactive environment, which can be upgraded to a control room simulator. The flexibility of the control instrumentation modeling scheme lets the user simulate numerous accident scenarios, as well as normal operational transients. Modifications and improvements to the model can be easily performed due to the block-oriented nature of the model. Although the existing model is specifically focused on modeling the GT-MHR, the model can be easily applied to any gas cooled reactor or reactors with a single-phase coolant on the primary side.

The core neutronics subsystem accounts for the main phenomena that occur during fast reactor transients. Each of these phenomena is characterized by a different time constant. The results of control rod withdrawal accidents are usually rapid transients whose time constants are determined by the lifetime of the prompt and the delayed neutrons and the reactivity insertion. Fuel and moderator temperature feedbacks have time constants determined by the heat capacity and conductivity of fuel and moderator.
In addition to the core neutronics model, the Simulink model includes a detailed model of the reactor core thermal hydraulics, along with an efficient and user-friendly controlling system. The thermo hydraulics model calculates the temperature distribution throughout the core, instead of attributing a single temperature to the whole core structure. Such a detailed core thermo hydraulics model is important for accurate modeling for two reasons. Firstly, knowing the temperature distribution within the core is crucially important when core temperatures are compared with core component temperature limits. Secondly, the temperature reactivity feedback due to the fuel and moderator are calculated separately and more accurately.

Our intent in developing the Simulink model was to initially reproduce the RELAP5 model of the GT-MHR and the RELAP5 results (developed by General Atomics), as a means of validating the Simulink code. Our thoughts were that once the RELAP5 results were reproduced then the Simulink model could be modified from this validated base state in order to identify the effect of various changes to this base model.
The reactor core model consists of two sections.
1- Neutronics model: Point reactor kinetics equations are used to calculate the reactor power.
2- Thermo hydrodynamics model: Heat transport by conduction and convection is simulated to calculate the fuel, moderator and coolant temperatures. These temperatures are used to calculate the fuel and moderator feedback.

Figure 8.1 Simulink diagram of the "Core" block
Although the existing Simulink model doesn’t include the balance of plant, the core and control room models accurately simulate transients in which the characteristics of the secondary side don’t change significantly during the simulation. The core and control room models are described in this Chapter, and results of a representative simulation are presented and compared with the results of RELAP5 for purposes of validation.

In Sections 8.4, 8.5, and 8.6, respectively, the Core Neutronics, Thermo Hydraulics and Control Instrumentation models are discussed. Each Section includes description of the methods that are used to model each subsystem. In the next Chapter, the FPRIT simulation results obtained by RELAP5 and Simulink are presented and compared. A parametric evaluation of the effects of the initial power level on the severity of a SURIT is left as a topic for a following Chapter.

8.4 CORE NEUTRONICS MODEL

The neutronics model of the GT-MHR core calculates the neutron population as a function of the reactor reactivity and the core neutronics parameters. The power is computed using the space-independent (or Point Kinetics) approximation, which assumes that the core power distribution can be written as a product of functions of space and time. Comparisons performed between space-dependent and point model calculations show that for the maximum reactivity transients possible for HTRs, there is very little
discrepancy in the behavior of the total reactor power with time [23] between space-dependent and space-independent calculations. This means that if the flux shape is not changed during the transient, the results of the point model are sufficiently accurate, as far as neutron kinetics is concerned. However, assumptions of space-time independence are not valid for the heat transfer calculations, because the shape of the axial temperature profile may change strongly during the power excursion.

The total power of the reactor is the sum of the immediate fission power, and the fission product and the actinide decay powers. The immediate fission power is the power that is released at the time of fission, and includes the power from the kinetic energy of the fission products and the power that is deposited in the core as a consequence of neutron moderation. Decay power is generated as the fission products and actinides undergo reactivity decay. In this Simulink model, we assume that, in fast transients, changes in the reactor power are dominated by changes in the fission power. Therefore, the fission product and actinide decay powers are assumed to remain constant during FPRIT and SURIT simulations.

The following equations are used to calculate the reactor fission power.

\[ \frac{d}{dt} \phi(t) = \frac{(\rho(t) - \beta)\phi(t)}{\Lambda} + \sum_{i=1}^{N_{\lambda}} \lambda_i C_i(t) + S \]  
\[ \text{Equation 8.1} \]

\[ \frac{d}{dt} C_i(t) = \frac{\beta f_i}{\Lambda} \phi(t) - \lambda_i C_i(t) \]  
\[ \text{Equation 8.2} \]
\[ \psi(t) = \sum_j \varphi(t) \]  

Equation 8.3

\[ P_j(t) = Q_j \psi(t) \]  

Equation 8.4

\[ P_{\text{total}}(t) = Q_j \psi(t) + P_{\text{decay}} \]  

Equation 8.5

where,

\[ \varphi(t): \text{Neutron flux} \]

\[ Ci(t): \text{Neutron precursor flux of group i} \]

\[ \beta: \text{Effective delayed neutron fraction} \]

\[ \Lambda: \text{Prompt neutron generation time} \]

\[ \rho: \text{Reactivity} \]

\[ f_i: \text{Fraction of delayed neutrons of group i} \]

\[ \lambda_i: \text{Decay constant of group i} \]

\[ S: \text{Source} \]

\[ \Psi(t): \text{Fission rate in s}^{-1} \]

\[ \Sigma_f: \text{Macroscopic fission cross section} \]

\[ P_f(t): \text{Immediate fission power in MeV/s} \]
\( Q_f \): Immediate fission energy per fission in MeV

\( X \): Conversion factor from MeV/s to watts

All the abovementioned parameters are specified as the inputs of the model and can be changed during the simulation through the Neutronics block.

To implement the Point Kinetics equations into the Simulink program, the “Neutronics” block has been developed. The Neutronics block includes two major subsystems: 1) Delayed Neutron Subsystem and 2) Reactivity Feedback Subsystem. The Delayed Neutron Subsystem calculates the immediate fission power, based on the above equations. The Reactivity Feedback Subsystem computes the reactivity feedback associated with the fuel, moderator and reflector temperatures. The rod banks’ worth is computed in a separate subsystem and is used along with the reactivity that is computed in the Reactivity Feedback Subsystem to calculate the total reactivity of the core.

Temperature reactivity feedback effects on the reactor are modeled through the inclusion of fuel temperature feedback, moderator temperature feedback, and reflector temperature feedback. The temperature through the core is calculated with the Thermo Hydraulics block, which is presented in the next Section. The reactivity feedback for the fuel, moderator and reflector, as a function of temperature, are specified by the user in the Reactivity Feedback Subsystem. The relation between the reactivity and temperature of the materials can be specified as an algebraic function or as a curve. Thus, the program uses accurate models of reactivity feedback over a wide temperature range for each of the
abovementioned core materials. Using accurate temperature feedback models is necessary, when the variations of temperature, and consequently, the feedback reactivity are significant. A user may disable any of the feedback mechanisms during simulation using disabling options that are provided in the Reactivity Feedback Subsystem.

Figure 8.2 presents the fuel reactivity as a function of fuel temperature at the Beginning of Equilibrium Cycle (BOEC), Middle of Equilibrium Cycle (MOEC), and End of Equilibrium Cycle (EOEC) that we use in our simulations. The equations shown in this figure are used to fit with a simple mathematical form the results of the code calculations that are presented in this figure for reactivity versus fuel temperature.

\[
y = 1.1871 \times 10^{-6} x^2 - 9.2948 \times 10^{-3} x + 9.1974 \times 10^0
\]

\[R^2 = 9.9844 \times 10^{-1}\]

\[
y = 1.1871 \times 10^{-6} x^2 - 9.2948 \times 10^{-3} x + 1.5158 \times 10^1
\]

\[R^2 = 9.9844 \times 10^{-1}\]

\[
y = 1.1871 \times 10^{-6} x^2 - 9.2948 \times 10^{-3} x + 1.4883 \times 10^1
\]

\[R^2 = 9.9844 \times 10^{-1}\]

**Figure 8.2** Fuel reactivity as a function of fuel temperature (By General Atomics)
Figure 8.3 presents the moderator reactivity as a function of moderator temperature at the BOEC, MOEC and EOEC. The reactivity feedback effect due to the moderator temperature is dominated by the density effect. As temperature increases, the moderator’s density decreases, leading to a decrease in its moderating power, which in turn leads a lower probability of fast and thermal non-leakage, and hence of a neutron being moderated to thermal neutron energies without escaping the reactor core.

**Figure 8.3** Moderator reactivity as a function of moderator temperature (By General Atomics)
The equations shown in this figure are used to fit with a simple mathematical form the results of the code calculations that are presented in this figure for reactivity versus moderator temperature.

Figure 8.4 shows the reflector reactivity as a function of reflector temperature at the BOEC, MOEC and EOEC. The reflector temperature is calculated by averaging the top and bottom reflectors’ temperatures.

\[ y = 2.1000 \times 10^{-9}x^3 - 7.7119 \times 10^{-6}x^2 + 1.1599 \times 10^{-2}x - 5.8210 \times 10^0 \]

\[ R^2 = 9.9968 \times 10^{-1} \]

**Figure 8.4** Graphite reactivity as a function of reflector temperature (By General Atomics)
The equation shown in this figure is used to fit with a simple mathematical form the results of the code calculations that are presented in this figure for reactivity versus reflector temperature.

**Simulink Neutronics Model Structure**

The “Neutronics” block receives fuel, moderator and reflector temperatures as input and calculates the reactor power. By double clicking on this block, the Simulink diagram of the "Neutronics" block will appear. The user specifies the initial power, delayed neutron fraction, prompt neutron generation time and the delayed neutrons’ specifications in this model. Two subsystems are placed in this model: The “Delayed Neutron” subsystem and the “Temperature Feedback” subsystem.

![Neutronics block schematic diagram](image)

**Figure 8.5** Neutronics block schematic diagram
The "Delayed Neutron" block calculates the concentration of delayed neutron precursors. By double clicking on this block, Figure 8.6 pops up, in which the user specifies the fraction of delayed neutrons and decay constant for each of six delayed neutron groups. To see more details of the Delayed Neutron block, the user can choose the “Look under mask” option after right clicking on the block. If the user does this, then a schematic will appear in which each delayed neutron precursor group is modeled by a “Group” block.

By double clicking on each of the "Group" blocks, the user can see a detailed model of the block. Each of the Group blocks models a delayed neutron precursor concentration equation.
**Figure 8.6** "Delayed Neutron" block dialog window
The “Temperature Reactivity” block simulates the temperature reactivity feedback. This block accepts the fuel, moderator, and reflector temperatures and calculates the reactivity associated with the temperature of each of these elements.

Figure 8.7 "Feedback" block dialog window

By double clicking on the Temperature Feedback block, the dialog box shown in Figure 8.7 will pop up that allows the user to disable or enable the function of this block. In this way, a user can easily compare the simulation response with and without feedback. Also the effects of temperature feedback due to the various elements (fuel, moderator, and reflector) can be identified by specifying in this dialog block dialog
window either fuel feedback, fuel and moderator feedback, or fuel and moderator and reflector feedback.

8.5 CORE THERMO HYDRAULICS MODEL

To study the reactor core dynamics, space dependent heat transfer calculations are essential, although zero-dimensional neutron kinetics equations are, in many cases, sufficient. The Core Thermo Hydraulics model simulates the heat transfer from the fuel to the moderator and from the moderator to the coolant. The temperatures of the fuel, moderator and reflector are calculated as a function of time at a flexible number of radial and axial locations. The number of locations that one employs in the calculations, of course, depends on the required accuracy.

In this Section, the Thermo Hydraulic model of the GT-MHR core is presented. In Section 8.5.1, the mathematical model of the reactor core heat transfer is explained. Thereafter, in Section 8.5.2, implementation of the heat transfer mathematical model with the Simulink program is discussed.

General Atomics RELAP5 coolant hole centered model

The Thermo Hydraulics model of our Simulink program is based on the coolant-hole centered concept, which has been developed by General Atomics. According to the RELAP 5 model of the GT-MHR developed by General Atomics, heat transfer by conduction and convection are simulated using a coolant-hole centered model. There are in total 10361 coolant holes within the core. All the coolant holes are modeled using a
single equivalent representative coolant hole, which is shown in Figure 8.8. The coolant-hole structure is divided into axial and radial nodes in such a way that the axial conduction within the flowing fluid and the solid elements of the core can be neglected. As specified in Figure 8.8, to calculate the temperature distribution using the coolant-hole model, the geometry of the model is divided into five axial regions and each axial region is divided into six radial nodes. Thus, in total, to match the General Atomics GT-MHR model, the coolant-hole structure in our Simulink Thermo Hydraulics model is, by default, divided into 30 nodes and the temperature is calculated at mesh points of each temperature node. However, the number of axial and radial nodes is flexible, and can be specified by the user, depending on the required accuracy and the computation time.
The heat is generated in the fuel compacts, which are radially located at the outer surface of the coolant-center model cylinder and axially placed between the top and bottom reflectors as shown in Figure 8.8. The total fuel height is 7.93 m and it is placed in a ring with an inner radius of 1.454 cm and outer radius of 1.709 cm. The fuel is divided into three axial layers (with the ratio from top to bottom of 2:3:5) and each layer
has three radial nodes with equal width. Therefore, the fuel is in total divided into nine nodes.

In the coolant-hole centered model, the coolant, which is He, flows in the channel in the middle of the coolant-hole, which is surrounded by the moderator. As shown in Figure 8.9, the coolant channel is divided into five axial nodes.

Figure 8.9 Coolant channel divisions
8.5.1.1 Heat transfer in fuel and graphite

The heat transfer in the fuel and moderator is studied by considering each node as a control mass system. Heat is transferred by conduction from the fuel to the moderator and then by convection to the coolant. To study the heat transfer in each conduction node, the energy balance equation is applied to the control mass system that represents the conduction node:

\[
\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \dot{E}_{st}
\]

Equation 8.6

where

\(\dot{E}_{in}, \dot{E}_{out}\) : rates of internal energy transfer in and out, respectively, across the surface of the system due to heat transfer

\(\dot{E}_g\) : rate of internal energy generation within the system

\(\dot{E}_{st}\) : rate of internal energy storage within the system

The energy stored in a control mass system, \(\dot{E}_{st}\), is calculated by:

\[
\dot{E}_{st} = \rho \nu c \frac{dT}{dt}
\]

Equation 8.7
where $\rho$ is the material density, $V$ is the node volume, which is constant in this case, $c$ is the material heat capacity, and $T$ is the average temperature of the node.

The rate of energy transfer to each node, $\dot{E}_{in}$, is specified by the energy transported into it from the adjacent nodes. On the other hand, the rate of energy transfer out of the node, $\dot{E}_{out}$, along is calculated based on the difference between the radial coordinates of the inner and outer surfaces of the node. In general, the rate of energy transfer from any surface is calculated by:

$$
\dot{Q} = -kA \frac{dT}{dr}
$$

**Equation 8.8**

where $k$ is the material thermal conductivity, $A$ is the area of conduction, and $r$ is the radial coordinate. As explained previously, in the coolant-hole model, with regards to radius, energy is transported radially inwards. For this reason, the above equation is written in such a way that $\dot{E}_{out}$ is positive when the temperature at the outer surface is higher than that of the inner surface.

The rate of internal energy generation within the system, $\dot{E}_{g}$, is calculated based on the total power of the core (which in the Simulink implementation of the model is calculated in the “Neutronics” block) and the volume of the node.
By substituting equations 8.7 and 8.8 in equation 8.6, we derived a differential equation. For each node $\dot{E}_{in}$ and $\dot{E}_{s}$ are defined as inputs and temperatures at the node boundaries are computed. This differential equation has been discretized in Simulink using forward difference, backward difference and central difference discretization schemes.

8.5.1.2 Heat transfer in the coolant

To model the heat transfer from Graphite to the coolant, the coolant channel is divided into a number of control volume systems. The energy rate balance equation is employed for each control volume to calculate the Helium temperature in the control volume. The energy rate balance equation for a control volume system is represented as [36]:

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i) - \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e)$$

**Equation 8.9**

$E_{cv}$: Energy of the control volume system

$\dot{Q}_{cv}$: net rate of energy transfer in the system by heat transfer
\( W_{cv} \): net work done by the control volume system

\( \dot{m}_i, \dot{m}_e \): mass flow rates at the inlet and exit, respectively

\( h_i, h_e \): fluid enthalpy at the inlet and exit, respectively

\( z_i, z_e \): elevation at the inlet and exit, respectively

\( V_i, V_e \): fluid velocity at the inlet and exit, respectively

\( g \): acceleration due to gravity

The mass flow rate into the control volume is assumed to be equal to the mass flow rate out of the control volume, which means \( \dot{m}_i = \dot{m}_e \). Furthermore, the number of calculations and consequently the computation time can be reduced by assuming that the difference in the velocity \((V_i, V_e)\) and elevation \((z_i, z_e)\) at the input and exit of the control volume system is negligible. These approximations have been made in the Simulink model.

8.5.1.3 Core Material

The coolant-hole model consists of three materials: 1) Fuel, 2) Graphite, and 3) Helium. H-451 Graphite is used as the moderator and reflector materials. The top and bottom portions of the coolant-hole are top and bottom reflectors, respectively. To calculate the temperature of the coolant-hole structure, the thermal conductivity \((k)\), the
heat capacity \((c_p)\) and the product of the mass density \((\rho)\) and heat capacity \((c_p)\) for all the aforementioned materials have to be specified, as a function of the material temperature. Thermal properties of the fuel compacts and H-451 Graphite, which we use in our simulations, are shown in Table 8.1 and Table 8.2, respectively.

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<th>Temperature (F)</th>
<th>Temperature (K)</th>
<th>Thermal Conductivity (k) W/m.K</th>
<th>Heat Capacity (Cp) (J/kg.K)</th>
<th>(\rho)Cp (J/m(^3).K)</th>
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**Table 8.1** Fuel compact thermal properties
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<th>Temperature (F)</th>
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<th>Heat Capacity (Cp) (J/kg.K)</th>
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**Table 8.2** Thermal properties of H-451 Graphite

**Simulink Implementation of RELAP5 Thermo Hydraulics Model**

The thermo hydraulic model of the core is modeled by the "Thermo Hydraulics" block presented in Figure 8.10. This block takes as input the reactor power calculated in the "Neutronics" block and, based on the reactor power, computes the temperature distribution throughout the coolant-hole structure, as well as the average temperatures of the fuel, moderator and reflector.
The Thermo Hydraulics block contains the coolant-hole geometrical specifications, and blocks to specify the fuel, moderator and coolant physical properties. As discussed earlier, the reactor core is divided into five axial locations. In the Thermo Hydraulics block, the fraction of power that is generated in each axial location is specified. The total reactor power is divided by the total number of coolant holes, which is 10361. As presently specified (with a configuration that matches that of the RELAP5 model of the GT-MHR), the coolant-hole structure is divided into five axial layers, each modeled by a "Row" block. Each "Row" block has two inputs: 1) the total power generated in that axial layer, and 2) the coolant inlet temperature. The inlet temperature of the first "Row" block is simply the inlet temperature of the coolant channel. The inlet temperature of the other "Row" blocks is the outlet temperature of the previous "Row"
block. The number of “Row” blocks can be easily customized to obtain the required accuracy.

The average temperatures of the fuel, moderator, reflector and coolant are calculated in the "Coolant-Hole" subsystem based on the temperatures calculated in each "Row" block.

“Row” blocks calculate the temperature along each axial layer at a selectable number of thermal nodes. Therefore, each "Row" block contains a number of "Node" blocks. There are two types of nodes in each row: 1) conduction nodes represented by "Node", and 2) convection node indicated by "HeNode". These two types of thermal nodes are described in the next Sections.

8.5.1.4 Conduction Node

A conduction node models one-dimensional heat transfer by conduction in a Cartesian, cylindrical or spherical coordinate system. Based on the selected coordinate system, the parameters that are required to specify the geometry of the node appear. For instance, if a cylindrical coordinate system is chosen, the node is a ring, which is specified by its outer radius, inner radius and height. Each conduction node consists of a single material that is specified in the dialog window. A sample dialog window, which appears by double clicking on the conduction node, is shown in Figure 8.11.

The conduction node block has three inputs: 1) rate of energy generated in the node (\( \dot{E}_g \)), 2) rate of energy transfer into the node (\( \dot{E}_{in} \)), and 3) temperature of the
adjacent node. The node temperature and the rate of energy transfer out of the node are calculated using the energy balance equation as explained in the previous Section.

As presented earlier, the heat transfer equation used in our analysis is a parabolic differential equation. A number of discretization schemes exist to solve this type of equation numerically [37]. Among those, this Simulink model lets the user select between the central, backward and forward difference schemes. Although generally the central difference scheme has the best accuracy, in some situations the initial condition forces one to use another type of discretization scheme. Therefore, the flexibility of applying different numerical schemes is important in some situations.
8.5.1.5 Convection Node

In each “Row” block, the heat transfer by convection is modeled by “Convection” nodes. The Convection node block has two inputs: 1) rate of energy transfer into the coolant (which in this case comes from the moderator) and 2) the coolant inlet temperature. The coolant outlet temperature ($T_h$) and the surface temperature ($T_s$) are evaluated in this block using Equation 8.9.
By double-clicking on the convection block, a dialog window appears that allows the user to specify the control volume geometry, namely the coolant channel radius, the channel height and the initial temperature of the coolant.

![Figure 8.12](image_url) "Convection node" block dialog window
As a part of the convection node block, a subsystem was developed to evaluate the coolant thermal properties, which is "He calculator" block. This subsystem calculates the coolant density, specific heat, thermal conductivity, and convection heat transfer coefficient as a function of the coolant temperature. Other single phased coolant may be considered by modifying the physical properties of the coolant in this block.

8.6 MODEL OF THE CONTROL INSTRUMENTATIONS

In this Section, the Simulink models of the controlling instruments are described. Models of control instruments help the user simulate and analyze various types of scenarios in order to study and evaluate the reactor dynamic response. The Simulink program’s “Control instruments” models are separated into two major categories: 1) model of the control room and 2) model of the neutron control assemblies.

8.6.1 Control room model

The reactor control is based on the physical quantities, which are measured with various accuracy, delay and reliability. The quantities of interest usually are: neutron flux; temperature of fuel, coolant and structures; coolant mass flow; coolant pressure; and coolant activity [23]. The control room model simulates a number of instruments that are available in most reactor’s control rooms, such as dials and gauges to monitor the control rods’ positions, the average coolant temperature, $T_{av} = (T_h + T_c)/2$, the coolant inlet and outlet temperatures, and the coolant mass flow rate. In addition, other instruments and
readings that are not available in a real control room, but that are important for understanding the dynamics of the plant, as modeled by Simulink, such as the temperature distribution throughout the core, average fuel temperature, average moderator temperature, average reflector temperature, reactor multiplication factor, reactor reactivity, fuel reactivity, moderator reactivity, and reflector reactivity are included for completeness.

Figure 8.13 presents the Simulink diagram of the control room model. On the right hand of this figure, gray color blocks, are used to display the reactor’s parameters. In addition, the reactor power is displayed by an LCD display and sketched in the strip chart.
Figure 8.13 Simulink diagram of the control room model
To monitor the temperature distribution in the core, the user can double click on the “Temperature Distribution” block on the control room form. The temperature distribution for the coolant-hole model that was discussed earlier is displayed at the 35 mesh points discussed earlier with a 5x7 matrix. In addition, the He temperature at five axial locations along the He channel is displayed.

In the following subsections, subsystems that were developed to control the reactor model characteristics are explained.

**Neutron Source**

A “Neutron Source” block was designed to model the external neutron source.

The relation between the photo-fission source strength and the initial fission power is determined by the reactor sub-critical multiplication. We have used the following Point Reactor Kinetic (PRK) equations to calculate the equilibrium fission power. The PRK equations were presented in Equations 8.1 and 8.2.

When the reactor reaches equilibrium, the fission power and the delayed neutron precursor concentrations are constant in time. Therefore,

\[
\frac{d}{dt}C_i(t) = 0 \quad \text{and} \quad \frac{d}{dt}\varphi(t) = 0
\]
After multiplying both sides of Equation 8.2 by $XQ_j\Sigma_f$, we obtain

$$\frac{\beta_i}{\Lambda}(XQ_j\Sigma_f)\varphi(t) = \lambda_i(XQ_j\Sigma_f)C_i(t) \quad (i = 1,6) \quad \text{Equation 8.10}$$

Now substituting the left hand side of Equation 8.10 into Equation 8.1 gives us (both sides of Equation 8.1 are multiplied by $XQ_j\Sigma_f$,

$$\frac{\rho(t)}{\Lambda} - \frac{\beta}{\Lambda}(XQ_j\Sigma_f)\varphi(t) + \sum_{i=1}^{6} \frac{\beta f_i}{\Lambda}(XQ_j\Sigma_f) + S(XQ_j\Sigma_f) = 0 \quad \text{Equation 8.11}$$

Further simplifications in Equation 8.11 give us

$$\frac{\rho(t) - \beta}{\Lambda}P_{fission} + \frac{\beta}{\Lambda}P_{fission} + S' = 0 \quad \text{Equation 8.12}$$

$$\frac{\rho(t)}{\Lambda}P_{fission} + S' = 0 \quad \text{Equation 8.13}$$

and finally, the equilibrium fission power corresponding to a specific external source is found as

$$P_{fission} = -\frac{\Lambda}{\rho(t)}S' \quad \text{Equation 8.14}$$
Using the above equation, we can numerically calculate the neutron source strength that is required to produce a specific fission power, $P$, in equilibrium.

**Automatic control rod adjustment**

This block automatically adjusts the control rods’ positions to make the reactor critical. When this switch is off, the user has to adjust the reactivity by changing the control rod position.

**SCRAM initiator**

This block initiates a SCRAM when the power increases beyond the safety margins. Upon initiating a SCRAM, all rod banks are inserted into the core with the speed that is specified on the “Controller” block.

The SCRAM can be initiated manually, by pressing the “ScramSignal” button, or automatically by specifying a maximum power on the “SCRAM Initiator” block. By double clicking on the “SCRAM Initiator” block a dialog window appears in which the reactor full thermal power and the maximum power ratio for the initiation of a scram are specified.
Neutron control assemblies

The neutron control assemblies’ model simulates the rod banks and their movement. Two subsystems are designed to model the rod banks: 1) “Controller” blocks that model the rod banks’ movement and 2) “Neutron Control Assemblies” subsystem that models the rod banks’ reactivity worth.

The “Controller” block is located on the control room model. Each rod bank is controlled by a “Controller” block. This block is connected to a button that activates the “Controller” block when the button is set to on. The rod bank’s position doesn’t change when the button is off.

By double clicking on the “Controller” block, a dialog window shown in Figure 8.14 pops up, which allows the user to specify the following parameters:

- Rod height: the total rod height in cm.
- Initial position: indicates the initial rod position measured from top of the core
- Drop time: time required for a fully withdrawn rod to insert completely on initiation of the SCRAM scenario
- Rod speed: specifies the speed of the rod when it is inserted or withdrawn
- Rod direction: indicates if the rod is withdrawn or inserted
While the “Controller” block simulates the movement of the rod banks, the “Neutron Control Assemblies” block has been developed to model the reactivity of the control rods. This block is located on the model main page, although the rod banks’ positions are specified by the models located on the control room model. Using the position of the rod bank, the rod bank’s reactivity is calculated on the “Reactivity Calculator” block. Besides a rod bank’s position, a rod bank’s reactivity worth depends
on the history of reactor operation. Rod bank reactivities are reported by General Atomics for the Beginning of Equilibrium Cycle (BOEC), Middle of Equilibrium Cycle (MOEC), and End of Equilibrium Cycle (EOEC). In our analysis, the BOEC and MOEC data are used for the start up and full power analysis, correspondingly.

By double clicking on the “Reactivity Calculator” block, a dialog window pops up and the total reactivity of each rod bank can be specified in this dialog. Although the total reactivity of rod banks is varies among rod banks, we assumed that the fraction of bank worth as a function of insertion fraction (shown in Figure 8.15) is the same for all rod banks. However, the function describing the fraction of a bank’s worth as a function of insertion can be defined for each of the rod banks differently. This function is specified by either an algebraic expression or a curve. Finally, knowing the insertion fraction for each rod, the reactivity associated with each rod bank is calculated by multiplying the bank fraction and the total bank worth.
8.7 CHAPTER CONCLUSION

A mathematical model has been developed by Simulink to model the transient behavior of the GT-MHR core. This code provides an interactive environment to model and study various types of transient scenarios. This code calculates the temperature distribution in the core model and the power of reactor model, as the reactor parameters vary during transients.
CHAPTER 9

GT-MHR FULL POWER REACTIVITY INSERTION TRANSIENT ANALYSIS

9.1 INTRODUCTION

In this Chapter, the reactor characteristics at full power as calculated by the Simulink model are presented and compared to RELAP5 simulation results obtained by General Atomics. In Section 9.2, the reactor characteristics at full power in steady state are studied. The FPRIT is investigated in Section 9.3. Finally, differences between the Simulink and RELAP5 results are discussed.

9.2 STEADY STATE FULL POWER

At MOEC full power, reactor criticality is achieved by having four rod-banks fully inserted and the fifth rod bank inserted by 60.8%. The coolant specifications at full power are also presented in Table 9.1. These specifications are used as the Simulink model inputs to calculate the temperature distribution in the coolant-hole model.
Using the parameters shown in Table 9.1, the temperature of the reactor core is calculated at steady state. Table 9.2 shows the temperature distribution at the coolant-hole mesh points defined earlier, which is obtained at full power using Simulink. The temperature differences between the RELAP and Simulink model results are shown in Table 9.3. They are very small. The maximum difference is less than 0.7%, and occurs at the most outer mesh point of the second row.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium mass flow rate</td>
<td>322.703 kg/s</td>
</tr>
<tr>
<td>Helium pressure</td>
<td>7.03 MPa</td>
</tr>
<tr>
<td>Helium inlet temperature</td>
<td>909.6 K</td>
</tr>
</tbody>
</table>

Table 9.1 Coolant specifications at full power
<table>
<thead>
<tr>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
<th>760.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>875.27</td>
<td>962.71</td>
<td>977.64</td>
<td>989.57</td>
<td>999.48</td>
<td>1013.48</td>
<td>1022.52</td>
<td>1026.90</td>
<td></td>
</tr>
<tr>
<td>1027.80</td>
<td>1102.03</td>
<td>1114.35</td>
<td>1124.21</td>
<td>1132.41</td>
<td>1144.11</td>
<td>1151.66</td>
<td>1155.33</td>
<td></td>
</tr>
<tr>
<td>1118.82</td>
<td>1144.77</td>
<td>1149.10</td>
<td>1152.57</td>
<td>1155.47</td>
<td>1159.62</td>
<td>1162.31</td>
<td>1163.61</td>
<td></td>
</tr>
<tr>
<td>1118.89</td>
<td>1118.93</td>
<td>1118.93</td>
<td>1118.94</td>
<td>1118.94</td>
<td>1118.94</td>
<td>1118.94</td>
<td>1118.94</td>
<td></td>
</tr>
</tbody>
</table>

**Table 9.2** Steady state temperature distribution in the coolant hole at full power using Simulink model (K)

<table>
<thead>
<tr>
<th>-0.01</th>
<th>-0.02</th>
<th>-0.02</th>
<th>-0.02</th>
<th>-0.02</th>
<th>-0.02</th>
<th>-0.02</th>
<th>-0.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.02</td>
<td>-0.12</td>
<td>-0.11</td>
<td>-0.08</td>
<td>-0.05</td>
<td>-2.28</td>
<td>-4.48</td>
<td>-6.63</td>
</tr>
<tr>
<td>0.08</td>
<td>1.01</td>
<td>1.02</td>
<td>1.00</td>
<td>1.02</td>
<td>-0.85</td>
<td>-2.68</td>
<td>-4.45</td>
</tr>
<tr>
<td>0.37</td>
<td>0.88</td>
<td>0.88</td>
<td>0.86</td>
<td>0.85</td>
<td>0.20</td>
<td>-0.43</td>
<td>-1.07</td>
</tr>
<tr>
<td>-0.17</td>
<td>-0.22</td>
<td>-0.23</td>
<td>-0.23</td>
<td>-0.24</td>
<td>-0.24</td>
<td>-0.24</td>
<td>-0.24</td>
</tr>
</tbody>
</table>

**Table 9.3** Temperature difference between RELAP5 and Simulink models (K)
Figure 9.1 shows temperature distribution at full power throughout the coolant-hole structure. Mesh points defined in Figure 8.8 are shown in this figure so that the reader can visualize the temperatures in the fuel, moderator, reflectors, and He channel regions.

Figure 9.1 Temperature distribution in the coolant-hole model at the full power (2D)

The average temperature of the fuel, moderator and reflector calculated by RELAP5 and Simulink and the differences between the calculated temperatures for the
two codes are presented in Table 9.4. The greatest difference is in the average fuel temperature, which is about 0.11%.

<table>
<thead>
<tr>
<th></th>
<th>RELAP5 (K)</th>
<th>Simulink (K)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Fuel Temperature</td>
<td>1126.41</td>
<td>1127.68</td>
<td>0.113%</td>
</tr>
<tr>
<td>Average Moderator Temperature</td>
<td>1109.09</td>
<td>1108.37</td>
<td>0.065%</td>
</tr>
<tr>
<td>Average Reflector Temperature</td>
<td>952.97</td>
<td>953.10</td>
<td>0.014%</td>
</tr>
</tbody>
</table>

Table 9.4 Average temperature of fuel, moderator and reflector calculated by RELAP5 and Simulink

The accuracy of the calculations of the average fuel and moderator temperatures is crucial, since the average fuel and moderator temperatures are used as the basis for calculating the reactivity. Table 9.5 presents the reactivity of the fuel, moderator and reflector at full power as calculated by RELAP5 and Simulink. As expected, based on the differences between the calculated temperatures for the two codes, the reactivities calculated by RELAP5 and Simulink are in good agreement. They exhibit roughly the same fractional errors as the fractional errors in the corresponding material temperatures.
### Table 9.5. Reactivity of fuel, moderator and reflector at full power

<table>
<thead>
<tr>
<th>Reactivity Type</th>
<th>RELAP5 ($)</th>
<th>Simulink ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Reactivity</td>
<td>6.194</td>
<td>6.186</td>
</tr>
<tr>
<td>Moderator Reactivity</td>
<td>-0.1727</td>
<td>-0.1716</td>
</tr>
<tr>
<td>Reflector Reactivity</td>
<td>0.0463</td>
<td>0.0467</td>
</tr>
</tbody>
</table>

9.3 FULL POWER TRANSIENT ANALYSIS

The FPRIT is simulated by withdrawing a fully inserted rod group when the reactor is critical at full power. A rod bank with the highest reactivity worth is chosen to be withdrawn. The rod bank is withdrawn with the speed of 3 cm/s, which is the maximum allowable withdrawal speed. Withdrawing the rod bank makes the reactor super critical, and consequently the reactor power will increase. The reactor scrams when the power to coolant flow ratio is 1.5; i.e. when reactor power increases to 150% of full power. When the reactor scrams, all rod banks are inserted. For a fully withdrawn rod bank, it takes 23.13 s to be inserted completely. Rod Bank Groups reactivity worth is shown in Table 9.6.
<table>
<thead>
<tr>
<th>Group No.</th>
<th>Reactivity (%)</th>
<th>Reactivity ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.6079</td>
<td>0.9355</td>
</tr>
<tr>
<td>Group 2</td>
<td>1.0094</td>
<td>1.5534</td>
</tr>
<tr>
<td>Group 3</td>
<td>1.3252</td>
<td>2.0393</td>
</tr>
<tr>
<td>Group 4</td>
<td>0.693</td>
<td>1.0664</td>
</tr>
<tr>
<td>Group 5</td>
<td>0.8677</td>
<td>1.3353</td>
</tr>
<tr>
<td>Group 6</td>
<td>1.0016</td>
<td>1.5413</td>
</tr>
<tr>
<td>Group 7</td>
<td>0.6675</td>
<td>1.0272</td>
</tr>
<tr>
<td>Group 8</td>
<td>0.7322</td>
<td>1.1268</td>
</tr>
<tr>
<td>Group 9</td>
<td>0.6258</td>
<td>0.9630</td>
</tr>
<tr>
<td>Group 10</td>
<td>0.7454</td>
<td>1.1471</td>
</tr>
<tr>
<td>Group 11</td>
<td>0.748</td>
<td>1.1511</td>
</tr>
<tr>
<td>Group 12</td>
<td>0.9841</td>
<td>1.5144</td>
</tr>
<tr>
<td>Group 13</td>
<td>3.1389</td>
<td>4.8304</td>
</tr>
<tr>
<td>Group 14</td>
<td>4.105</td>
<td>6.3171</td>
</tr>
<tr>
<td>Group 15</td>
<td>2.6135</td>
<td>4.0219</td>
</tr>
<tr>
<td>Group 16</td>
<td>3.9142</td>
<td>6.0235</td>
</tr>
</tbody>
</table>

*Table 9.6* Rod Bank Groups reactivity worth for the FPRIT analysis (by General Atomics)
9.3.1 Variation of Reactor Power

To study the FPRIT, at $t=600$ s the chosen rod bank is withdrawn. The reactor power increases to 150% (900 MW) of full power at $t=642.6$ s using the Simulink model and at $t=642.9$s using the RELAP5 model. Figure 9.2 shows the power trace during the FPRIT, and after scram, using the Simulink model. In addition, the relative difference between the Simulink and RELAP5 results is presented in this figure. The Simulink and RELAP5 codes calculate power during the FPRIT with less than 0.4% relative difference.

Figure 9.2 Variation of the reactor power during FPRIT using the Simulink and RELAP5 models
9.3.2 Variation of Reactor Temperature

Evaluation of the reactor temperatures during the FPRIT is crucial from two stand points. Firstly, the reactivity feedback associated with the average fuel and moderator temperatures, greatly affects the total reactivity of the core and consequently the reactor power. Secondly, the local temperature of the fuel during the transient is crucially important, since the fuel temperature should not exceed certain limits. In this Section, we discuss the variation of average fuel and moderator temperatures, as well as the coolant outlet temperature. Furthermore, the variation of local fuel temperature is discussed.

Figure 9.3 presents the average fuel, moderator and He outlet temperatures. As shown, the average fuel temperature increases by about 30 degrees during the transient. Figure 9.4 presents the difference between the average fuel, moderator and He outlet temperatures calculated by the RELAP5 and the Simulink models. As shown, during the transient, the differences in the average fuel, average moderator and He outlet temperatures are less than respectively 0.15%, 0.08% and 0.08%.
Figure 9.3 Variation of the average fuel, average moderator and He outlet temperatures during a FPRIT using the Simulink model.

With the Simulink model, we are able to calculate the fuel temperature locally. Figure 9.5 shows the variation of the core temperature at the third axial divisions of the coolant-hole. The seven curves in the figure represent the temperatures at the seven radial meshes of the corresponding axial division. The maximum fuel temperature during the transient is 1200.57 K and occurs at \( t=642.89 \) s (42.89 s after the beginning of transient).
Since the limitation on the fuel temperature is about 1600 K, even the temperature at the hottest spot is considerably lower than the maximum allowable temperature.

**Figure 9.4** Differences between average fuel, average moderator and He outlet temperatures calculated by the Simulink model and calculated by the RELAP5 model during a FPRIT
9.3.3 Variation of Reactor Reactivity

Figure 9.6 shows the variation of the core reactivity during the transient. During the first few seconds, when the core temperature does not change considerably, the reactivity change is mainly due to withdrawing the rod bank, which increases the reactivity. According to Figure 9.6, the average fuel temperature begins to change after a few seconds, which decreases the reactivity associated with the fuel. Although increases in the moderator and reflector temperatures also change the core reactivity, the change in the fuel temperature has the greatest impact (Figure 9.7). Therefore, after the first few
seconds of the transient, the core reactivity depends not only on the positive reactivity insertion due to rod bank withdrawal, but also the negative reactivity insertion due to fuel temperature increase. As a result, the rate at which the core reactivity grows begins to decrease.

**Figure 9.6** Variation of the reactor reactivity during transient using Simulink and RELAP5 models
An interesting observation is obtained, when we decrease the fuel heat capacity. By decreasing the fuel heat capacity, the fuel temperature rises faster and the fuel reactivity decreases faster. Thus, the total core reactivity begins to decrease even before reactor power reaches 150% of the full power.
9.4 CHAPTER CONCLUSION

The Simulink model presented in Chapter 8 was used to study the FPRIT of the GT-MHR and was validated against a RELAP5 model developed by General Atomics. The results of the Simulink and RELAP5 models are in close agreement. According to the results, in the event of a FPRIT, the average and local temperatures of the core are considerably below the corresponding temperature limits, if control rods are inserted into the core at 150% of full power. The Simulink code allows one to model a scram initiation time and to determine what powers (and correspondingly what average and local temperatures) would be achieved if a scram were initiated for a FPRIT from some setpoint with some setpoint error.
CHAPTER 10

GT-MHR START-UP REACTIVITY INSERTION TRANSIENT ANALYSIS

CHAPTER SUMMARY

In this Chapter, we describe the application of the Simulink code to the analysis of a series of Start-up Reactivity Insertion Transients (SURITs). The SURIT is considered to be a limiting protectable accident in terms of establishing the dynamic range of a SiC power monitor because of the low count rate of the detector during the start-up and absence of the reactivity feedback mechanism at the beginning of transient. The SURIT is initiated by withdrawing a rod bank when the reactor is cold (300 K) and sub-critical at the BOEC (Beginning of Equilibrium Cycle) condition. Various initial power levels have been considered corresponding to various degrees of sub-criticality and various source strengths. An envelope of response is determined to establish which initial powers correspond to the worst case SURIT.

10.1 INTRODUCTION

To evaluate the power monitoring requirements for the GT-MHR that are most demanding for a SiC diode power monitor, a Simulink program model of the GT-MHR core has been employed to study the transient behavior of this reactor. In this Chapter, the
Start-up Reactivity Insertion Transient (SURIT), which is considered as an essential accident scenario in determination of the detector response time, is discussed. The SURIT is simulated using the Simulink dynamic model of the reactor core and results of the simulation are presented.

The fast increase in the reactor power can potentially lead to two types of fuel failure by exceeding the maximum allowable local temperature or reaching the limitation on the rate of energy release from individual microsphere fuel particles. To detect the fast increase of the reactor power in case of accidents and consequently to trip the reactor, a number of reactor parameters are monitored during the reactor operation. Safety trips of the GT-MHR are the neutron flux to He mass flow ratio, primary coolant pressure, core inlet and outlet temperatures, and turbomachine speed. Among these safety trips, the neutron flux measurement is very fast and reliable [23] in order to capture the fast increments of reactor power. Although other monitoring parameters such as the coolant outlet temperature measurement are sufficiently reliable and provide information about the core condition, they respond with a significant delay [23]. Therefore, the neutron flux measurement is specifically important among the other reactor monitoring parameters. Due to significance of the neutron monitoring instrumentation in terms of the response time, the adequacy of the SiC neutron monitoring channel response time to rapid increment of the reactor power should be examined. Furthermore, identifying the acceptable response time of the power monitoring channel is a major step in specifying the dynamic range of the power monitoring system.

In order to establish a basis to study the sufficiency of the detector response time, the most demanding accident scenario for the neutron monitoring system response time
has to be identified. Accident scenarios such as accidental withdrawal of control rods, loss of poison material from the core, insertion of reactive material into the core, changes in geometrical core configuration, loss of coolant and blower failure and start-up accidents have been qualitatively studied for HTRs. Among those, the Start up Reactivity Insertion Transient (SURIT) is considered to be the most limiting protectable accident in terms of establishing the dynamic range of the SiC power monitoring system.

10.2 THE START UP REACTIVITY INSERTION TRANSIENT

In the analysis of the accidents occurring at power operation such as the RIA, it is important to find the worst conditions for which the accident can occur. The maximum temperatures reached during an accident and the rate of power increase varies considerably according to initial power. Therefore, the RIA has been studied at two power level extremes; the full power and the start up. In each case we have assumed that the maximum number of control rods which can be moved simultaneously are withdrawn at the maximum speed, and that their configuration is the one giving the maximum reactivity increase. The Full Power Reactivity Insertion Transient (FPRIT) simulation results were presented in Chapter 9. According to the simulation results, the average and local temperatures of the core are considerably below the corresponding temperature limits.

The typical start-up transient is a continuous insertion of reactivity resulting in too short a reactor period. The behavior of the GT-MHR for a SURIT is much different than its behavior for a reactivity insertion transient that is initiated from full power. Since the heat capacity of the reactor core is large, the core temperature generally increases slowly.
in response to a power increase. Moreover, heating of the core as a consequence of fissions is insignificant for reactor powers that are below the power range, since by definition the power range is defined as the range of powers for which fission heating of the core is significant. Therefore, temperature reactivity feedback becomes a significant mechanism for limiting core reactivity only after the reactor power enters the power range and only after a time delay that is due to the thermal capacitance of various elements of the core. Therefore, the rate of reactivity insertion is larger in the case of start-up reactivity insertion since the positive reactivity inserted due to the rod withdrawal is not being compensated by the temperature reactivity feedback. Consequently, although accidents at zero-power in a cold core seldom leads to dangerous temperatures, the rate of energy release in individual microsphere TRISO fuel particles (in GT-MHR) can be severely high because of the rapid power increase.

Besides the general concern with respect to the rate of power increase, the SURIT is a particularly challenging protectable accident for a SiC detector channel with the SiC detector located in the Reactor Core (RC) or in the Reactor Core Cooling System (RCCS) of the GT-MHR, if the SiC detector is operated in the pulse mode. The SURIT is challenging because the scram setpoint may have to be set at low values in order to protect the core, and because the count rate is low at low powers. This means that a long counting time may be required in order to count enough pulses for the power level to be established with good accuracy. The scram initiation time is the sum of the counting time and the time that it takes to unlock the control rod drive mechanisms and begin to drive the control rods into the core. We anticipate that the counting time greatly exceeds the time that it takes to unlock the control rod drive mechanisms and begin to drive the
control rods into the core. Therefore, in our analysis we assume that the scram initiation time equals the counting time. This counting time may be long for a SiC detector channel with the SiC detector located in the RC or in the RCCS of the GT-MHR. For the SURIT, the reactor power increases to the scram set point due to reactivity insertion due to control rod withdrawal. The rate of increase of the reactor power may be large as the reactor power enters the power range. The power of the reactor may increase greatly during the scram initiation time. In order to protect the core it may be necessary to sense and respond to a SURIT while the reactor power is low and initiate a rate cutback, if a sufficiently high rate of power increase is detected. This too may prove to be challenging due to low count rates and correspondingly poor statistics at low powers.

In conclusion, for the reasons stated above, we believe that the SURIT is a limiting protectable accident in terms of establishing the dynamic range of a SiC neutron monitoring system.

The SURIT is studied with the ultimate goal of identifying combinations of 1) reactor power scram setpoints and 2) “scram initiation times” (the time in which a scram must be initiated once the setpoint is exceeded) for which the GT-MHR core is protected in the event of a continuous withdrawal of a control rod bank from the core from low powers. This goal will be accomplished in future based on the results presented in this Chapter and the limitations on the rate of energy release from the fuel. In addition, we ultimately intend to identify the necessity of including a “rate cutback” (powered insertion of the control rods into the core that is based on a detected rapid rate of increase of reactor power) as an element of the GT-MHR reactor control and reactor protection systems.
10.3 SURIT MODEL ASSUMPTIONS AND INITIAL CONDITIONS

The SURIT that we have thus far modeled is initiated by withdrawing a rod bank, when the reactor is cold and sub-critical. We assume that the reactor is in the BOEC (Beginning of Equilibrium Cycle) condition. We assume that the temperature throughout the core is constant and equal to 300 K. The He inlet temperature is also set to 300 K. Table I shows the He characteristics for the SURIT analysis. We assumed that the He inlet parameters remain constant during the SURIT, since we are concerned about the short term transients. Also, similar simulations by the RELAP5 program [30], [31] that include the balance of the plant show that the inlet parameters change slightly during the transient and that the assumption of having constant He inlet parameters is acceptably accurate, when the transient is studied for a relatively short time after the transient.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>He inlet temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>He mass flow rate</td>
<td>16.86 kg/s</td>
</tr>
<tr>
<td>He pressure</td>
<td>0.2758 MPa</td>
</tr>
</tbody>
</table>

Table 10.1 He inlet characteristics during the SURIT

The SURIT simulation is initiated with the GT-MHR in a state in which Rod Bank Groups 1 and 2 are fully withdrawn from the core and the remaining rod bank groups are fully inserted. The SURIT simulation is initiated from this state by withdrawing Rod
Bank Group 3 at a rod withdrawal rate of 3 cm/s, which is specified by General Atomics as the maximum rod withdrawal speed. The rod banks’ worths at the BOEC are shown in the Table 10.2. It can be seen from this Table that Rod Bank Group 3 has the largest worth of any of the rod banks, and in this sense the SURIT that we have analyzed is a limiting case.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Reactivity (%)</th>
<th>Reactivity ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>2.9405</td>
<td>4.5251</td>
</tr>
<tr>
<td>Group 2</td>
<td>1.8718</td>
<td>2.8805</td>
</tr>
<tr>
<td>Group 3</td>
<td>3.0101</td>
<td>4.6322</td>
</tr>
<tr>
<td>Group 4</td>
<td>2.3113</td>
<td>3.5568</td>
</tr>
<tr>
<td>Group 5</td>
<td>0.9049</td>
<td>1.3925</td>
</tr>
<tr>
<td>Group 6</td>
<td>0.6870</td>
<td>1.0572</td>
</tr>
<tr>
<td>Group 7</td>
<td>0.6666</td>
<td>1.0258</td>
</tr>
<tr>
<td>Group 8</td>
<td>0.5607</td>
<td>0.8629</td>
</tr>
<tr>
<td>Group 9</td>
<td>0.6562</td>
<td>1.0098</td>
</tr>
<tr>
<td>Group 10</td>
<td>0.5825</td>
<td>0.8964</td>
</tr>
<tr>
<td>Group 11</td>
<td>0.8929</td>
<td>1.3741</td>
</tr>
<tr>
<td>Group 12</td>
<td>0.7439</td>
<td>1.1448</td>
</tr>
<tr>
<td>Group 13</td>
<td>0.5825</td>
<td>0.8964</td>
</tr>
<tr>
<td>Group 14</td>
<td>1.1235</td>
<td>1.7289</td>
</tr>
<tr>
<td>Group 15</td>
<td>0.8526</td>
<td>1.3121</td>
</tr>
<tr>
<td>Group 16</td>
<td>0.5232</td>
<td>0.8051</td>
</tr>
</tbody>
</table>

Table 10.2 Rod Bank Groups reactivity worth for the SURIT analysis (by General Atomics)
The initial reactivity worths of the fuel, moderator and reflector are shown in Table 10.3. Using Table 10.2 and Table 10.3, the initial reactivity of the core has been calculated. This value is important in establishing the sub-critical multiplication of the core and the relationship between the assumed value for the neutron source strength and the initial reactor power. For core temperatures of 300 K, using the data in Table 10.2 and Table 10.3, one can calculate that with Rod Bank Groups 1 and 2 fully withdrawn from the core and the remaining rod bank groups (except for Rod Bank 3) fully inserted the reactivity equals -3.7852 dollars, which corresponds to a numerical value for the reactivity of -2.46 %. This is the value of the reactivity, when the transient is started. The reactor becomes critical while the third rod bank is being withdrawn.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reactivity ($)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>12.2014</td>
<td>At 300 K</td>
</tr>
<tr>
<td>Moderator</td>
<td>1.7556</td>
<td>At 300 K</td>
</tr>
<tr>
<td>Reflector</td>
<td>-2.9786</td>
<td>At 300 K</td>
</tr>
<tr>
<td>Rod banks</td>
<td>-21.6951</td>
<td>Two banks fully withdrawn</td>
</tr>
<tr>
<td>Total initial reactivity</td>
<td>-3.7852</td>
<td></td>
</tr>
</tbody>
</table>

**Table 10.3** The core material reactivities at the beginning of the SURIT
As mentioned above, the SURIT scenario that has been simulated with Simulink assumes that the SURIT begins when the reactor is cold with a small initial fission power that is a consequence of a neutron source. The source strength is not based on specifications either for an external source or for a photoneutron source, per se. Rather it has been calculated based upon an initial fission power that has been specified by GA [30] and the initial core reactivity that is calculated in Table 10.3. Since the reactor is sub-critical, the external neutron source is related to the equilibrium fission power through the sub-critical multiplication of the core. The equilibrium fission power is assumed to equal $5.09 \times 10^{-7}$ W [30]. This value of the equilibrium fission power is presumably consistent with photoneutron production and the assumed value of the decay power $4.7 \times 10^5$ W that has been provided to us by GA [30]. As an aside, the value of the decay power is assumed to be constant and equal to $4.7 \times 10^5$ W throughout the transient.

Details regarding the calculation of the neutron source strength are provided earlier in Section 8.6.2. As mentioned above, we assume that there is a photo-fission source, and that the magnitude of the photo-fission source corresponds to a fission power of $5.09 \times 10^{-7}$ W, which was specified by GA. The relation between the photo-fission source strength and the initial fission power is determined by the reactor sub-critical multiplication, which is discussed below. At this point, we state only that the initial fission power is very small compared to the decay heat power (the power that is deposited in the core as a consequence of the decay of fission products), because only gamma rays with an energy that exceeds the photo-fission threshold can possibly create a neutron in a photo-fission event. The reactor power is the sum of the fission power and the decay heat power.
The initial fission power is zero in our simulation, despite the fact that the transient is begun with a fission power that is consistent with the photo-neutron source strength. The resolution of this seeming paradox is that the simulation is run until the equilibrium is established, and then the control rod withdrawal is begun from this equilibrium condition. The neutron source strength initially, and throughout the simulation, is \( S=3.13 \times 10^{-5} \text{ W.s}^{-1} \) (Equation 8.14), which is consistent with the fission power of \( 5.09 \times 10^{-7} \text{ W} \), as discussed above. The fission power is allowed to establish equilibrium, based on sub-critical multiplication, as embodied in the reactor kinetic equations, before the control rod withdrawal is initiated. The fission power reaches the equilibrium fission power after a few times 55 seconds, the half-life of the longest-lived delayed neutron precursor. However, the longest lived delayed neutron precursor group produces only a small fraction (\( \beta_i/\beta=0.00027 \)) of the total delayed fission neutrons, and hence the transient has been started (i.e. the control movement has been initiated) at \( t=100 \text{ s} \) for convenience, since the reactor power is nearly in equilibrium with the neutron source strength at this time. The approach that is described above has been adopted so that the Simulink model has an opportunity to calculate a consistent set of delayed neutron precursor concentrations, before the SURIT is initiated. This approach simplifies the input to the code, and thereby increases the integrity of the calculations.

10.4 RESULTS OF SURIT SIMULATION

As described above, the simulation was started with zero initial fission power, but with \( S=3.13 \times 10^{-5} \text{ W.s}^{-1} \). The simulation was run for 100 s before control rod movement was initiated. By this time, the fission power is close to the equilibrium fission power.
Therefore, the withdrawal of Rod Bank Group 3 was initiated at t=100 s. In this Section, a number of reactor core parameters such as power, reactivity, and temperature during the SURIT are presented.

Figure 10.1 and Figure 10.2 show traces of the reactor power during the transient. Despite the rapid increase in power that results as a consequence of the rod bank withdrawal, Rod Bank Group 3 becomes fully withdrawn before the fission power reaches the trip point. Therefore, the reactivity insertion is discontinued as a consequence of the rod bank reaching its mechanical limit, before the reactor power reaches the trip point. For this reason, the SURIT that we have analyzed may not be the most limiting case, for the case of the withdrawal of a single rod bank. It may be that a SURIT that is initiated from a higher power level may be more limiting, which will be studied in the next Section.
Figure 10.1 Variation of the reactor power during the SURIT with an external neutron source of $S=3.13 \times 10^{-5} \text{ W.s}^{-1}$.
The maximum reactor power in this case is 313 MW. Therefore, the reactor power does not increase to 900 MW, the reactor set point that provides protection to the core for a reactivity insertion from full power. Although the reactor power doesn’t reach the scram setpoint during the course of the SURIT, the rate of reactor power increase is large. Further studies need to be conducted in order to specify the limitation on the rate of energy release from the fuel particles.
Figure 10.3 shows the trace of the total reactivity of the core versus time. At the moment that the insertion of positive reactivity into the core is stopped, as a consequence of the rod bank reaching its mechanical limit, the rate of increase of reactor power decreases, due to heating of the core and the negative reactivity that is inserted into the core as a consequence of negative reactivity feedback.

![Figure 10.3 Variation of the total reactor reactivity during SURIT with an external neutron source of S=3.13x10^{-5} W.s^{-1}](image-url)
The reactor average fuel, moderator and reflector temperatures are shown in Figure 10.4. Compared to variation of the reactor power and reactivity, the variation of the fuel temperature is not large. In addition, the maximum allowable fuel temperature is well beyond the maximum temperature of the fuel during SURIT.

**Figure 10.4** Variation of the average fuel, moderator and reflector temperatures during the SURIT with an external neutron source of $S=3.13 \times 10^{-5}$ W.s$^{-1}$.
The temperature distribution throughout the He channel is presented in Figure 10.5. The nodes are listed in increasing numerical order from the core inlet to the core outlet. Therefore, the He outlet temperature, which is used as one the reactor safety trips, is labeled as “Row 5” in Figure 5. As shown, the He outlet temperature has increased by 80 degrees after more than 1000 s from the beginning of transient, while the reactor power has increased by several orders of magnitude in less than a few seconds. The slow response time of the He temperature implies the importance of the neutron flux measurement in order to monitor the fast transients.

Figure 10.5 Temperatures of the He channel’s nodes during SURIT with an external neutron source of $S=3.13 \times 10^{-5}$ W.s⁻¹
In conclusion, for the SURIT that was analyzed, the reactor fission power never reaches the FPRIT trip point of 900 MW. It was assumed in these simulations that Rod Bank Group 3 was withdrawn from the core continuously at the maximum withdrawal rate until the rod bank group reached its mechanical stop. Rod Bank Group 3 is located within the inner reflector and has the highest reactivity of any rod bank group. Because Rod Bank Group 3 reached its mechanical limit, before the reactor power reached the FPRIT trip point of 900 MW, it is not clear that we have analyzed the worst case. It may be that a SURIT that is initiated from a higher power level may be more limiting. In addition, it should be noted that reactor protection is not assured for the SURIT, simply because reactor power is restricted in the transient to values below those associated with the scram setpoint for the FPRIT. Most importantly, the rapid rate of increase of reactor power during the SURIT may induce thermal stresses in the fuel that are unacceptably large.

10.4.1 Effect of the Neutron Source Strength on the SURIT

In the previous Section, the SURIT was examined when we used an arbitrarily small neutron strength that is equivalent to the reactor operating with a fission power of $5.09 \times 10^7$ W. Although the reactor power didn’t reach the scram set point of 900 MW during the SURIT with the neutron source that we used, we considered the possibility that reactor power reaches the set point (or peak at a higher level), if a different neutron source were used in the calculation. Therefore, a SURIT that is initiated from a higher power level may be more limiting. For this reason, in this Section, we describe the
application of the Simulink code to the analysis of a series of SURITs, for which the initial power is varied. An envelope of response is determined to establish which initial powers correspond to the worst case SURIT.

In this Section, the analysis of the SURIT for the GT-MHR, for SURITs that are initiated with the GT-MHR in a state in which: 1) Rod Bank Groups 1 and 2 are fully withdrawn from the core, 2) The remaining rod bank groups are fully inserted, 3) The reactor is cold (300 K) and sub-critical at the BOEC (Beginning of Equilibrium Cycle) condition and 4) The neutron sources range from $10^{-3}$ W.s$^{-1}$ to $10^7$ W.s$^{-1}$. For these conditions, Rod Bank Group 3 (the rod bank with the largest worth of any of the rod banks) is withdrawn at the maximum rod withdrawal speed.

\[\begin{array}{c}
10^{-3} \\
10^{-1} \\
10^{1} \\
10^{3} \\
10^{5} \\
10^{7}
\end{array}\]

Figure 10.6 Variation of the reactor power during the SURIT using different neutron source strengths with a linear scale for power
Figure 10.6 shows variation of the reactor power during the SURIT using different neutron source strengths. In addition, the reactor power during the SURIT is shown on a logarithmic scale in Figure 10.7. Neutron sources of strength $10^{-3}$, $10^{-1}$, 10, $10^3$, $10^5$, and $10^7$ W.s$^{-1}$ are examined. As we increase the neutron source strength, we expect that the reactor power increases more rapidly (on an absolute scale), since at the beginning of the transient the reactivity is equal for all cases and larger neutron sources will lead to a faster growth in the absolute (as opposed to the fractional) reactor power.

**Figure 10.7** Variation of the reactor power during the SURIT using different neutron sources’ strengths that is shown in the logarithmic scale
It can be seen in Figure 10.6 and Figure 10.7 that although the reactor power is larger at the beginning of transient when a large neutron source is used, the smallest neutron source leads to the largest power peak. This behavior can be explained when we consider the variation of the reactor reactivity, which is shown in Figure 10.8, with time.

**Figure 10.8** Variation of the reactor reactivity during the SURIT using different neutron sources’ strengths
The trace of reactivity versus time is almost identical for all neutron sources for reactor powers below the power range (below ~ 1% power). When the reactor power is below the power range heating is negligible and the change in the reactivity with time is only due to rod withdrawal. Therefore, as seen in Figure 10.8, the reactivity is equal for all cases up to t=350 s. At this time, the core temperature begins to increase, in the case of using large neutron sources, since the reactor power has increased to ~ 1% power by this time. For the smaller neutron source strengths, the reactor enters the power range later and hence with a greater positive reactivity having been inserted into the core, as a consequence of control rod motion. Thus, for the smaller neutron source strengths, reactor power peaks at larger values, before negative fuel and moderator temperature reactivity feedback (which is roughly proportional to the time integral of reactor power for these fast transients) compensates for the positive reactivity of the control rods, and reactor power turns over. According to Figure 10.6 and Figure 10.7 the rate of power increase becomes larger when a smaller neutron source is used. Therefore, a small neutron source models a conservative scenario both in terms of the power peak and rate of power increase.

Figure 10.9 shows the average fuel and moderator temperatures, when the SURIT is modeled using various neutron source strengths. Similar to the reactor power, the peak temperature and the rate of temperature increase is higher as a smaller neutron source is used.
To study the power monitoring requirements for the GT-MHR that are most demanding for a SiC Schottky diode power monitor, (namely the protection of the SURIT), we developed a Simulink model to study the transient behavior of the GT-MHR. In this Chapter, we described the application of the Simulink code to the analysis of the start-up reactivity insertion transient for the GT-MHR. If in the cold and subcritical reactor and in the presence of a small neutron source (with an external neutron source of \( S=3.13\times10^{-5} \text{ W.s}^{-1} \) ), the rod bank with the largest worth of any of the rod banks is
withdrawn at the maximum rod withdrawal speed, then the maximum reactor power in this case is 313 MW; i.e., the reactor fission power never reaches the FPRIT trip point of 900 MW. In addition, it should be noted that reactor protection is not assured for the SURIT, simply because reactor power is restricted in the transient to values below those associated with the scram setpoint for the FPRIT. The rapid rate of increase of reactor power during the SURIT may induce thermal stresses in the fuel that are unacceptably large. Additional research is necessary to resolve this issue.

Furthermore, we described the application of the Simulink code to the analysis of a series of SURITs, for which the initial power is varied. An envelope of response was determined to establish which initial powers correspond to the worst case SURIT. In conclusion, we found that using a small neutron source strength models the SURIT conservatively, since it results in the highest peak power and highest rate of power increase.
CHAPTER 11

DISCUSSION

11.1 INTRODUCTION

Thus far, we have described, in the first seven Chapters, the development, modeling, and testing of the high speed neutron flux monitoring channel. In Chapters 8 to 10, we presented a dynamic model of the GT-MHR along with the analysis of two reactivity insertion transients. In this Chapter, we summarize our discussion by evaluating the performance of the developed neutron-monitoring channel, when it is employed to monitor the GT-MHR neutron flux. This discussion ties together the SiC monitoring channel performance, which is presented in the first part of the dissertation, with the specific requirements of the GT-MHR in terms of neutron flux monitoring, which was partly presented in the second part of the dissertation.

The SiC detector configuration was developed and mathematically analyzed in Chapter 2. A high-speed electronic channel was designed and modeled in Chapters 3, 4 and 5. In Chapters 6 and 7, the channel was built based on the design presented earlier and tested under various conditions to assess the channel performance. In the previous Chapters, the channel performance has been studied, independent of the reactor characteristics. In fact, operation of the designed monitoring channel is strongly
influenced by the type of the reactor, in which the channel is used. We focus our study on four characteristics of the monitoring channel, which more-or-less depend on the type of the reactor. These characteristics are listed as follows:

1) Linear response of the detector channel to variation of the reactor power,
2) Detector lifetime that should be more than a reactor refueling cycle
3) Channel response time that should ensure an adequately fast generation of a reactor trip signal in the case of an accident
4) Channel dynamic range that should extend over several decades of reactor power so that the entire power range can be covered with a reasonable number of monitoring systems.

Figure 11.1 shows the relation between different parameters, which are essential in the development of a monitoring channel. In this Chapter, we discuss the interconnections between the operation of the monitoring channel and the reactor characteristics based on our results from previous Chapters and discussions provided by other researchers.

In Section 11.2, we discuss the linearity of the detector. In Section 11.3, we calculate the dynamic range of the monitoring channel, when it is applied to the GT-MHR. The detector lifetime will be studied in Section 11.4. In Section 11.5, we discuss the adequacy of the channel response time to GT-MHR transients. In Section 11.6, we explain some advantages of the voltage sensitive system in comparison to the charge
sensitive system, when the SiC detector is used to monitor the GT-MHR power. Finally, in Section 11.6, we summarize our discussions in this Chapter.
11.2 LINEARITY OF THE DETECTOR RESPONSE

The linearity of the detector response to both fast and thermal neutron fluxes was examined in Chapter 7. As we will discuss in the next Sections, we consider using the detector in both fast and thermal neutron flux fields in the GT-MHR. As shown in Figure 11.1, the linearity of the channel is mainly specified by the design of the detector channel. The discrimination level has been set high enough so that the gamma ray induced pulses will not be counted. Therefore, the channel responds linearly to the reactor power. However, there are two exceptions to the detector linearity. Firstly, as shown in Figure 7.25, in a thermal neutron flux, the detector count rate is higher at the beginning of the experiment. A short time constant damage phenomenon [38] causes nonlinearity in the response at the beginning of the experiment. Secondly, in a fast neutron field, the detector is damaged, if the detector is exposed to a high level of fast neutrons (Section 7.6). Therefore, using the detector in an elevated fast neutron flux is not practical, at least at the room temperature. Other studies indicate that the detector lifetime increases at higher temperatures.

11.3 CHANNEL DYNAMIC RANGE

The dynamic range of the monitoring channel is an important parameter in the development of the monitoring channel, since it specifies the number of monitoring systems that are required to monitor the entire power range. The dynamic range of the
channel is defined such that the channel monitors the power with an acceptable accuracy and adequate response time, within the designated power range. Since the SiC neutron-monitoring detector operates in the pulse mode, the accuracy of the channel is specified by the count rate of the detector. As the channel count rate at full power increases, the dynamic range of the channel increases in proportion to the square root of the count rate, since the count rate at the low power end of the dynamic range increases proportionately with the channel count rate at full power and since the fractional accuracy of the channel is proportional to the reciprocal of the square root of the count rate.

As shown in Figure 11.1, the dynamic range of the channel depends on the detector location in the GT-MHR and the design of the monitoring channel. Disregarding the detector location in the reactor, the dynamic range of the monitoring channel is limited by the speed of the channel electronics. This limitation was explicitly discussed in Chapters 3 and 4. As shown, in our voltage sensitive system, the discriminator dead time limits the electronic count rate of the channel, for which the channel operates with acceptable precision. The maximum electronic count rate is determined by the discriminator dead time and requirements for acceptable channel precision.

From a more general perspective, considering the detector location in the reactor, the maximum count rate of the channel is specified by the speed of the electronic channel, the detector configuration and the neutron flux at the detector location. To distinguish between the case when the maximum count rate of the channel is specified by the detector configuration and the neutron flux at the detector location, as opposed to the case when the maximum count rate of the channel is specified by the speed of the
electronic channel, we distinguish between the physical maximum count rate and the electronic maximum count rate. The electronic maximum count rate has been discussed above. It is specified by the speed of the electronic channel. On the other hand, the physical count rate of the detector is limited by the detector configuration (the detector’s sensitivity per unit fluence) and the neutron flux at the detector. In the case that the detector physical maximum count rate is less that the detector maximum electronic count rate, the channel operates at count rates that are less than its electronic count rate. Because the individual SiC diodes are very small, their sensitivity to neutron flux is small, and consequently the possibility that the detector physical maximum count rate is less that the detector maximum electronic count rate is a real possibility. For this reason, the design of the monitoring channel is coupled to the specific type of the reactor that is being considered.

We have considered two locations to place the detector in the GT-MHR: 1) in the central reflector and 2) in the Reactor Cavity. In the following discussion, we distinguish between the detector sensitivity per unit neutron fluence (with units of counts per n/cm²), which is an intrinsic property of the detector, apart from the dependence of this sensitivity upon the neutron energy spectrum; and the detector sensitivity per unit power (with units of counts per MW), which depends upon the placement of the detector within the reactor.
11.3.1 Inside Reflector

The neutron flux inside the central reflector of the GT-MHR at full power has been calculated [39]. Based on the calculated neutron flux, the count rate of the detector channel has been calculated, when our specific design of the detector is used [39] (Package 1). As an example, the average count rates of the monitoring channel at full power at $R=117$ cm and $R=153$ cm from the center of the core are $C_1=5.89\times10^5$ cps and $C_2=1.21\times10^6$ cps (Table 11.1). Although the neutron flux inside the central reflector is very large, the channel physical count rate is significantly smaller than the channel maximum electronic count rate, due to the small size and correspondingly small sensitivity of the individual diode detectors to neutron flux. The neutron flux is its largest in the central reflector of detector locations that we have considered. Therefore, if we want to increase the detector count rate we need to change the detector physical count rate (i.e. the detector configuration), a topic which is discussed in Section 11.3.3.

11.3.2 Reactor Cavity

The physical count rate of the detector in the reactor cavity is $2.89\times10^2$ cps [39]. This small physical count rate results in a large uncertainty even at the full power for counting times that are on the order of seconds.
<table>
<thead>
<tr>
<th>R=117 cm</th>
<th>Total Count Rate</th>
<th>Triton Count Rate</th>
<th>Detector Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.89x10^5</td>
<td>5.78x10^5</td>
<td>39 days</td>
</tr>
<tr>
<td>R=153 cm</td>
<td>1.21x10^6</td>
<td>6.39x10^5</td>
<td>35 days</td>
</tr>
</tbody>
</table>

Table 11.1 Channel count rate and lifetime in the central reflector

11.3.3 Increasing The Detector Sensitivity To Fluence

A number of parameters in the detector configuration can be changed to increase the detector physical count rate. These parameters are: 1) the detector diameter, 2) detector thickness, and 3) the LiF radiator thickness. In this Section, we discuss the effect of variation of each parameter.

11.3.3.1 Increasing the Detector Diameter

Increasing the detector diameter increases the count rate by both increasing the fast neutron recoil count rate and increasing the number of tritons passing through the detector in proportion to the increase in detector area. Although increasing the detector diameter is practical in terms of increasing the sensitivity, the detector diameter imposes serious restrictions on the bandwidth of the system. Simulations in Chapter 4 show that the if the detector diameter is more than 500 microns, the overall bandwidth of the detector-cable system is less than 1 GHz. Considering the bandwidth of the voltage sensitive preamplifier, the overall bandwidth of the system becomes less than 500 MHz.
This bandwidth limits the acceptable electronic count rate of the channel by increasing the dead time. Therefore, if we increase the detector diameter on one hand to increase the detector physical count rate, on the other hand we increase the channel dead time, and thereby decrease the detector electronic count rate. The selected detector diameter of 500 micron is the maximum acceptable diameter that enables the monitoring channel to record with electronic count rates of greater than $10^6$ cps with a reasonable dead time.

11.3.3.2 Increasing the Detector Thickness

Another way to increase the detector sensitivity to fluence is to increase the detector thickness. By increasing the detector thickness, we increase the detector volume. Consequently, for the same fast neutron interaction rate per unit volume, the rate of fast neutron interactions within the detector volume increases linearly with increasing detector thickness due to the change of the detector volume. On the other hand, the triton interaction rate within the detector active volume is not a function of detector thickness. Although the triton interaction rate is not affected, the tritons deposit more of their energies, when they pass through larger detector thicknesses, up to the point at which the detector thickness is larger than the range of tritons in SiC. Therefore changing the detector thickness affects the detector sensitivity only by changing the fast neutron interaction rate within the detector volume. As mentioned above, the fast neutron count rate changes linearly with respect to the detector thickness. For example by doubling the detector thickness at R=157 cm, the overall count rate increases by less than 25% (since the fast neutron count rate is less than 50% of the overall count rate) and at R=117 cm the count rate increases negligibly, since the fast neutron count rate is not dominant.
11.3.3.3 Increasing the LiF Thickness

Finally, the LiF thickness is used to control the detector sensitivity to neutron fluence. Since the LiF radiator emits tritons as it absorbs thermal neutrons, variation of the LiF thickness does not affect the fast neutron count rate. On the other hand, the LiF thickness is an essential parameter in specifying the triton production rate, and consequently the detector sensitivity to neutron fluence. Various radiator thicknesses have been used in the proposed IRIS neutron monitoring system, developed by WEC, to change the detector sensitivity to neutron fluence [6]. Although the detector sensitivity to neutron fluence can be increased from the LiF thickness that we have used in our calculations (1µm), there are two issues associated with increasing the LiF thickness. Firstly, increasing the LiF thickness does not change the sensitivity linearly, and after a point, the detector sensitivity remains constant as the LiF thickness is increased. Increasing the LiF thickness, eventually results in absorption of the tritons that are born in the outermost radiator layers by the radiator itself. This effect is not important when the radiator thickness is far less than the triton range. Besides absorption of tritons, increasing the radiator thickness decreases the geometric efficiency of the detector configuration. Therefore, although the triton production rate in the radiator is a linear function of the radiator thickness, the detector sensitivity to neutron fluence is not a linear function of radiator thickness, because of geometric efficiency changes, at small radiator thicknesses, and self-absorption at large radiator thicknesses.
Another important consequence of increasing the radiator thickness is that the pulse height spectrum of the tritons as they penetrate the detector is widened. The spectrum is widened because tritons lose more energy in the radiator layer as the layer thickness is increased. As a result, although increasing the radiator layer may increase the net count rate of tritons detected by the detector, the pulse height spectrum is expanded toward the low energy region of the spectrum and might be filtered by the discriminator.

To summarize our discussion, increasing the LiF radiator layer thickness increases the triton production rate and consequently increases the triton count rate. However, the increase of the count rate is limited. Numerically, if the thickness of the LiF radiator layer is increased from 1 micron to 20 micron (the range of triton particles in the LiF layer), the triton count rate increases by a factor of ten at the most. If the triton count rate is not a significant portion of the detector overall count rate, the effect of increasing the radiator thickness is less significant.

11.3.4 Calculation Of The Dynamic Range

MCNP5, TRIM and MATLAB simulations show that, with a voltage sensitive preamplifier, the detector is able to count tritons at an electronic count rate of approximately $4 \times 10^7$ cps with less than 10% count loss. This high electronic count rate allows the neutron flux to be monitored effectively over a wide dynamic range, with the width of the dynamic range being limited by the required accuracy of the monitoring system on the low count rate end of the dynamic range. Due to capability of the power monitoring system to operate at electronic count rates as high as $4 \times 10^7$ cps, the dynamic
range of the flux monitoring channel is large. For example, with account rate as high as 4x10⁷ cps at full power, even if the dynamic range covers five orders of magnitude, the flux monitoring channel operates with better than 5% accuracy, throughout the entire dynamic range, assuming a detector counting time of one second. Consequently, the neutron flux can be monitored from 10⁻³ % to 100% of full power with an acceptable precision. The following figure shows the accuracy of the monitoring channel over dynamic ranges from 10⁻⁴ % to 100% power. At high power, the accuracy of the channel is restricted by the count loss due to the discrimination dead time and at low power, the accuracy is limited by statistical error, because of the low count rate. As mentioned above, in our calculations, we assumed that the detector counting interval is one second. If the detector needs to respond faster, the counting statistics at low power becomes less accurate (Section 11.5) and for equal accuracy at low powers, the dynamic range of the channel decreases in proportion to the reciprocal of the square root of the counting time. Therefore, the required response time of the monitoring system must be specified to obtain the accuracy of the monitoring system and its dynamic range.
In addition to the statistical error and the error due to the discriminator dead time, $^6$Li burn up may cause an error in the precision of the detector channel at the end of the reactor cycle.

As mentioned above, although the electronic channel is able to process counts at an electronic count rate of $4 \times 10^7$ counts/s; based on our MCNP simulations, the maximum achievable physical count rate is less than $4 \times 10^7$ counts/s, due to limitations on
the detector sensitivity per unit power. We are investigating other GT-MHR in-core locations to improve the detector sensitivity per unit power in order to achieve the maximum count rate that can be processed by the detector electronic channel. A detector physical count rate of $8.7 \times 10^5$ (Table 11.1) at full power limits the dynamic range to about four orders of magnitude, as shown in the above figure, assuming a counting time of 1 second and that the acceptable limit on accuracy at low powers is 5%.

At R=117 cm, the physical count rate at full power is about $5.78 \times 10^5$ cps. If the power range is expanded down to 0.1% of full power, the physical count rate at this power is about $5 \times 10^2$ cps, which results in power being monitored with better than 5% accuracy for a counting time of 1 second. To improve the detector sensitivity per unit power for the detector at this location we must increase the detector sensitivity per unit fluence. As discussed previously, the detector sensitivity per unit power can be increased in three ways. Increasing the detector thickness, which is not effective, since the neutron flux is dominated by thermal neutrons. Increasing the detector diameter, which is not an option either, because the detector capacitance degrades the pulse resolution of the channel by increasing the pulse width. Finally, increasing the LiF thickness, which can improve the thermal neutron count rate by a factor of ten, at most.

At R=153 cm, the sensitivity per unit fluence is controlled by two parameters, the detector and the radiator thicknesses. At this location, it is possible to reach the maximum electronic count rate of the channel, which is about $5 \times 10^7$ cps.

In the reactor cavity, increasing the detector thickness is not effective as a means of increasing the detector sensitivity per unit fluence, because the fluence is not very
energetic. Since the detector operates at a very low count rate, increasing the detector diameter (or connecting the detectors in parallel) will not increase the dead time significantly, even though the width of individual pulses is increased. However, even if the detector area is increased by a factor of ten, the detector count rate is less than 3000 cps. The low physical count rate in the reactor cavity decreases the dynamic range drastically.

11.4 THE DETECTOR LIFETIME

The SiC detector lifetime is a crucial parameter in selection of the detector location. The SiC detector is radiation hard and operates at higher temperatures, when compared to other types of semiconductor detectors, such as Si detectors. However, the radiation resistance of the detector might not be sufficiently high to withstand the neutron fluxes for at least a reactor cycle. The radiation resistance of the SiC has been addressed in numerous publications [41], [42] and is being studied closely at the Ohio State University. The SiC detector operates after exposure to triton fluence of $1.1 \times 10^{15}$ cm$^{-2}$ [43] and the fast neutron fluence of $1.7 \times 10^{17}$ cm$^{-2}$ (E > 1MeV) [43]. Using these numbers, we estimate the detector count rate in the inside reflector only based on the damage from tritons. As shown in Table 11.1, the detector operates for about a month in the central reflector, assuming only tritons damage the detector. Considering the fast neutron damage decreases the estimate of the detector lifetime even more. On the other hand, the detector lifetime in the reactor cavity is several years. Here we see the trade off between the detector dynamic range and the detector lifetime.
11.5 RESPONSE TIME OF THE MONITORING CHANNEL

Thus far, we discussed how the monitoring channel fits into the GT-MHR in terms of the maximum achievable electronic and physical count rates, the detector dynamic range, and the detector damage, as a function of different reactor locations. The low count rate of the detector at low powers limits the dynamic range. The manner in which the dynamic range at low powers is limited by low count rates is a critical issue that we address here in more detail as we discuss how fast the channel must respond and scram the reactor in the case of accidental transients in order to protect the reactor. The answer to this question depends on two parameters as shown in Figure 11.1:

1) The variation of the reactor power and temperature during the transients: If the derivative with respect to time of the reactor power and the reactor temperature during transient scenarios is large, then the reactor instrumentation has to detect the accident and respond quickly to avoid reaching the failure temperature of the fuel. If the derivative with respect to time of the power and temperature is not large, the speed of the monitoring channel response is not critical. The Simulink model presented in previous Chapters allows us to determine the necessity of a fast response of the channel by simulating different transient scenarios. As discussed, in both FPRIT and SURIT transients, the reactor does not reach the maximum fuel temperature, even if we do not scram the reactor. The large heat capacity of the fuel and moderator slows down the derivative with respect to time of the temperature, which allows more time to respond to reactor transients.
2) Electronic channel design: when the reactor power reaches the scram set point, the statistical error of the channel count rate may delay the initiation of a scram signal. As the statistical error increases (due to the low count rate of the channel), the possible delay time in initiating the trip signal increases. For example, consider the following situation:

In the SURIT, we would like to scram the reactor when the reactor power reaches 1% (this number is subject to change, we are just making an example) of the full power. There are delays in initiating a scram and delays in scram actuation. In this analysis, we consider only the delay is scram initiation. It is assumed, as before that the counting time is 1 second. If the detector is located in the reactor cavity and we put 10 detectors in parallel to increase the count rate, then at 1% of full power, the channel count rate is 28.9 cps. If one assumes that a scram signal is not sent until the counts exceed the scram setpoint value by $3\sigma$, then the channel will not send the trip signal unless the count rate is 45 cps. Since 45 cps corresponds to 1.5 % of full power, it is clear that counting statistics may result in a delay in the initiation of a scram signal, beyond the presumed 1 second counting time. The exact length of the delay depends upon the rate of increase of reactor power and the time that it takes reactor power to increase from 1% to 1.5% of full power.

If we repeat the analysis assuming that the detector count rate is $1.21\times10^6$ cps (R=153 cm) at full power, then the reactor will trip at $1.21\times10^4+110$, which corresponds to 1.0091% of the full power. Therefore, the higher count rate improves the response time by changing the initiation of the scram from 1.5 % of the full power to 1.0091% of the full power.
ADVANTAGES OF USING THE VOLTAGE SENSITIVE PREAMPLIFIER

Using the voltage sensitive system is more advantageous than using the charge sensitive system to monitor the GT-MHR neutron flux. We compare these two systems at two reactor locations: In core and ex-core.

11.6.1 Inside Reflector

The count rate of the detector in the GT-MHR central reflector is $5 \times 10^5$ cps. This count rate is typically too high for a charge sensitive system to process. However, as shown in Figure 11.2, the voltage sensitive system operates with a very small fraction of lost counts at this count rate.

The in-core position of the detector imposes additional performance criteria, which can only be delivered by the voltage sensitive system. Since the detector operates in a high-temperature high-radiation environment in the central reflector, a long length of the MI cable has to be used to transmit the detector signal. The high capacitance of the cable makes the charge sensitive system impractical for this application. However, as shown in Chapter 5, the voltage sensitive system can still operate without a significant degradation in the channel performance.

11.6.2 Reactor Cavity

The current design of the SiC detector yields a very low count rate outside of the core in the reactor cavity. Therefore, a number of SiC detectors have to be connected in
parallel, or the SiC diameter has to be increased, to increase the channel count rate by a several orders of magnitude. Both changes increase the detector capacitance. Our analysis in Chapter 5 showed that the detector capacitance has a great impact on the overall performance of the channel, even if a short length of cable is used. Therefore, using the charge sensitive system is not possible. On the other hand, although the voltage sensitive system, with this large capacitance, will not be able to operate at very high count rates, it will be able to handle the count rates on the order of thousands of counts per second that would be required of a detector in this location.

The main advantage of the charge sensitive system is the ability of this channel to record the spectrum efficiently, because of the built-in MCA in this channel. On the other hand, the spectroscopy is cumbersome with the voltage sensitive system. Since all that we care to do is to establish a channel count rate that is linear with the reactor power, spectroscopy is not necessary for our flux-monitoring channel.

11.7 CHAPTER CONCLUSION

In this Chapter, we summarized our discussion by evaluating the performance of the developed neutron-monitoring channel, when it was employed to monitor the GT-MHR neutron flux. The linearity of the detector count rate to the reactor power, and the power monitoring channel dynamic range was studied at two reactor location: in the central reflector and in the Reactor Cavity. As discussed, the dynamic range of the monitoring system covers about four decades of the reactor power, when the detector is located in the central reflector. However, the detector lifetime in the central reflector is
less than the reactor refueling cycle. On the other hand, the detector lifetime considerably increases, when the detector is located in the Reactor Cavity. In this case, the dynamic range of the channel is limited in the Reactor Cavity.

Channel response time that should ensure an adequately fast generation of a reactor trip signal in the case of an accident was discussed. Based on the FPRIT and SURIT, a fast response of the monitoring channel is not required for these transients.
CHAPTER 12
SUMMARY AND CONCLUSION

In this dissertation, a mathematical model of the SiC detector and its processing channel has been introduced and presented. Simulation techniques using TRIM and MATLAB can be useful tools for designing detector channels. We have used TRIM and MATLAB to model the detector current output pulse for SiC semiconductor detectors as power monitors for the GT-MHR reactor. Pulse propagation through the detector channel can be simulated in order to optimize the detector characteristics with respect to speed and resolution. We have developed a model of the rest of the detector channel with a MATLAB code.

Simulations show that an electronic channel that is based on a voltage sensitive preamplifier is able to monitor the neutron flux with count rates on the order $10^8$ counts/s with less than 25% count loss. With a voltage sensitive preamplifier, of the type that we have specified, the speed of the channel is limited by the discriminator dead time. Similar simulations show that with a charge sensitive preamplifier, the fraction of the counts that are lost increases drastically. Thus, to design a fast counting system, we described a counting system based on the use of a voltage sensitive preamplifier.
We simulated an electronic channel that is based on a voltage sensitive preamplifier system, where the preamplifiers are cascaded. Based on the simulated pulse height spectrum of the preamplifier output voltage, it has been concluded that using three cascaded preamplifiers suits the discriminator requirements with respect to the discriminator input voltage. In addition, after three stages of amplification the pulse rise time and pulse width are less than the discriminator dead time.

The detector-cable model has been introduced to investigate the effect of the detector and cable electrical and physical characteristics on the output signal of the detector at the preamplifier input. The system response has been presented both in the time and frequency domains. As discussed, although the very high frequency components of the detector output signal are attenuated and distorted in the detector-cable system, the overall system performance is acceptable. Since the simulated system bandwidth is broader than that of the subsequent component in the channel, which is the preamplifier, the detector-cable system does not contribute significantly to signal distortion compared to the preamplifier.

Testing the processing channel without radiation has been described in Chapter 6. The performance of the MI cable has been observed. Although the MI cable has a relatively large resistance and capacitance, it does not attenuate and distort the fast pulses drastically. In the next step, the bandwidth of the system has been measured. The upper cut off frequency of the system is shifted towards frequencies close to 400 MHz, when we include the effect of the cable and the oscilloscope.
In Chapter 7, the preamplifier output voltage has been measured. The rise time of the preamplifier output voltage is between 500 ps and 700 ps, and the pulse width is about 1.5 ns. The pulse shape of the preamplifier output voltage found experimentally matches the pulse shape calculated from simulations. Furthermore, the voltage sensitive system setting has been presented. The linearity of the detector in both thermal and fast neutron fluxes has been presented. Based on the pulse height spectrum of the neutron flux, we have set the discrimination level at 40 mV to separate gamma ray induced pulses from pulses induced by neutrons. The energy to discrimination level correspondence for the voltage sensitive system is calculated as 4.585 keV/mV. Since we set the discrimination level to 40 mV, the channel is able to count incident particles that deposit more than 183.4 keV in the detector. The degradation of the detector in a fast neutron field was presented and discussed. As presented, the channel count rate decreases as the detector is irradiated in a fast neutron field. The SiC channel count rate decreased to zero counts when it was placed in the OSURR’s AIF at full power in less than 35 minutes.

In Chapter 8, a mathematical model has been developed in Simulink to model the transient behavior of the GT-MHR core, to study the limiting transients for the SiC monitoring channel. This code provides an interactive environment to model and study various types of transient scenarios. This code calculates the temperature distribution in the core and the power of the reactor during transients.

In Chapter 9, the Simulink model presented in Chapter 8 has been used to study FPRITs in the GT-MHR and has been validated against a RELAP5 model developed by General Atomics. The results of the Simulink and RELAP5 models are in close
agreement. At full power in steady state, the Simulink model calculates the average fuel, moderator and reflector temperatures with 0.113%, 0.065% and 0.014% accuracy, respectively, compared to the RELAP5 model. The maximum difference in the local temperatures, which are calculated by Simulink and RELAP5 codes, is less than 0.7%. In the most limiting FPRIT that has been modeled, the reactor power increases to 150% of the full power (900 MW) at 42.6 s from the initiation of the transient using the Simulink model, at which point the reactor scrams. The maximum fuel temperature during the transient is 1200.57 K and occurs at 42.89 s after the beginning of transient. Since the design limit on the fuel temperature is about 1600 K, even the temperature at the hottest spot is considerably lower than the maximum allowable temperature. The Simulink and RELAP codes calculate power during the FPRIT with less than 0.4% relative difference.

In Chapter 10, we have described the application of the Simulink code to the analysis of the start-up reactivity insertion transient for the GT-MHR. According to the Simulink simulation of the SURIT, the maximum reactor power is 313 MW; i.e., the reactor fission power never reaches the FPRIT trip point of 900 MW. In addition, it should be noted that reactor protection is not assured for the SURIT, because the rapid rate of increase of reactor power during the SURIT may induce thermal stresses in the fuel that are unacceptably large. Additional research is necessary to resolve this issue.

In Chapter 11, the linearity of the monitoring channel count rate in response to the reactor power and the power monitoring channel dynamic range have been studied at two reactor locations: in the central reflector and in the Reactor Cavity. The dynamic range of the monitoring system covers about four decades of the reactor power, when the
detector is located in the central reflector. However, the detector lifetime in the central reflector is less than the reactor refueling cycle. On the other hand, the detector lifetime considerably increases when the detector is located in the Reactor Cavity. In this case, the dynamic range of the channel is limited in the Reactor Cavity.

A fast neutron flux-monitoring channel based on the use of SiC detector was developed in this dissertation. Detector locations in the GT-MHR were specified and properties of the channel at each location were discussed. The in-core monitoring system can potentially reduce the number of monitoring instruments that cover the entire power range to two, instead of three.

We suggest further research in two areas. Firstly, the lifetime of the detector was calculated assuming that the detector was operating at the room temperature. However, the lifetime of the detector at elevated temperatures will be extended. More modeling and experiments are required to estimate the detector lifetime at in-core operating temperatures. Secondly, other detector configuration can increase the channel count rate, without introducing more damage to the detector. Development of the other detector configurations can be helpful in maximizing the dynamic range of the channel by increasing the channel count rate.
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APPENDIX A

MATLAB CODE FOR MODELING DETECTOR, VOLTAGE SENSITIVE PREAMPLIFIER AND DISCRIMINATOR
xq=[1.4840E-04 1.09E+02
1.5360E-04 3.43E+01
1.5980E-04 3.67E+01
1.6910E-04 4.85E+01
1.7500E-04 2.56E+01
1.7690E-04 7.91E+00
1.7700E-04 1.58E+00
1.7670E-04 3.65E+00
1.7650E-04 2.04E+00
1.7630E-04 1.18E+00
1.7580E-04 2.70E+00
1.7550E-04 1.10E+00
1.7560E-04 3.20E-01
1.7560E-04 9.29E-01
1.7540E-04 1.38E+00
1.7530E-04 4.48E-01
1.7510E-04 2.00E-02
1.7310E-04 1.81E+00
1.7190E-04 3.91E-01
1.7170E-04 1.50E-01
1.7070E-04 3.43E-01
1.7060E-04 7.21E-02
1.7050E-04 8.99E-02
5.7070E-04 6.41E+02
8.6790E-04 4.63E+02
5.9040E-04 3.32E+02
9.5380E-04 7.61E+02
9.6310E-04 2.44E+01
9.8010E-04 5.15E+01
....
....
7.0520E-04 1.10E+02
7.6060E-04 1.15E+02
8.2530E-04 1.37E+02
8.7830E-04 1.28E+02
9.1220E-04 9.62E+01
9.4070E-04 8.20E+01];
m=100;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%DETECTOR MODEL

%Inputs: Detector Thickness, Bias Voltage, Electron and Hole Mobility, Doping, Events Rate, Time Frame and Step
%Inputs: Number of Particles, Number of Interactions for Each Particle, Interaction History for Each Particle
%Outputs: Detector Output Current, Collection Time for Electrons and Holes

%Defining Detector Specifications
d=10*10^(-4);  %thickness
v=100;   %voltage applied
un=900; up=100;  %mobility for electron and hole
n=10^15;     %doping
ehp=8.4;  %Energy required to make an electron-hole pair
vd=(1.6*10^(-19)*n*d^2)/(2*10*8.85*10^(-14));   %full depleted voltage

%Electric Field Calculation
x=0:.0001:d;
e=-((v+vd)/d-2*x*vd/d^2);

%Defining Time Frame and Step
step=10^(-11);     %End of the program
final=1.1*10^(-5);
initial=0;
t=initial:step:final;
dimension=size(t,2);

%Time Interval Generator between adjacent events
ti(1)=0;  %first event occurs at this time
rate=1*10^7;  %event rate
for f=2:m
    ti(f)=ti(f-1)-(1/rate)*log(rand(1,1));
end

%Calculating output current
index=1;
det_out=0;

%calculation of current generated by each charge in each position
%The number of interactions for each particle
n=[23
% m=particle id
% n=interaction id
% Detector output current (electron and holes) due to m, n

for j=1:m
    for i=1:n(j)
        te=(d^2/(2*un*vd))*log((v+vd)*(1-(xq(index,1)*2*vd)/(d*(v+vd)))/(v-vd))+ti(m);
        th=-d^2*log(1-xq(index,1)*2*vd/(d*(v+vd)))/(2*up*vd)+ti(m);
        tem(1,j)=te;
        thm(1,j)=th;
        flage=t<te;
        flagh=t<th;
        flagt=t>ti(j);
        ie=(xq(index,2)*1000*1.6*10^-19/(ehp*d^2))*(2*vd*xq(index,1)/d-
            (v+vd))*(2*un*exp(-2*un*vd*(t-ti(j))/d^2)).*flage+(2*up*vd*(t-
            ti(j))/d^2)).*flagh).*flagt;
        for r=1:dimension
            if ie(r)~=0
                if ie(r)/ie(r)~=1
                    ie(r)=0;
                end
            end
        end
        det_out=det_out+ie;
        index=index+1;
    end
    k=find(t>ti(j));
    expon(j)=(log10(det_out(k(1)))-log10(det_out(k(1)+8)))/(8*step);
    amplitude(j)=det_out(k(1));
end
Voltage Sensitive Preamplifier

Inputs: Lower cutoff frequency (f1), upper cutoff frequency (f2), gain, detector output current (det_out)

Outputs: Preamplifier transfer function(amp_tf), preamplifier output voltage(amp)

\[
f1=10^5;\]
\[
f2=1.8*10^9;\]
\[
w1=2*\pi*f1;\]
\[
w2=2*\pi*f2;\]
\[
gain=10;\]
\[
s=tf('s');\]
\[
amp_tf=((\text{gain}/w1)*s)/((s/w1+1)*(s/w2+1));\]
\[
\text{bode}(\text{amp_tf})\]
\[
amp_{in}=50*\text{det_out};\]
\[
amp=\text{lsim}(\text{amp_tf},\text{amp}_{in},t);\]

Discriminator Model: Non-Paralizable

Inputs: discrimination level(level), delay(dis_delay), deadtime, preamplifier output voltage (amp)

Outputs: number of counts(VoltageSensitiveSuccess)

VoltageSensitiveSuccess(loop,1)=0;
\[
\text{level}=10^(-5);\]
\[
\text{dis\_delay}=0;\]
\[
\text{deadtime}=3.3*10^(-9);\]
\[
\text{counter}=1;\]
\[
\text{dis\_out Voltage}=\text{zeros}(1100001,1);%(\text{final-initial})/\text{step};\]
\[
\text{while \text{counter}<(\text{final-initial})/\text{step}\}\]
\[
\quad \text{if } ((\text{amp}(\text{counter}+1,1)>\text{level}) \& (\text{amp}(\text{counter},1)<\text{level}));\]
\[
\quad \quad \text{VoltageSensitiveSucess(loop,1)=VoltageSensitiveSucess(loop,1)+1;}\]
\[
\quad \quad \text{dis\_out Voltage(counter+dis\_delay:counter+dis\_delay+deadtime/step)=1;}\]
\[
\quad \quad \text{counter=counter+250;}\]
\[
\quad \text{end}\]
\[
\text{counter=counter+1;}\]
\[
\text{end}\]
%Discriminator Model : Paralizable
%Inputs: discrimination level(level), delay(dis_delay), deadtime,
%preamplifier output voltage (amp)
%Outputs: number of counts(VoltagePara)
VoltagePara(loop,1)=0;
level=$10^{-5}$;
dis_delay=0;
deadtime=$3.3*10^{-9}$;
counter=1;
dis_outVoltagePara=zeros(1100001,1);%(final-initial)/step);
while counter<(final-initial)/step
    if ((amp(counter+1,1)>level) & (amp(counter,1)<level));
        if dis_outVoltagePara(counter)==0
            VoltagePara(loop,1)=VoltagePara(loop,1)+1;
        end
        dis_outVoltagePara(counter+dis_delay:counter+dis_delay+deadtime/step)=1;
    end
    counter=counter+1;
end
VoltageSensitiveSucess(loop,1)
VoltagePara(loop)
loop
end
APPENDIX B

EXAMPLE OF A TRIM SIMULATION INPUT
<table>
<thead>
<tr>
<th>NAME</th>
<th>No.</th>
<th>Energy(eV)</th>
<th>Depth in the target (A)</th>
<th>Initial Lateral Position Y (A)</th>
<th>Initial Lateral Position Z (A)</th>
<th>Direction (X)</th>
<th>Direction (Y)</th>
<th>Direction (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-1</td>
<td>1.00</td>
<td>2730000</td>
<td>5999.94</td>
<td>-106814.78</td>
<td>890217.04</td>
<td>0.33</td>
<td>0.82</td>
<td>0.47</td>
</tr>
<tr>
<td>a-2</td>
<td>1.00</td>
<td>2730000</td>
<td>7670.67</td>
<td>-798853.15</td>
<td>605966.27</td>
<td>0.94</td>
<td>-0.10</td>
<td>-0.34</td>
</tr>
<tr>
<td>a-3</td>
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Table B-1. TRIM input file for 2.73MeV tritons which are emitted uniformly within 1µm LiF. The detector diameter is 200µm.

Make this file in Excel and enter it in TRIM as a .dat file.
Figure B.1. TRIM input for 2.73MeV tritons
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<th>Initial Lateral Position Z (Å)</th>
<th>Direction (X)</th>
<th>Direction (Y)</th>
<th>Direction (Z)</th>
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Table B.2. TRIM input file for 2.05MeV alpha particles which are emitted uniformly within 1µm LiF. The detector diameter is 200µm.
Figure B.2. TRIM input for 2.05MeV alpha particles
APPENDIX C

EXAMPLE OF A TRIM SIMULATION OUTPUT
Figure C.1. TRIM output which shows the tritons' path going through LiF, Al, Au and SiC layers.
This is a TRIM output file. Information is entered into Excel form and after processing, the Excel file is Input to the Detector Model.

SRIM-2003.17

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<th>Numb</th>
<th>Energy (keV)</th>
<th>Depth (A)</th>
<th>Lateral Distance (A)</th>
<th>Se</th>
<th>Atom</th>
<th>Recoil Energy (eV)</th>
<th>Disp. VAC.</th>
<th>Placing VAC.</th>
<th>INTERstitials</th>
<th>Sputtered</th>
<th>Transmitted</th>
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Special Calculation based on TRIM.DAT file.

Li  Displacement Energy of Li = 0025.00000 eV
Latt. Binding Energy of Li = 0003.00000 eV
SurfaceBind. Energy of Li = 0001.67000 eV

F  Displacement Energy of F = 0025.00000 eV
Latt. Binding Energy of F = 0003.00000 eV
SurfaceBind. Energy of F = 0002.00000 eV

Al  Displacement Energy of Al = 0025.00000 eV
Latt. Binding Energy of Al = 0003.00000 eV
SurfaceBind. Energy of Al = 0003.36000 eV

Au  Displacement Energy of Au = 0025.00000 eV
Latt. Binding Energy of Au = 0003.00000 eV
SurfaceBind. Energy of Au = 0003.80000 eV

Si  Displacement Energy of Si = 0015.00000 eV
Latt. Binding Energy of Si = 0002.00000 eV
SurfaceBind. Energy of Si = 0004.70000 eV

C  Displacement Energy of C = 0028.00000 eV
Latt. Binding Energy of C = 0003.00000 eV
SurfaceBind. Energy of C = 0007.41000 eV

Collision History

Notes: Only Ion Collisions which produce Displacements are tabulated.
Atom Sums and Averages are Incomplete if Recoil Cascades Leave Target.
Target DISPlacements = VACancies + REPLACement Collisions.
Target VACancies = INTERstitials + Sputtered + Transmitted Atoms.
Recoil Atoms which end at the surface, are not counted (see manual).
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<th>(A)</th>
<th>Y Axis</th>
<th>Z Axis</th>
<th>(eV/A)</th>
<th>Hit</th>
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<th>VAC.</th>
<th>REPLAC.</th>
<th>INTER</th>
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<td>0000000.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Ion 0000001:  
For All Ions to date:

| Displacements | = 000000.0 | Average Displacements/Ion | = 0000000.00 |
| Replacements  | = 000000.0 | Average Replacements/Ion  | = 0000000.00 |
| Vacancies     | = 000000.0 | Average Vacancies/Ion     | = 0000000.00 |
| Interstitials | = 000000.0 | Average Interstitials/Ion | = 0000000.00 |
| Sputtered Atoms | = 000000.0 | Average Sputtered Atoms/Ion | = 0000000.00 |
| Transmitted Atoms | = 000000.0 | Average Transmitted Atoms/Ion | = 0000000.00 |

For Ion 0000002:  
For All Ions to date:

| Displacements | = 000000.0 | Average Displacements/Ion | = 0000000.00 |
| Replacements  | = 000000.0 | Average Replacements/Ion  | = 0000000.00 |
| Vacancies     | = 000000.0 | Average Vacancies/Ion     | = 0000000.00 |
| Interstitials | = 000000.0 | Average Interstitials/Ion | = 0000000.00 |
| Sputtered Atoms | = 000000.0 | Average Sputtered Atoms/Ion | = 0000000.00 |
| Transmitted Atoms | = 000000.0 | Average Transmitted Atoms/Ion | = 0000000.00 |

For Ion 0000003:  
For All Ions to date:

| Displacements | = 000000.0 | Average Displacements/Ion | = 0000000.00 |
| Replacements  | = 000000.0 | Average Replacements/Ion  | = 0000000.00 |
| Vacancies     | = 000000.0 | Average Vacancies/Ion     | = 0000000.00 |
| Interstitials | = 000000.0 | Average Interstitials/Ion | = 0000000.00 |
| Sputtered Atoms | = 000000.0 | Average Sputtered Atoms/Ion | = 0000000.00 |
| Transmitted Atoms | = 000000.0 | Average Transmitted Atoms/Ion | = 0000000.00 |

Ion Energy Depth Lateral Distance (A) Se Atom Recoil Target Target Target Target
Numb (keV) (A) Y Axis Z Axis (eV/A) Hit Energy(eV) DISP. VAC. REPLAC INTER

For Ion 0000001:  
For All Ions to date:

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| Transmitted Atoms | = 000000.0 | Average Transmitted Atoms/Ion | = 0000000.00 |

For Ion 0000002:  
For All Ions to date:

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| Vacancies     | = 000000.0 | Average Vacancies/Ion     | = 0000000.00 |
| Interstitials | = 000000.0 | Average Interstitials/Ion | = 0000000.00 |
| Sputtered Atoms | = 000000.0 | Average Sputtered Atoms/Ion | = 0000000.00 |
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For All Ions to date:

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| Sputtered Atoms | = 000000.0 | Average Sputtered Atoms/Ion | = 0000000.00 |
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Sputtered Atoms   = 000000.0   Average Sputter Atoms/Ion     = 0000000.000
Interstitials     = 000000.0   Average Interstitials/Ion     = 0000000.000
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Displacements     = 000000.0   Average Displacements/Ion     = 0000000.000

For Ion 0000005:
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Interstitials     = 000000.0   Average Interstitials/Ion     = 0000000.000
Vacancies         = 000000.0   Average Vacancies/Ion         = 0000000.000
Replacements      = 000000.0   Average Replacements/Ion      = 0000000.000
Displacements     = 000000.0   Average Displacements/Ion     = 0000000.000

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<td>-4293.0</td>
<td>Al</td>
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For Ion 0000009:

- For All Ions to date:
  - Displacements = 000000.0
  - Replacements = 000000.0
  - Vacancies = 000000.0
  - Interstitials = 000000.0
  - Sputtered Atoms = 000000.0
  - Transmitted Atoms = 000000.0

---

For Ion 0000009:

- For All Ions to date:
  - Displacements = 000125.0
  - Replacements = 000006.0
  - Vacancies = 000119.0
  - Interstitials = 000125.0
  - Sputtered Atoms = 000000.0
  - Transmitted Atoms = 000000.0

---

Ion Energy Depth Lateral Distance (A) Se Atom Recoil Target Target Target Target
Numb (keV) (A) Y Axis Z Axis (eV/A) Hit Energy(eV) DISP. VAC. REPLAC INTER

---

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For Ion 0000010:

For All Ions to date:

† Displacements  = 000000.0  Average Displacements/Ion  = 0000055.600  
† Replacements  = 000000.0  Average Replacements/Ion  = 0000002.500  
† Vacancies     = 000000.0  Average Vacancies/Ion     = 0000053.100  
† Interstitials = 000000.0  Average Interstitials/Ion = 0000055.600  
† Sputtered Atoms= 000000.0  Average Sputter Atoms/Ion = 0000000.000  
† Transmitted Atoms= 000000.0  Average Transmitted Atoms/Ion = 0000000.000  

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APPENDIX D

PSPICE MODEL OF THE MINERAL INSULATED CABLE
Figure D.1. The schematic diagram of the PSice cable modeling
APPENDIX E

SiC SEMICONDUCTOR DETECTOR PROPERTIES
PACKAGE 1

The first package includes two diodes. The diameter of each diode is 500µm and the diode thickness is 10µm. Figure E.1 shows the top view of the package. In the case of using this package, only one detector can be used at a time. Thus, the other one has to be connected to ground. Therefore, in addition to the common pin (No.2), one of the others should be grounded. So two of the pins are grounded and the other one is connected to the center wire. To reverse bias the diode the polarity of the center wire is made negative with respect to ground.

Figure E.1 The top view of the SiC diode detector package
Figure E.2 shows the schematic structure of a SiC diode detector. The detectors we are using were fabricated by vapor-phase epitaxy onto high purity 4H-SiC substrate wafers with a nitrogen (n+) dopant concentration of $10^{18}$ cm$^{-3}$. The n– layer, with nitrogen dopant concentration of $10^{15}$ cm$^{-3}$ and 10µm thickness, were applied to a conducting SiC wafer substrate. The Schottky metal contact layer was covered with a 1µm layer of gold.

![SiC Schottky diode detector configuration](image)

**Figure E.2** SiC Schottky diode detector configuration

**PACKAGE 2**

The second package contains four diodes. The advantage of using this package is that more than one diode can be used at a time. Each detector has a diameter of 200µm and a thickness of 5µm. Other properties are similar to the first package.
PACKAGE 3

The third package contains one power diode, which is CSD10030 made by CREE. Tables E.1 and E.2 present the maximum rating and electrical characteristics of the diode, correspondingly. Figure E.3 shows a CREE diode (picture from CREE website [44]). This diode is mounted in the package shown in Figure 7.16.

Figure E.3 CREE power diode from CREE website [44]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetitive Peak Reverse Voltage</td>
<td>$V_{RRM}$</td>
<td>300 V</td>
</tr>
<tr>
<td>Surge Peak Reverse Voltage</td>
<td>$V_{RSM}$</td>
<td>300 V</td>
</tr>
<tr>
<td>DC Blocking Voltage</td>
<td>$V_{DC}$</td>
<td>300 V</td>
</tr>
<tr>
<td>Average Forward Current $(T_C=150^\circ C)$</td>
<td>$I_{F(AV)}$</td>
<td>10 A</td>
</tr>
<tr>
<td>Repetitive Peak Forward Surge Current $(T_C=25^\circ C, t_P=8.3ms, Half Sine Wave)$</td>
<td>$I_{FRM}$</td>
<td>40 A</td>
</tr>
<tr>
<td>Non-Repetitive Peak Forward Surge Current $(T_C=25^\circ C, t_P=10ms, Pulse)$</td>
<td>$I_{FSM}$</td>
<td>200 A</td>
</tr>
<tr>
<td>Power Dissipation $(T_C=25^\circ C)$</td>
<td>$P_{tot}$</td>
<td>79 W</td>
</tr>
<tr>
<td>Operating Junction and Storage Temperature</td>
<td>$T_J, T_{stg}$</td>
<td>-55 to +175 °C</td>
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</table>

**Table E.1** Maximum ratings of CSD10030 diode [44]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Typical</th>
<th>Max</th>
</tr>
</thead>
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<tr>
<td>Forward Voltage</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$I_F = 10A \ T_J=25^\circ C$</td>
<td>$V_F$</td>
<td>1.2V</td>
<td>1.4V</td>
</tr>
<tr>
<td>$I_F = 10A \ T_J=175^\circ C$</td>
<td></td>
<td>1.4V</td>
<td>1.8V</td>
</tr>
<tr>
<td>Reverse Current</td>
<td>$I_R$</td>
<td>50 mA</td>
<td>200 mA</td>
</tr>
<tr>
<td>$V_R = 300V \ T_J=25^\circ C$</td>
<td></td>
<td>1000 mA</td>
<td>2000 mA</td>
</tr>
<tr>
<td>$V_R = 300V \ T_J=175^\circ C$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Capacitive Charge</td>
<td>$Q_C$</td>
<td>11.5 nC</td>
<td></td>
</tr>
<tr>
<td>$V_R = 300V, \ I_F = 10A, \ di/dt = 500\ A/ms, \ T_J = 25^\circ C$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Capacitance</td>
<td>$C$</td>
<td>660 pF</td>
<td>62 pF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62 pF</td>
<td>58 pF</td>
</tr>
<tr>
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</table>

Table E.2 Electrical characteristics of CSD10030 diode [44]
APPENDIX F

Simulink DIGRAMS OF THE GT-MHR CORE MODEL
This simulation is based on the PRK model of the reactor. These equations calculate neutron population as a function of time with seven differential equations; one is used to calculate the total neutron population and the other six equations model six group delayed neutrons. Fuel and moderator temperature feedbacks are modeled in this block.

Figure F.1 Simulink diagram of the "Neutronics" block
This block calculates the power due to delayed neutron precursors. The reactor can be modeled with an arbitrary number of delayed neutron groups equal or less than six.

**Figure F.2** Detailed diagram of the "Delayed Neutron" block
Figure F.3 A delayed neutron precursor concentration equation as set in Simulink
In the block, the fuel, moderator, and reflector feedback reactivities are calculated as a function of the fuel, moderator, and reflector temperatures.

**Figure F.4** Simulink diagram of the "Feedback" block
Local heat transport by conduction and convection is simulated using a coolant-hole centered model. The coolant-hole geometry is defined in this module. Also, the fuel, moderator, and coolant properties are specified. Heat transfer equations are solved in the "Core Model" block.

Figure F.5 Simulink diagram of the "Thermo Hydraulics" block.
The coolant-hole is divided into five axial locations, which are represented by "Row" blocks. In each row, the average temperatures of the fuel and moderator and also the He outlet temperature are calculated based on the He inlet temperature and the energy generated in the row.

Figure F.6 Simulink diagram of the coolant-hole model
Figure F.7 Simulink diagram of the axial row of the coolant-hole model
Figure F.8 Simulink diagram of the conduction node which is used in the coolant-hole model
Figure F.9 Simulink diagram of the convection node which is used in the coolant-hole model
Helium density, specific heat and kinematic viscosity and also the convection heat transfer coefficient are calculated based on the He temperature, pressure and flow rate.

Figure F.10 Simulink diagram of the "He calculator" block
This subsystem has been designed to automatically adjust the control rods' positions in order to make the reactor critical. One control rod is moved at a time.

**Figure F.11** Simulink diagram of the "Auto Control" block
Figure F.12 Simulink diagram of the "Controller" block