MODELING THE KINETIC BEHAVIOR OF REFLECTED-REACTOR SYSTEMS NEAR AND ABOVE PROMPT CRITICAL

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ABSTRACT

The safe operation of a fast burst reactor (FBR) depends directly on the knowledge, experience, and judgment of the operating staff to understand the mechanisms by which experiments influence the reactor's behavior. Fast burst reactors are a unique class of research reactors that generate high yield, self-terminated power pulses from reactivity insertions exceeding prompt critical. These reactors are typically very compact, fueled with fully enriched uranium-235, and unmoderated. Therefore, experiments positioned near or within the core become neutronically linked to the reactor, and influence its kinetic behavior. Since experiments can cover a broad range of conditions, the potential exists for an inadvertent over-insertion of reactivity during a pulse operation, producing a yield capable of damaging the reactor.

To reduce this heavy reliance on human component of reactor operation, we evaluated the kinetic behavior of the Sandia Pulsed Reactor III (SPR III), a FBR, over a wide range of experimental conditions, looking for relationships among measured parameters. Given this data, we determined the physical bases for the observed relationships. Further we modified the theoretical models to account for these observed relationships. The result of our analysis is a modified reflected point-reactor kinetics model of SPR III that adequately simulates the experiment-reactor system under all observed conditions. We used experimental data and computer simulations to validate the resulting models.

The results show that experiments neutronically behave as loosely coupled reflectors. Further, the kinetic behavior of the reflected reactor during a pulse can be adequately modeled by treating the reflected neutrons in a manner analogous to additional delayed neutron groups. As found in this study, there are multiple components to the time-response of the reflectors. This variation in response is dependent on the material composition and distance of the experiments from the core.

1. Introduction

A fast burst reactor (FBR) is normally a physically small assembly of highly enriched uranium metal, unmoderated and operated in air. These reactors operate in a pulse mode, where they generate a rapid ‘burst’ of intense high-energy neutrons (‘fast’ neutrons). Although the power output of these reactors at the peak of the pulses is extremely high, often exceeding 100,000 megawatts, the pulse duration is very short, on the order of one millisecond or less.

In early designs, the cores were small in size such that all experiments were correspondingly small and separated from the core. Later, large central cavities were introduced in the core to provide access to regions of higher neutron flux levels. Experiments were either located within the core, or positioned as close as possible to the exterior of the core to achieve the maximum flux levels. Also, significant amounts of excess reactivity were designed into the reactors to allow compensation for the influences of large experiments. The closeness of the reactor core and experiment results in an interrelationship that produces a neutronically coupled system, where the experiment can strongly affect the neutronic behavior of the core. Depending on the experiment’s composition, position, and function, a variety of kinetics effects may be observed in the modified reactor system. Consequently, the reactor operating staff must determine and understand the influence of an experiment before attempting to perform a pulse.

A complicating factor in these operations is that often the kinetic effects introduced by the experiments may not be obvious until the pulse is actually performed, such as when the experiment appears to alter the effective neutron lifetime of the system. Neutron lifetime changes only become observable after a reactor exceeds prompt critical, which puts the system into a time regime where the facility’s protective features may be challenged should the operating staff make an incorrect decision in the pulse setup.

When considering the effects of experiments on FBRs, another factor must be acknowledged. These reactors are designed to operate in time frames that normally exceed the response time of their electromechanical protection systems. The reactors can produce pulses that deposit large amounts of energy into the fuel in significantly less than one millisecond, while most protection systems will take tens of milliseconds to detect and respond to a system parameter exceeding a trip level. Therefore, the reactors rely on the inherent shutdown mechanism of fuel expansion due to heating to terminate the pulse, and the protection system becomes a backup system to mitigate post-pulse heat generation. Consequently, the reactor must be accurately configured for the desired pulse size before the pulse is performed. This situation results in a direct reliance on the operating staff for the ultimate safety of the reactor; a condition normally avoided in the design and operation of other reactor types. While human error can certainly have a strong effect on any reactor, it becomes a direct concern in FBRs, as engineering features cannot be used as compensating measures.

To investigate and remedy this problem, we evaluated the kinetic behavior of the Sandia Pulsed Reactor III (SPR III), a FBR, over a wide range of experimental conditions. The results show that experiments neutronically behave as loosely coupled reflectors. Further, the kinetic behavior of the reflected reactor during a pulse can be adequately modeled by treating the reflected neutrons in a manner analogous to additional delayed neutron groups. As found in this study, there are multiple components to the time-response of the reflectors. This variation in response is dependent on the material composition and distance of the experiments from the core. Consequently, we developed a modified reflected point-reactor kinetics model of the FBR that adequately simulates the experiment-reactor system under all observed conditions[3, 8]. We used additional experimental data and computer simulations to validate the model.

2. Sandia Pulsed Reactor III

Sandia National Laboratories has operated fast burst reactors since 1961 to provide an irradiation source for testing electronic components and systems designed to operate in adverse radiation environments. Sandia designed and built the SPR III (unless noted, all information regarding SPR III is from reference 1), achieving initial criticality in 1975, to provide the neutron irradiation characteristics of earlier FBRs over a much larger experiment volume to allow the testing of complete electronic subsystems rather than individual components. SPR III features a 16.5-cm usable diameter central cavity of, but its main design innovation is the use of external reflectors for reactivity control rather than internal fuel-loaded control and pulse rods. The external reflectors, coupled with an external fuel clamping system, allowed the fuel plates to be fabricated with no penetrations except the central cavity, reducing stress effects on the plates.

The reactor has a total fuel mass of 258.0 kg, cast into 18 plates, and stacked to form a right concentric cylinder with a fuel height of 36.83 cm and a diameter of 29.7 cm. The fuel is uranium metal, enriched to 93% U-235, alloyed with 10% Molybdenum, gamma-phase stabilized with a heat treatment, and aluminum-ion plated.

As shown in Figure 1, SPR III is mounted on a stand that contains the electromechanical systems for operating the reactor. The reactor is controlled with three external copper control reflectors and an aluminum pulse reflector, each covering essentially one quadrant of the outer surface of the core. The control reflectors are driven with electric motors, and the pulse reflector uses an electromagnetic drive to insert the reflector in about 200 milliseconds.

With the reactor in its normal operating position, the core centerline is roughly 135 cm above the floor. The SPR III core is divided into two halves at the axial centerline. The core halves are separated by about 8.9 cm when the reactor is shutdown, and are brought into contact with each other when the reactor is to be operated. The dropping of the safety block by turning off an electromagnetic coupling is the primary shutdown mechanism for the reactor protection system.

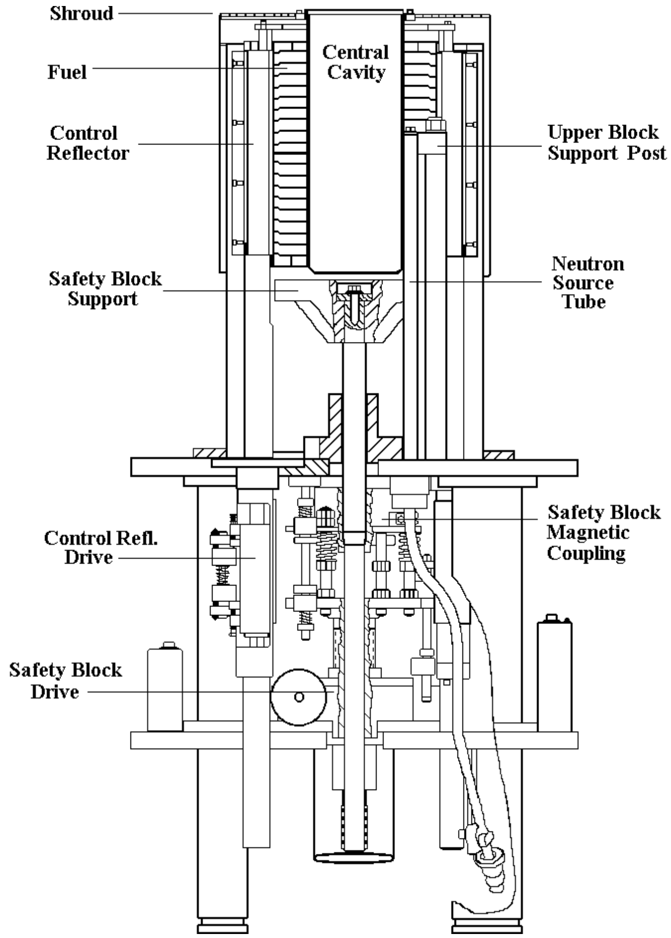

Figure 1: SPR III reactor and stand (adopted from reference 1).

During normal operations, a shroud covers the reactor to provide a controlled volume for the nitrogen cooling system, and for decoupling the reactor somewhat from experiments. The shroud is composed of boron carbide, enriched in B-10, sandwiched within two sheets of aluminum. The B-10 reduces the potential for thermal neutrons returning to the core and causing surface heating effects, however higher energy neutrons are not captured. Table I displays the operational characteristics of SPR III when operated with no experiment in place. These values are typical, and represent an envelope for normal operations.

In the 1980's, an operational diagnostics system, the Pulse Analysis System, was developed for the SPR facility. The Pulse Analysis System is a computer controlled digital data acquisition system coupled to a fast neutron detector and other diagnostic sensors. Custom software was developed at the facility to provide the operating staff and experimenters with pulse characteristics and operational parameters that were previously unavailable. The system has been used in several studies, including the evaluation of the kinetics effects of the fission-activated pumped laser experiment[7].

The first step in a pulse operation is to measure the reactivity worth of the experiment. The reactivity worth is determined by conducting a low power delayed critical operation with the experiment in place. The difference in reactivity worth between the observed delayed critical positions of the control elements with and without the experiment in place is the experiment's reactivity worth. This parameter is not used directly in the pulse setup, but it provides important information to the operating staff. First, they use it to monitor experiment status from one operation to the next when performing multiple operations on the same experiment. Unintentional changes in configuration or positioning may be detected before they can inadvertently affect the pulse outcome. Second, and equally important, the experiment's reactivity worth can provide some indications of what its effect will be on the neutron kinetics during the pulse. The experiment's reactivity worth is not used to accurately predict its kinetics effects, as there are several intangible variables that must be accounted for, but the configuration

Table I: Nominal Pulse Characteristics for SPR III[8]

Parameter	Design Value
Control Element Bank Reactivity Worth	$9.45
Pulse Element Worth	$1.10
Safety Block Reactivity Worth	> $10
Control Element Reactivity Worth at Delayed Critical	$3.50
Fuel Material Melting Point	1130^o C
Nominal Maximum Pulse Yield	300^o C
Reactivity Insertion for Nominal Pulse Yield	$1.10
Initial Reactor Period	30 μs
Pulse Full Width at Half Maximum	90 μs
Total Energy Yield	6.6 MJ
Peak Power Level	120,000 MW

and reactivity worth of the experiment are compared to previous operations to allow the operating staff to anticipate the experiment's influence on the reactor.

The next step in the pulse operation is to measure the reactivity worth of the pulse element. Although the pulse element does not physically change from one operation to the next, its relative reactivity worth in the system is interrelated to the experimental configuration and the positions of the three control elements. The interrelationship is due to the effect of the control element positions on the axial flux profile on the core. The control reflector position varies depending on the amount of reflection due to the experiment. As the elements are repositioned, the symmetry of the axial flux profile changes[8]. To measure the pulse element worth without actually performing a pulse, an operation called a 'minipulse' is conducted. The minipulse is a power transient conducted with a system reactivity worth of slightly less than that of prompt critical. This operation allows the operator to measure the reactor period and yet terminate the transient before any fuel heating has occurred or a significant amount of neutron dose has been delivered to the experiment. To conduct this measurement, the operating staff must estimate the value of the pulse element. This value is used to adjust the control elements to partially compensate for insertion of the pulse element. The measured reactor period is directly related to the system reactivity, from which the pulse element reactivity worth is calculated.

The pulse element reactivity worth is one of two key values in setting up the reactor for the pulse operation. It represents the best available information to the staff as to the interrelationship between the experiment and the reactor, and to the behavior of the system as a single entity. The second key value is the desired reactivity insertion for the pulse. This is the value that the operating staff determines to be the amount of reactivity necessary to be inserted during the pulse sequence to produce the yield required for the experiment. The desired insertion value is normally selected based on observed yields for previous operations with similar experiments. This value is often determined in a manner similar to the adjustment for the minipulse. Previous pulse histories are reviewed for similar experiments, and where data is sparse or unavailable the staff may opt to perform multiple pulses while working up from low levels to the desired yields. Given these two values, the staff is now prepared to continue with the next phase of the operation.

The actual pulse operation is similar to the minipulse operation, except that the pulse is not terminated prematurely. Based on the data collected, the operator and supervisor independently determine the adjustment necessary on the reference control element to provide the system reactivity desired to produce the intended yield. The independence helps enhance operational safety by reducing the potential for error in the determination, which requires several calculations and table lookups. After the staff concurrence, the operator repositions the reference control element and pulses the reactor.

There are two points in the process that require subjective decisions by the operating staff, the compensation for the minipulse, and the adjustment for the pulse. Both of these decisions depend on the understanding of the influence of the experiment on the kinetic behavior of the reactor. At either of these two steps, an error in judgment by the staff could lead to damage to the reactor ranging from an insignificant error in the pulse size to either physical damage to the mechanical systems of the reactor or even core disruption and partial melting of the fuel.

3. Reflected Point-Reactor Kinetics

Based on work with the original SPR, Coats[3] developed a reflected point-reactor model. He envisioned pseudo-populations of neutrons in the reflector that would ultimately be reflected back into the core and, therefore, modeled them in a manner similar to the traditional delayed neutron groups. This model provided the best explanation of the observed system behavior. It was, however, limited to SPR and the experiments that it could perform. With the advent of SPR III and its central cavity, larger and more complex experiments could be performed. Therefore, it was necessary to re-evaluate the model and modify it to account for new observations, which is the thrust of this paper.

For most experiments conducted in SPR III, a single energy group can adequately represent the neutrons. This is reasonable given that the reactor operates at a near-fission energy spectrum, and the B-10 loaded shroud minimizes the introduction of thermal neutrons into the core from external sources. The model can be applied to the more general case, where it may be appropriate to consider multiple energy group formulations; however, the basic principles and interpretations of the results would not change significantly.

The derivation also accounts for all of the transit times associate with the leakage of neutrons, migration to the reflector. In contrast, traditional reflected kinetics models assume that the neutron population in the reflector is in time-equilibrium with the population in the core, neglecting the transit times, and that the residence time is characterized by the neutron lifetime in the reflector (see for example, references 4, 6, 9, and 10). While these assumptions lead to reasonable results at low reactivity insertions, they do not model the changes in pulse symmetry that were observed by Minnema[7, 8]. The complication of the model presented here is that it is difficult to determine the delay and residence times from basic nuclear parameters.

Modeling of the reflected neutron population from a reflector with MCNP[2] demonstrates the time dependent behavior of the phenomenon, as the neutrons lose energy and escape the reflector. Figure 2 shows the neutron flux in a reflector as a function of time after a fission-spectrum neutron is ‘fired’ at the reflector from 10 cm away.

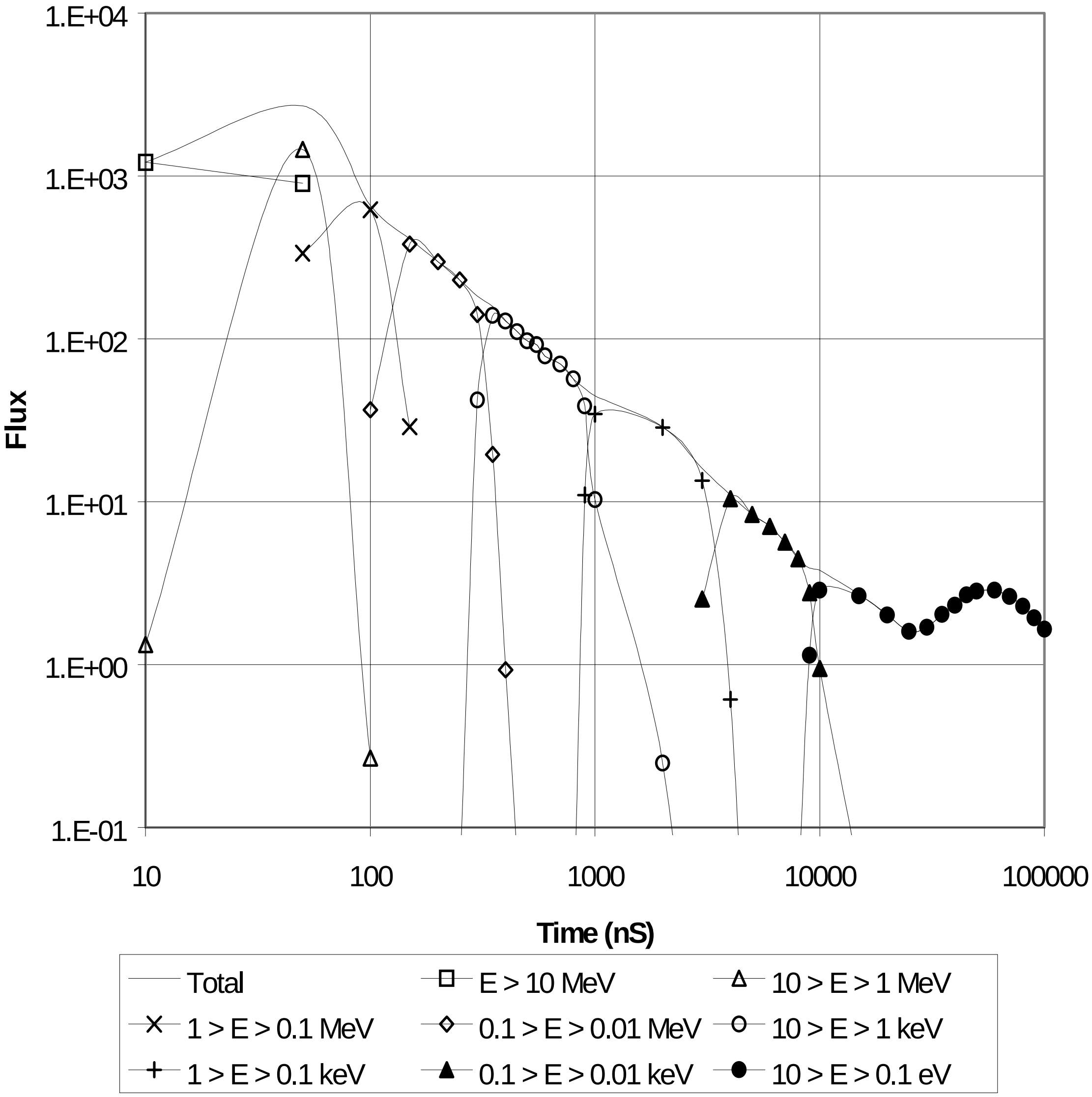

Figure 2: Reflected neutron flux from a polyethylene reflector for an initial fission-spectrum neutron, 'fired' at the reflector from 10 cm away at time zero.

The time dependency of the reflected neutrons is a function of the reflector composition, as is demonstrated in figure 3, which shows a comparison of several reflector materials under the same experiment conditions.

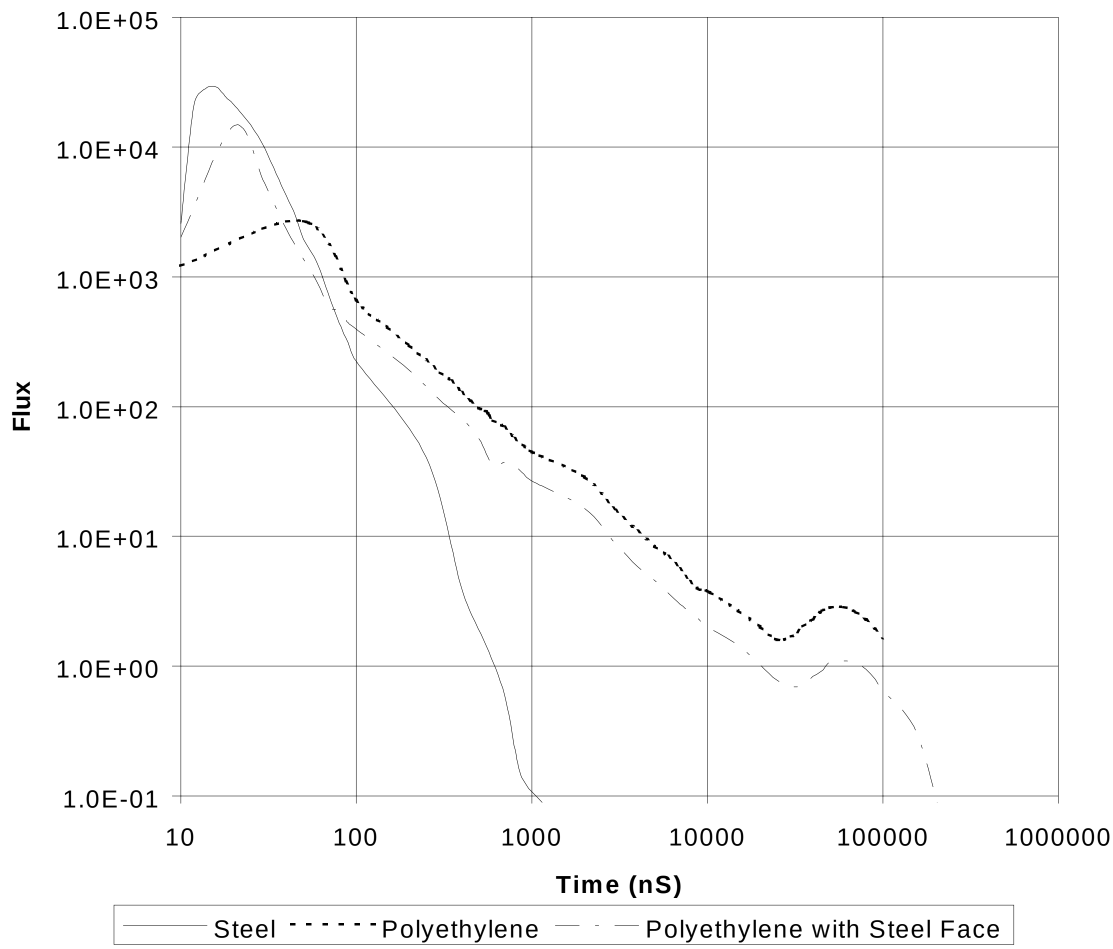

Figure 3: The time dependent behavior of reflected neutrons as a function of the reflector composition.

With the delayed-neutron, the time-dependent diffusion equation is[5]:

$$\frac{\partial n}{\partial t} = Dv\nabla^2 n - \Sigma_a vn + (1-\beta)k_\infty \Sigma_a vn + \sum_i \lambda_i C_i + S_o \text{, where} \tag{1}$$

$$\frac{\partial C_i}{\partial t} = \beta_i k_\infty \Sigma_a vn - \lambda_i C_i \text{,} \tag{2}$$

and S_o represents the leakage neutrons that are reflected back into the core. To account for multiple scatters within the reflector, and the resultant spread in the neutron energy, each reflector is represented by multiple neutron groups, each with its own characteristic residence time and return transit time. Therefore, the reflected neutron source term becomes[3]:

$$S_o = \sum_j \frac{C'_j(t-\tau'_{4j})}{\tau_{3j}}, \text{ and} \quad (3)$$

$$\frac{\partial C'_j}{\partial t} = \beta'_j k_\infty \Sigma_a vn\left(t-\tau'_{2j}\right) - \frac{C'_j(t)}{\tau_{3j}}. \quad (4)$$

Subscript *j* represents the various energy groups of the reflected neutrons and other terms are defined as follows:

$C'_j(t)$	population at time t of neutrons of energy group *j*, which will ultimately reenter the core as reflected neutrons;
$\tau'_{2j} = \left(\tau_{2j} + \tau_{1j}\right)$	delay time between when a neutron is created in the core and when it appears in the *j*th energy group;
$n(t-\tau'_{2j})$	neutron population in the core at time $(t-\tau'_{2j})$;
β'_j	fraction of fission neutrons, which escape the fuel and return to the fuel as reflected neutrons of energy group *j*;
τ_{3j}	mean residence time in the reflector for a neutron of the *j*th energy group, before being reflected back into the fuel; and
$\tau'_{4j} = \left(\tau_{4j} + \tau_{5j}\right)$	delay time between when a neutron in the *j*th energy group leaks from the reflector and is absorbed in the fuel.

For this application, it must also be assumed that the spatial distribution of reflected neutrons is similar to that of source neutrons in the fuel region. Using separation of variables and using the Helmholtz equation to introduce the buckling term B^2, the following equation results:

$$\frac{dn}{dt} = \left[-L^2B^2 - 1 + (1-\beta)k_\infty\right]\Sigma_a vn + \sum_i \lambda_i C_i + \sum_j \frac{C'_j(t-\tau'_{4j})}{\tau_{3j}}. \quad (5)$$

In general, this is a weak assumption, given that reflectors would generally not be positioned to totally surround the fuel region. Further, this assumption is not to imply that spatial effects of the experiments are not present in such a reactor. To the contrary, it has been demonstrated the location of the experiments directly lead to changes in the pulse element worth as a function of control element position[8]. However, the design of the reactor and shroud ensures that no other movable reflectors can be positioned as close to the core as the control and pulse elements. Therefore, the spatial effects of other reflectors (i.e., the experiments) are secondary to those of the control systems, and flux profile changes are minimal.

Under steady-state conditions, the critical condition results in:

$$k_\infty \frac{(1+\beta')}{(1+L^2B^2)} = 1. \quad (6)$$

For an unreflected system, the term $1/(1+L^2B^2)$ is the non-leakage probability. Recognizing that the value of $\beta' = \sum_j \beta'_j$ represents a reduction in leakage, then $(1+\beta')/(1+L^2B^2)$ is the non-leakage probability of the reflected system. Define:

$$k = k_\infty \frac{(1+\beta')}{(1+L^2B^2)}, \text{ and} \quad (7)$$

$$\ell_o = \ell_\infty \frac{(1+\beta')}{(1+L^2B^2)}. \quad (8)$$

Recalling that $\ell_\infty = 1/v\Sigma_a$, $\ell = \ell_o/k$, and $\rho = (k-1)/k$, and defining $\beta^* = \beta'/k$, the reflected point-reactor kinetics equations reduces to:

$$\frac{dn}{dt} = \frac{[\rho - (\beta + \beta^*)]}{\ell} n + \sum_i \lambda_i C_i + \sum_j \frac{C'_j(t - \tau'_{4j})}{\tau_{3j}}, \quad (9)$$

$$\frac{dC_i}{dt} = \frac{\beta_i n}{\ell} - \lambda_i C_i, \text{ and} \quad (10)$$

$$\frac{dC'_j}{dt} = \frac{\beta'_j}{\ell} n(t - \tau'_{2j}) - \frac{C'_j(t)}{\tau_{3j}}. \quad (11)$$

These equations allow one to derive the reflected point-reactor kinetics equations directly from the diffusion equation, using the modified non-leakage probability term.

To complete the derivation of terms used in this model, recall the basic design of the SPR III reactor, in that all control mechanisms are external reflectors. Consequently, in considering the behavior of the reactor in the presence of reflectors, one must also take into account the control and pulse elements. Assume that a bare core configuration consists of the fueled region of the reactor with no reflectors in place, including the control and pulse elements and other supporting structure. Therefore, there is no reflection term in the non-leakage probability, and one can define the following terms as representative of the bare core:

$$k^B = k_\infty \frac{1}{1+L^2B^2}, \text{ and} \quad (12)$$

$$\ell_o^B = \ell_\infty \frac{1}{1+L^2B^2}, \quad (13)$$

where superscript B denotes a bare reactor. Representing all reflectors (control, pulse, structure, and experiments) as perturbations from k^{B} and ℓ_{o}^{B} leads to the conclusion that:

$$k = k^{B}(1+\beta'), \text{ and} \tag{14}$$

$$\ell_{o} = \ell_{o}^{B}(1+\beta'). \tag{15}$$

4. Implications of the Modified Reflected Point-Reactor Kinetics Model

Before discussing the application of this model to SPR III, it is valuable to consider the general implications of this formulation. The only parameters that change with experiments are the time constants, τ_2', τ_3, and τ_4', and the experiment's contribution to β'. Note that

- τ_2', the time delay for transit between the core and the experiment, is a function of the distance between the two, and the energy of the leakage neutron. Since the core parameters do not change with experiment, the energy of the leakage neutrons is independent of the experimental setup and, thus, this parameter is only a function of distance;

- τ_3, the time constant representing the residence time of a neutron energy group in the experiment, is a function of the material composition of the experiment;

- τ_4', the time delays for transit from experiment to core, is a function of the distance between the two, and the energy of the reflected neutron; and

- β'_{exp}, the reflected neutron fraction from the experiment, is a function of material type, location (central cavity versus external), and distance.

Therefore, no adjustment to the basic core parameters is required to account for varying experiment conditions. One need only know the basic configuration of the experiment. Given these factors, the above equations directly lead to some conclusions about the implications of the model regarding the reactor's behavior:

1. Recalling that β' is the sum of contributions from individual reflectors (control elements and experiment), equation 14 leads to the conclusion that the contributions from an experiment, when in place, are balanced exactly by the change in control element positions. Therefore, the measured experiment reactivity worth is a direct measure of the contribution from the experiment. Therefore, for a reflected system, the sum of β' and β provides a true normalization, since the contribution of the reflectors must be accounted for. The general implication is directed towards efforts to calculate the value of k for a reflected system, and then attempting to evaluate the kinetic behavior from the resulting value. Often, the reflector contributions can be significantly greater than the delayed

neutron fraction. If not accounted for, then one would greatly exaggerate the estimated impact on a change in k to a reflected system. A more appropriate approach would be to calculate the value of k with and without reflectors in place, to determine the reflector worth, and then use the value $(\beta+\beta')$ to normalize to dollars. This will improve the situation somewhat, however, as can be seen from equation 9, one also needs to have an understanding of the time constants involved before the kinetic effects of a reflector can be fully appreciated.

2. From equation 14, a negative experiment reactivity worth can be seen to result from a situation where the experiment impacts k^{B} by reducing the unreflected non-leakage probability. Since an experiment external to the reactor cannot induce more neutrons to leak from the reactor than otherwise, external experiments can never be negative worth. Only absorbing experiments within the central cavity can result in what would appear as higher leakage, by reducing the number of neutrons that would normally transit the central cavity and re-enter the fuel. For an experiment with a negative reactivity worth, the control element contributions must be increased by an equal amount to re-establish the critical condition.

3. Neutron generation time for the reflected core is determined by combining equations 14 and 15, yielding $\ell = \ell_{o}^{\mathrm{B}} / k^{\mathrm{B}}$. This equation demonstrates that neutron generation time is always equal to the generation time for the bare core, independent of the presence of reflectors. This may not seem intuitive at first, but recall that the neutron generation time is a characteristic of the prompt neutrons that are created and absorbed without ever escaping the core. The reflector source term has accounted for the time delays associated with reflected neutrons separately, and therefore the generation time would not be affected.

4. Equation 15 shows that neutron lifetime is a function of the contribution from reflectors, which includes both the control elements and the experiments. This effect is contrary to that on the neutron generation time. To satisfy equation 14 at the critical point of $k=1$, then, as discussed in #1 above, the sum of the various reflector contributions will always equal the same value. Therefore, while the presence of experiments does affect neutron lifetime, the influence is independent of their nature.

5. Validation of the Model with SPR III Observations

As stated earlier, the Pulse Analysis System is normally used during all reactor pulse operations, resulting in a large body of measurements of the kinetics behavior of SPR III and of the influence of experiments. Coupling the operations log sheets and the Pulse Analysis System results together provides a large amount of data that characterizes each operation.

For the purpose of this study, a database of almost 700 pulse operations covering a wide range of experiments was constructed. Typical experiments at the facility can range from large quantities of polyethylene and fissile material in the central cavity to large quantities of steel near the external surfaces of the core. Experiment reactivity worths ranged from -$3.10 to +$2.40, and included both central cavity and external locations. Since most experiments were complex and composed of multiple materials, and were not well described in operating logs, so they were categorized only by reactivity worth and relative location.

The most obvious and most often observed influence of experiments on FBRs such as SPR III has been the change in initial reactor period for a given reactivity insertion. This effect is demonstrated in figure 4. The common interpretation of this observation has been to assume that the reflected neutrons from the experiments have changed the effective neutron lifetime of the system, which was demonstrated in the previous section.

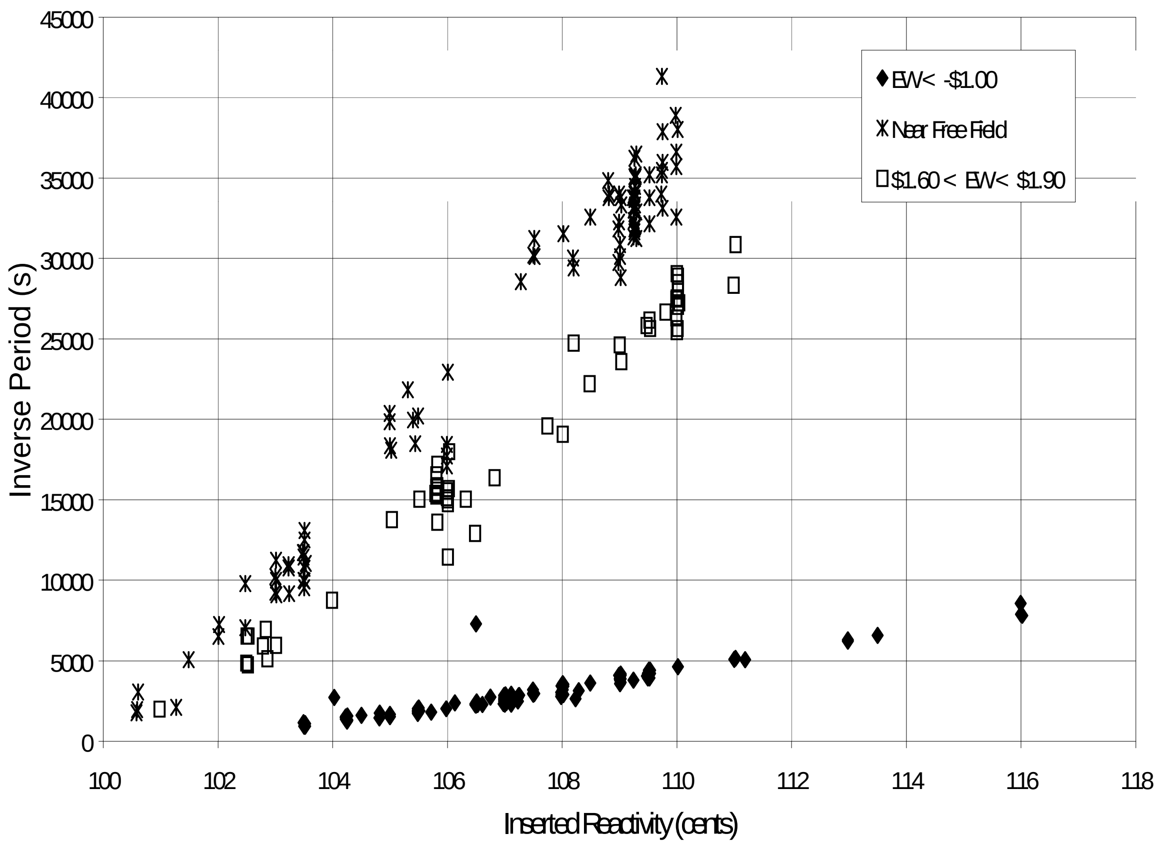

Figure 4: The inverse of the initial reactor period as a function of inserted reactivity, grouped by experiment worth[8].

Other effects are also observed with changes in experiment conditions, including the pulse yield as a function of inserted reactivity, and the peak power[8]. Since the negative temperature coefficient of the fuel was believed to be relatively constant and independent of initial reactor period, these observations were originally perceived to be due to changes in the control element differential worths such that the inserted reactivity was changing from the free field calibration of the elements. Figure 5 demonstrates the change in the negative temperature coefficient as a function of experiment reactivity worth.

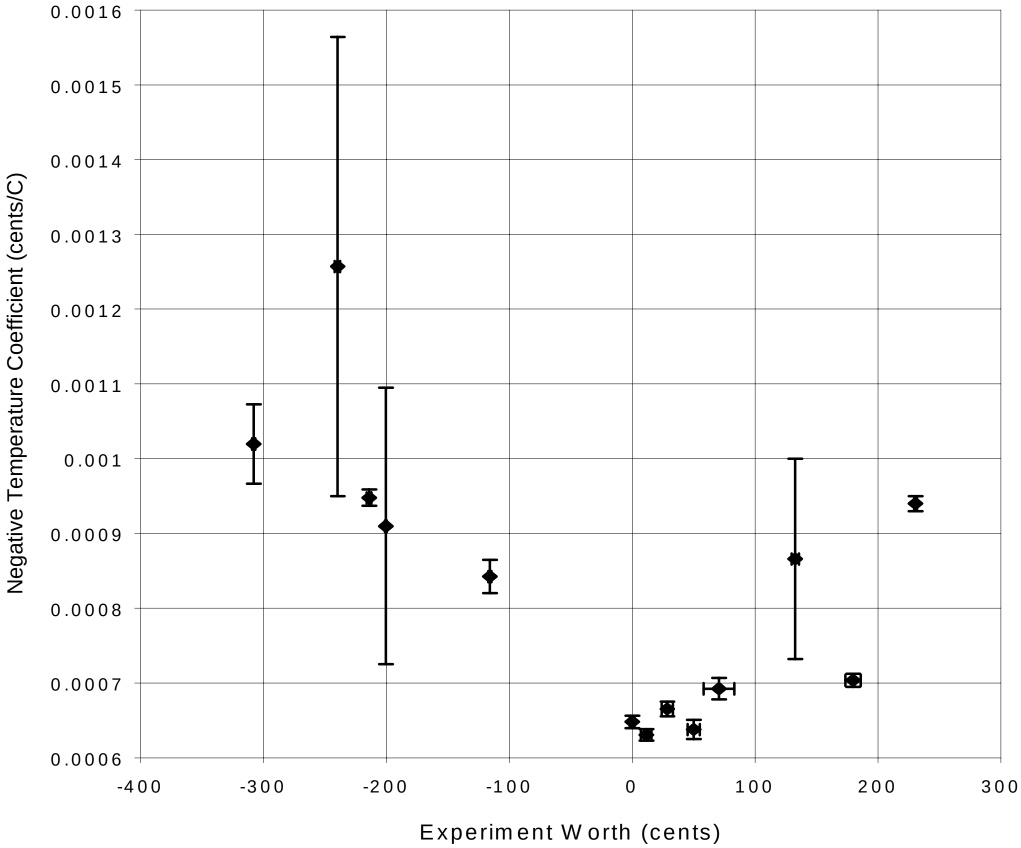

Figure 5: The negative temperature coefficient for discrete experiments, shown as a function of experiment reactivity worth. The error bars represent $\pm 1\sigma$. [8]

Pulse characteristics collected with the Pulse Analysis System demonstrated that other parameters were also changing unexpectedly. These parameters were indications that the symmetry of the pulse was affected by the experiment. Since traditional theories indicated that as long as delayed neutrons could be ignored, as is the case when operating in the prompt critical reactivity regime, then the pulse should be symmetrical. The only exception to this would be due to the influence of thermoelasticity, which would lead to a predictable change in the symmetry. However, the observed changes were not consistent with these predictions, and in some cases were in exactly the opposite direction. These observations could not be accounted for by changes in neutron lifetime, since the symmetry of the pulse is independent of the lifetime.

Table II demonstrates the results of validating the modified reflected point-reactor kinetics model against one group of experiments. The experiments used for evaluation were located in the reactor's central cavity. They were composed of combinations of steel and polyethylene, and may contain small quantities of enriched uranium, typically on the order of a few grams. Consequently, they are negative reactivity worth experiments. The model used three groups to account for all reflectors, one for the control elements and the other two for the experiment's fast and slow components. Note in particular the ratio of the full-width-half-maximum (FWHM) to the period, which is a measure of the symmetry of the pulse. Traditional point-reactor kinetics would suggest that this ratio should be a constant value of 3.525, if delayed neutrons can be ignored.

Table II: High Negative Worth Internal Experiment Pulse Comparison[8]

	Insertion ($)	Initial Period (μs)	Temperature Increase (C)	FWHM (μs)	FWHM/Period Ratio
Actual: (n = 8)	1.0425	710 ± 57	100 ± 7	2783 ± 221	3.92
Model:	1.0425	664	96	2594	3.91
Actual: (n = 6)	1.055	536 ± 31	123 ± 6	2161 ± 135	4.03
Model:	1.055	500	121	2001	4.00
Actual: (n = 23)	1.07	392 ± 26	149 ± 6	1620 ± 84	4.14
Model:	1.07	379	151	1567	4.14
Actual: (n = 11)	1.08	311 ± 30	176 ± 8	1319 ± 90	4.26
Model:	1.08	324	173	1368	4.22
Actual: (n = 11)	1.095	242 ± 9	204 ± 5	1060 ± 39	4.39
Model:	1.095	263	206	1147	4.36
Actual: (n = 2)	1.13	160	250	740	4.63
Model:	1.13	176	271	827	4.70

Model Parameters: Experiment Worth = -$2.14 (Control reflector worths are increased to compensate for negative worth.)

Parameter	Group 1	Group 2	CE Group
β'	$1.78	$0.36	$3.24
τ'_2	15 ns	3,000 ns	16 ns
τ_3	30 ns	75,000 ns	40 ns
τ'_4	20 ns	50 ns	20 ns

The model adequately demonstrates the changes in pulse behavior under a variety of experiment conditions, as shown in figure 6. This figure shows how SPR III yields change with the various types of experiments conducted.

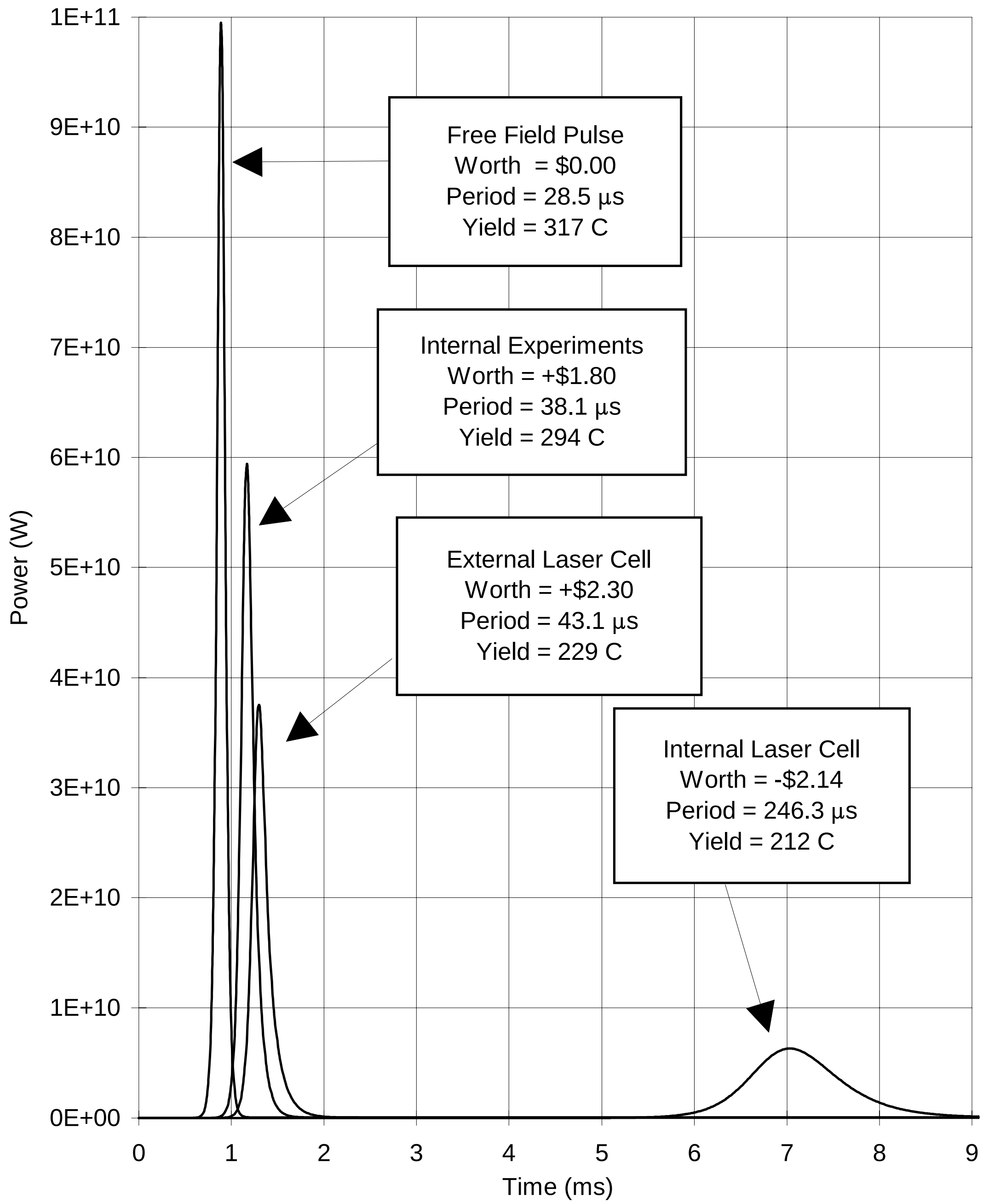

Figure 6: Calculated power histories for SPR III pulses under four experimental conditions, as described. The reactivity insertion was the same for all four pulses, equal to $1.10.[8]

6. Conclusions

The modified reflected point-kinetics equations derived above demonstrate that reflected neutrons will appear to the reactor as delayed neutrons, but on different time scales from those normally associated with delayed neutron precursors. This leads to the observation that the influence of reflected neutrons will vary based on the rate of change in the neutron flux:

1. Slow transients, where the reactor period is much longer than the reflector time delays, are not affected by reflectors dynamically, as $n(t-\tau_2') \rightarrow n(t)$ and $C'(t-\tau_4') \rightarrow C'(t)$. This is the case in most minipulse operations, which are performed with periods of around 200 milliseconds. This will also explain why kinetics models that do not account for the time delays will provide reasonable results below prompt critical.

2. For fast transients, the time delays could result in the reflected neutrons returning to the core within the timeframe of the pulse. This would result in extending the backside of the pulse, changing the symmetry.

3. For very fast transients, depending on reflector time constants, it would be possible for the pulse to 'outrun' some energy groups of reflected neutrons, similar to ignoring delayed neutrons in fast transients. Under most conditions this is unlikely, since distances are short and neutron energies are high, but may be observed under some conditions where the residence time constant is very long. In this case, the reflected neutrons would return to the core in the power tail, and could result in a secondary power oscillation. (This has been observed on rare occasions with particular experiments on SPR III.)

4. In most cases, the reflected neutrons from the experiments will tend to influence the pulses in a variety of ways. Depending on the individual time constants, these influences could result in slower initial periods, broader pulses, and/or asymmetric pulse shapes.

β'_{exp} is a function of both size and proximity of the experiment in relation to the core. The solid angle within which a reflected neutron will re-enter the core is, however, inversely proportional to distance; therefore, only close or extremely massive experiments will have significant values of β'_{exp}'s.

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