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Fast Shutter for Low Background Radiation Environments at SPR III¹

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Abstract

A fast shutter system has been developed and used to isolate experiments from the radiation emitted after the main pulse of the Sandia Pulsed Reactor, SPR III. In about 15 ms the system moves a massive 20 kg shield in front of the beam port aperture in the facility shield wall. A second gravity-driven shutter is dropped into place in about 200 ms. The total attenuation achieved in the beam intensity is about a factor of one hundred. The shutter assembly was used, along with a sensitive detection system, to observe the gamma ray flux emitted by various materials activated by the neutron beam at levels nine orders of magnitude smaller than the gamma flux level at the target during the reactor pulse.

I. INTRODUCTION

The beam port through the shield building (kiva) that surrounds the fast burst reactor, SPR III, at Sandia National Laboratories (SNL) has been very useful for a wide variety of experiments ever since it was drilled in 1967. Its primary useful feature is that it delivers a high intensity beam to target objects while providing space all around that beam for experimental equipment that can be extremely well isolated from the reactor radiations. Because of the fact that the wall surrounds the reactor, the only path for radiation between the core and the outside test region is either through the port or the wall. This is more important than it might first seem because neutrons are so easy to scatter around shield walls and through holes and cracks in a temporary shield that might be assembled inside the kiva.

Recently, some significant improvements have been made to the facility that have rendered it much more useful and adaptable to the requirements of users. The primary motivation for developing the system was to support an experimental program at the Nevada Test Site (NTS), which required the observation of activation induced in various materials soon after

irradiation by neutrons from a nuclear burst. For these tests it was necessary to protect both the object being irradiated and the detector system (used to monitor the induced activity) from the radiation from the core during the tail of the pulse.

The problem at NTS was that certain equipment in an experimental alcove had to be able to regain function soon after the main radiation pulse, but the background radiation level was too high to permit the monitoring of the system performance. Initial investigation indicated that the neutrons, scattered and moderated in the alcove, activated materials in the vicinity of or even within the instrumentation. The sources of this late-time activity had to be identified experimentally because theoretical modeling had predicted late-time radiation levels as much as ten times lower than what was observed.

The configuration of the SPR III facility appeared to be appropriate for the investigation of this problem, provided a ready method could be found to allow observation of the very low activation induced in the test materials after a pulse from the core located seven meters away. First, modifications have been made to the reactor cable runs so that the reactor can be operated near the beam port. The intensity through the port to the outside exposure area can thereby be enhanced by about a factor of four. (The distance between the core and the object can be reduced from about seven to less than three meters.) SPR III has not yet been operated next to the beam port, although SPR II was some years ago. The tests discussed below were conducted with the reactor at its usual position at the center of the kiva. Second, to further isolate experiments designed to measure phenomena that take place after the main pulse, a fast shutter system with additional collimators and shields was developed and used for tests conducted in 1992.

The primary purpose of this paper is to provide the test community with information about these expanded capabilities and about the new configurations and test equipment that are available.

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II. THE TEST CONFIGURATION

A. The SPR III Core, Kiva, and Beam Port

The geometry of the reactor, the kiva shield, and the beam port are shown in Figure 1. The shield building for the reactor is a dome of high density concrete 1.37 m thick. The inside surface is also protected by 10 cm of gypsum and 10 cm of boron-loaded gypsum. The beam port is a steel-lined penetration that consists of a 25.4-cm-diameter tube at the inside of the wall that steps up to a 30.5-cm-diameter tube toward the outside. Various collimator structures can be inserted to customize the beam. In the case of the experiments to be discussed below, plates of borated polyethylene and lead with appropriate aperture sizes were inserted into and behind the port to form a 10-cm-diameter beam at the target.

the object. In that arrangement the beam, after leaving the main collimator, did not strike anything other than the object. In that case, a 7-cm-thick polyethylene plate was placed next to the core to enhance the fluence of thermal neutrons that induce the activation in the target. By being next to the core these neutrons were also collimated by the apertures and therefore did not directly irradiate the detector or its shield.

Calculation, however, indicated that more thermal fluence could be obtained at the target by removing the polyethylene next to the core and surrounding the target with a polyethylene moderator "doghouse" as shown in Figure 2a. Therefore the use of the configuration with no doghouse was discontinued for the active tests. Indeed, the tests showed that the doghouse arrangement increased the thermal fluence by 57%, but, as one might expect, the scattered radiation increased the background at the detector substantially.

Figure 1. Beam Configuration

B. The Shield and Shutter Geometries

Outside the port additional shield walls containing apertures for the beam and for protecting the detectors were assembled on two tables that also supported the shutter systems. The shutter systems were mounted on one table while the shield and apertures were mounted on the other to minimize the shocks transferred to the instrumentation systems. Actually, three different arrangements were investigated during the tests, but time was limited, and it turned out that only the last two, represented in Figures 2a and 2b, were used in the active tests. In all cases, a layer of boron-loaded material (boral) was placed between the beam and the detector alcove to reduce the activation around and within the detector.

The layout was originally designed for configuration 2a without the polyethylene moderating "doghouse" surrounding

The Figure 2b layout was tried during the second week of tests because calculations indicated that a substantial portion of the background at the detector was coming through the edges of the collimator, and that it might be reduced by placing part of the main aperture behind the fast shutter. However, this layout change could not be accomplished very well because the support structure for the fast shutter system interfered with the positioning of the aperture wall.

The apertures, collimators and shields were made up of layers of polyethylene, boral, lead and steel. The relative thicknesses were partially based on beam transport calculations performed by the MCNP code [1], and partially by our ability to respond on short notice to design changes.

Figure 2a.

Figure 2b.

Figure 2. Collimator and Shield Arrangements Outside the Kiva

C. The Shutter Systems

The fast shutter is driven by an very sophisticated gas-activated piston mounted in a two-compartment, cylindrical chamber. Devices with high pressures on large areas can be very dangerous, and in all cases the piston motion must be precisely controlled from the time the chambers are pressurized until they are totally discharged. The entire sequence is handled by an electronic control system that provides limitations on the sequences and the pressures allowed in the chambers, the firing mode and time, and the venting of the gases. A data acquisition system records the history of the gas system during the event, and the data is analyzed and stored by a computer system.

The outputs of as many as four accelerometers can be mounted on various parts of the system to record the accelerations and velocities of the event. The results are digitized and analyzed to produce immediate plots of the motion parameters vs time. The entire system, called HYGE, was designed and fabricated for another purpose for which the deceleration history at the end of the motion was the important parameter. It was designed to safely decelerate a 20-kg mass at 5000 g (acceleration of gravity at the earth's surface), and reach speeds of 45 m/s in 15 cm of travel. The maximum pressure allowed in the cylinders is about 6.9×10^6 Pascals (1000 psig). The deceleration phase was controled by layers of wool pads placed between the back of the shaft plate on which the experiment was mounted (in this case the shutter) and the outside of the driving cylinder. The configuration, without the pads, is shown in Figure 1. For this application the pads were used to cushion the shutter from damage at the end of its travel.

It takes a few hundred milleseconds to assemble the reactor in preparation for the pulse, and a few tens of milleseconds to move the shutter, so in order to coordinate the two events, the following timing sequence was arranged. After the reactor was configured for a pulse, a signal from the firing of the burst rod was delayed and then used to fire the shutter gas drive. Because it takes about 200 ms for the burst rod to move into place, and about 80 ms until the shutter starts moving after the trigger pulse arrives, the trigger was delayed 120 ms before being sent to the HYGE. Just as the shutter arrived at the edge of the aperture, a laser beam was uncovered to a photodetector that fired a neutron generator and initiated the reactor pulse. There is usually approximately 50 ms of time available after fuel assembly before a wandering (background) neutron will initiate the pulse (ahead of the neutron generator). The neutron generator will initiate the pulse within 1 ms of the trigger.

By this time the shutter was at maximum speed as it entered the aperture and was being decelerated by wool pads. To achieve the fast closure it was necessary to allow some overshoot in the travel, and as a result a narrow pulse of radiation passed by the shutter during this time. For this application of the HYGE the maximum deceleration reached only 200 g.

The triggering of the neutron generator on the arrival of the shutter at the edge of the aperture minimized the jitter in the time between the reactor pulse and the shutter closure.

An additional shutter composed of steel and polyethylene was dropped in front of the aperture at the same time, but took about 200 ms to fall into place. Its fall was initiated by a solenoid latch at the same time as the fast shutter.

III. RADIATION TRANSPORT CALCULATIONS

Although the basic hardware structure design had to be frozen before the radiation transport calculations for the shields and collimators could be carried out, the calculations were very useful in two ways. First, (as mentioned in Section II), they were used to help determine the relative thicknesses, positions, and materials to be used in the final assembly. Second, they were used to predict the detector signals for various configurations and target materials as a function of time.

Examples of the predicted signals at the detector location, as calculated with the MCNP code are shown in Figure 3. A more extensive summary of these calculations is contained in reference 2. The three heavy lines in descending magnitude represent the signal with both shutters open, the signal with the fast shutter closed, and the signal with both shutters closed. In the three cases there is no target object in place to be activated. One can imagine that the signal would start on the line representing the signal with both open shutters, then shift down to the second line as the fast shutter closes, and then to the third as the gravity shutter closes. Superimposed on this shifting signal would be the radiations from the activated object. Their potential contributions are represented by the lighter lines drawn in the same figure and identified in the legend.

An example of what one might look for is the following. Without the shutters in place, the activity of a suitable mass of aluminum might not be observable until 100 s after the pulse, as one can see in Figure 3. But with both shutters in place, which occurs 200 ms after the pulse, it might be seen. This is because the background has by that time dropped to the bottom "heavy" line in the figure. In addition, the activity of a polyethylene object would not be observable at all with the present system. The calculated signals in Figure 3 were for the configuration shown in Figure 2a which was used during the first week of the active tests. The configuration shown in Figure 2a without the "doghouse", in which the thermal neutrons came from the polyethylene plate next to the core, was not used during the dynamic tests because it was felt that with the core in the center of the kiva, there would not be enough beam intensity.

Figure 3. Predicted Core and Activation Dose Rates in the Beam

IV. RESULTS

A. Fluence Measurements

Neutron fluence monitors and TLD gamma-ray dosimeters were placed at many places beyond the kiva wall to characterize the radiation environments with the shutters open and closed. Sulfur, gold, and nickel foils were placed in the beam to determine the magnitude of the neutron fluence and the attenuation of the shutters. The signals were too weak for neutron measurements outside the beam with the foils that we had available. For the determination of the fluences, it was assumed that the spectrum shape for the fast neutrons was the same as that determined earlier inside the SPR III cavity lined with polyethylene. At the thermal end of the spectrum, the shape and magnitude were also determined by scaling the gold foil results (obtained from cadmium covered and bare foils) to the same spectrum.

The results of these measurements are shown in Table 1.

Table 1. Neutron Fluence at the Target Position

Configuration	$\Phi(0.5 \text{ eV})$ (n/cm ²)	$\Phi(3 \text{ MeV})$ (n/cm ²)	$\Phi(10 \text{ keV})$ (n/cm ²)
Bare core with no poly	1.50E+7	7.40E+9	6.05E+10
7 cm poly plate at core	2.33E+9	2.03E+9	1.70E+10
Poly doghouse at the target	3.67E+9	6.93E+9	5.81E+10

In Table 1, the $\Phi(E)$ stands for the integral neutron fluence in the pulse where with $E = 0.5 \text{ eV}$ it is the fluence less than that energy, but for $E = 3 \text{ MeV}$ and $E = 10 \text{ keV}$, it stands for the fluence greater than the respective energy.

The neutron fluences listed in column 2 show that the thermal fluence obtained from the beam striking the polyethylene

dog house at the target location was only 57% higher than for the case with the polyethylene placed next to the reactor. On the other hand, the TLD data indicated that the additional neutron scattering caused by the polyethylene raised the gamma-ray background at the detector by a factor of 30. This does not mean that 15 ms after the reactor pulse, when the fast shutter is closed, the gamma-ray background at the detector would be a factor of 30 higher. The activity induced in the polyethylene dies away rapidly. The question is, what additional lasting activity is induced by these locally generated thermal neutrons? Only the active measurements and calculations could shed light on that question.

B. The Active Measurements

The gamma-ray histories were measured with three detector systems -- a scintillator-photodiode, a scintillator-low-gain-photomultiplier tube (PM), and scintillator-high-gain PM tube. Since only the high-gain PM tube arrangement was used for the activation measurements, and because it was the most successful detector, only results obtained with that system are discussed here. The scintillator was made of 10-cm-diameter plastic NE-102. For more information about the detectors, see Reference 2.

Traces of the detector signal vs time obtained with the shutters open and with the shutters operating are shown in Figure 4. The detector was in the beam line for both measure-

Figure 4. Measured Open- and Operating-Shutter Dose Rates in the Beam

ments, and there was no other target. During the recording period the flux could be followed over eight orders of magnitude because the PM tube was electronically switched from a low-gain to a high-gain mode after the main reactor pulse [2]. The effectiveness of the shutters is clearly visible in the differences between the two traces. The events are noted on the figure. Because the fast shutter underwent a single bounce and

got out of line with the aperture for a short time, a secondary peak appears in the lower trace. It turned out that this extra flux peak did not cause a serious problem with the interpretation of the data, and served as a useful fiducial mark. The combined gamma signal attenuation by the shutters was about a factor of one hundred.

When the detector was moved into the shielded alcove next to the beam, traces like those in Figure 5 were obtained.

Figure 5. Activation Dose Rates in the Detector Alcove

The trace with the lower flux at late times is from the case with a steel target. The other shows the signal produced by the 0.8 second half life activity of a lead target. Without the shutter and shield systems it would not have been possible to see the activation of the lead.

C. Evaluation of the Results

The collimator, shield, and shutter systems were very successful in isolating the activated target and the detector from the reactor-generated radiation during the tail of the pulse for many of the targets that were investigated. Analysis showed that there were no unexpected activity values observed. The shutter, the electronic control, and the data acquisition systems operated reliably. The only major features that can be easily improved upon would be an increase in signal and in signal to background ratio so that more weakly activated materials could be evaluated.

V. DISCUSSION AND CONCLUSIONS

A. Improvements

There are a number of obvious improvements that can be made to the system that the authors believe can raise the signal levels by a factor of three and raise the signal to background

level by a factor of ten. In fact, most of these changes would have been made at the outset if time and funds had been available. The improvements might be the following:

- Move the reactor close to the beam port. This will raise the signal by a factor of about four.
- Change the HYGE support stand so the shutter can be placed closer to the kiva port exit.
- Use the configuration in which the thermal neutrons are generated by the polyethylene slab next to the core inside the kiva. There would then be a minimum of scattering that can activate materials near the detector.
- Use better and more massive shielding whose design can be controlled in advance by MCNP transport calculations.
- Improve shutter design by incorporating optimized materials, better deceleration techniques that eliminate the bounce, better shutter shape to more effectively cover the aperture, and perhaps a system to release the gravity shield at an earlier time.
- Provide a secondary shutter that protects the detector during the main pulse.
- Use the fabricated bracket, which was designed to hold the target and be mounted on the fast shutter, so that as the shutter covered the aperture, the target would be yanked out of the beam and into the detector alcove. (This configuration has not been tested.)

B. Other Uses

The fast shutter system is worth consideration for use in any test situation for which monitoring an experiment after irradiation in a reactor environment is necessary. The shutter and shield system effectively isolates the target object and any monitoring instrumentation from the tail of the radiation pulse so that very small effects can be evaluated. Some suggested uses are the following:

- Recovery of Function- when does the object regain function within specifications after being irradiated? Potential targets are radiation monitoring systems for personnel, space systems, power and research reactors, general electronics, and optical systems.
- Damage Annealing- the basic properties of semiconductor materials and electronics can be investigated by the study of parameter histories after irradiation.
- Activation Analysis- the case described in this paper is an example that required observation over many orders of magnitude.

VI. REFERENCES

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- [2] "Hunter's Trophy Late Time Gamma, Vol. 1: AGT/UGT Correlations", POR 7503-1, Science Applications International Corporation, P. O. Box 19057, Las Vegas, NV, 89119-0057, March 1994.

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