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Benchmark Field Study of Deep Neutron Penetration*

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ABSTRACT

A unique benchmark neutron field has been established at the Lawrence Livermore National Laboratory (LLNL) to study deep penetration neutron transport. At LLNL, a tandem accelerator is used to generate a monoenergetic neutron source that permits investigation of deep neutron penetration under conditions that are virtually ideal to model, namely the transport of mono-energetic neutrons through a single material in a simple geometry. General features of the Lawrence Tandem (LATAN) benchmark field are described with emphasis on neutron source characteristics and room return background. The single material chosen for the first benchmark, LATAN-1, is a steel representative of Light Water Reactor (LWR) Pressure Vessels (PV).

1. Introduction

In recognition of significant safety and economic issues associated with radiation-induced embrittlement of reactor pressure vessels, the U. S. Nuclear Regulatory Commission (NRC) sponsored the light water reactor pressure vessel surveillance dosimetry improvement program (LWR-PV-SDIP) over the last decade or more to improve, maintain, and standardize neutron dosimetry, damage correlation, and the associated reactor analysis procedures used to predict the integrated effect of neutron exposure to LWR-PV. Owing to the complexity of this embrittlement phenomenon, experimental and calculational strategies formulated in the LWR-PV-SDIP were subsequently implemented in a multi-laboratory international program.

Four principal laboratories collaborated in the conduct of this program:

Centre D'Etude De L'Energie Nucleaire/Studiecentrum Voor Kernenergie (CEN/SCK),
Mol, Belgium;

Hanford Engineering Development Laboratory (HEDL),
Richland, Washington;

National Bureau of Standards (NBS), Gaithersburg, Maryland;

Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee.

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Subsequently, collaboration with additional European laboratories was established:

Rolls-Royce & Associates, Ltd., (RRA), Derby, U. K.

United Kingdom Atomic Energy Establishment Winfrith (UKAEEW),
Winfrith, U.K.

Kernforschungsanlage, Jülich, GmbH, (KFA), Jülich,
Federal Republic of Germany.

Through the complementary capabilities of personnel at these seven laboratories, it has been possible to carry out a productive and highly cost-effective program. The major benefit of LWR-PV-SDIP has been and continues to be a significant improvement in the accuracy of the assessment of the current metallurgical condition and the remaining safe operating lifetime of LWR-PV.¹ These efforts have been extensively reported in the ASTM-EURATOM series of symposia on Reactor Dosimetry, and a review of the status and accomplishments of the LWR-PV-SDIP was presented at the very last symposia in Jackson Hole.²

Benchmark fields have served as important elements in implementing experimental and calculational strategies adopted in the LWR-PV-SDIP. In the broadest sense, a benchmark neutron field represents a practical test bed for the testing, validation, and confrontation of different methods, be they experimental or theoretical. Progress by trial and error is, perhaps, the essence of benchmark field work. One essential characteristic of a benchmark field is that all environmental variables are well controlled and accurately defined. Benchmark fields can be used primarily for calculational purposes. In many instances they are used for both experimental and calculational purposes simultaneously.

Independent contributions from U. S. and EURATOM laboratories participating in LWR-PV-SDIP benchmark field studies have confirmed the existence of a serious and persistent discrepancy between neutron field calculations and experiment. The calculated-to-experimental (C/E) ratio is considerably less than unity in LWR-PV environments. Moreover, this discrepancy increases, i.e., C/E decreases farther from unity, with increasing neutron energy and with increasing depth of penetration into the PV.

This discrepancy is the most significant issue in current LWR-PVS neutron dosimetry efforts. Since the PV is non-replaceable, radiation induced embrittlement of the PV controls the effective lifetime of a nuclear power plant. Because of the critical nature of the PV, successful resolution of this discrepancy would have a major impact on current plant life extension (PLEX) efforts for LWR.

It must be emphasized that the same general discrepancy has arisen in another international neutron dosimetry program conducted for completely different reasons. Within nearly the same time frame that LWR-PV-SDIP was conducted, a joint US-Japan program was carried out to re-evaluate radiation exposures of atom bomb survivors. A final report describing the results and conclusions of this program, which has been designated by Dosimetry System 1986 (DS86), has been issued.³ In general, studies of Hiroshima and Nagasaki atom bomb survivors have provided valuable data for quantifying the effects of radiation on man. These data have been used by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for comprehensive assessments of the effects and risks of ionizing radiation. Conclusions of UNSCEAR reports^{4,5} often form the basis that governments use for policy decisions on radiation protection standards.

An essential part of this joint U.S.-Japan re-assessment program for evaluating radiation doses at Hiroshima and Nagasaki has been the replication of Little Boy in the form of a critical reactor assembly. Replication of Little Boy, which was the atom bomb exploded at Hiroshima, was faithfully accomplished at Los Alamos National Laboratory (LANL). Available specifications together with

spare or excess parts were used to set up and operate the Little Boy replica as a low power critical reactor assembly at LANL. Replication of Little Boy included the thick steel casing of the bomb. The thickness of this casing varied with polar angle, with a minimum thickness at the waist of the assembly (90°), which is comparable to the nominal 8-inch thickness of a LWR-PV. The steel casing thickness increases with decreasing polar angle to a maximum thickness near the top of the assembly (0°) that is considerably larger than the nominal LWR-PV thickness. Consequently, the Little Boy replica shares one significant feature with all LWR-PV-SDIP benchmarks, namely deep penetration neutron transport in steel.

In view of the sparsity of neutron dosimetry data that actually exists from the Hiroshima and Nagasaki sites,⁶ calculations have been relied upon to generate A-bomb radiation exposures. Hence, this Little Boy replica constitutes a benchmark radiation field for the testing and intercomparisons of experimental and calculational radiation metrology methods. Rigorous testing of these calculational methods using the Little Boy benchmark was a crucial aspect of this program. Extensive experimental and calculational efforts have been expended to characterize the radiation field emitted by the Little Boy replica.⁷⁻⁹ Both the neutron and gamma-ray components of this mixed radiation field have been addressed. These Little Boy replica characterization efforts are reviewed in Chapter 2 of the final report on DS86,¹⁰ where it is concluded that the C/E ratio is acceptable at the waist of the critical assembly (90°), but C/E decreases and can be as low as 0.7 at the top of the critical assembly (0°).

This C/E trend is evident in nuclear research emulsion (NRE) neutron spectrometry carried out at the Little Boy replica.^{11,12} However, the more detailed absolute power normalization experiments of the Little Boy replica conducted with solid state recorders (SSTR)¹³ yield a C/E behavior for these NRE data that is qualitatively identical to LWR-PV-SDIP benchmark results. More specifically, one finds that C/E decreases with increasing penetration from approximately 0.7 at 90° to 0.5 at 0° . Moreover, these NRE data also confirm the trend for C/E to decrease with increasing neutron energy.

2. Speculative Ad-Hoc Solutions

The persistent nature of this discrepancy in different LWR-PV-SDIP benchmark fields, such as the PCA, VENUS and NESDIP, has fueled the speculation that deficiencies exist in the neutron cross section of iron. In fact, two different groups have introduced different adjustments of the inelastic cross section of iron to obtain improved C/E ratios.¹⁴⁻¹⁷ However, these adjusted iron cross sections do not provide consistent improvements, but rather results that vary from one LWR-PV environment to another.

Concern about the uniqueness of such cross section adjustments has already been raised.² Indeed, arbitrary changes in the iron inelastic cross section can reduce the magnitude of this discrepancy for certain cases, but there is no definitive experimental basis for making these adjustments. It is, therefore, not surprising to learn that this (non-unique) adjustment does not consistently provide unproved C/E ratios in other environments.

Perhaps an even simpler ad-hoc solution can be obtained by adjusting the high energy portion of the fission neutron spectrum. Indeed, the physics of deep penetration transport in reactor environments places considerable importance on the high energy portion of the fission spectrum. Moreover, for deep penetration neutron transport, emphasis is not placed on a fixed energy region of the fission neutron spectrum, but rather shifts upward in energy as the depth of penetration increases. Deficiencies in this high energy region, in particular use of a source term that provides too few high energy neutrons, could qualitatively explain both the energy and penetration dependent trends of the discrepancy obtained in the LWR-PV-SDIP and the Little Boy benchmarks.

Examination of the experimental data defining the higher energy region of the fission neutron spectrum, especially above 8 MeV, reveals very poor statistical precision. Moreover, the latest comparison

between theory and experiment¹⁸ suggests significant uncertainties in this high energy region of the fission neutron spectrum. However, arbitrary adjustments of the high energy region of this spectrum can yield solutions that possess the same non-uniqueness obtained from cross section adjustments.

3. Deep Penetration Neutron Benchmark Field

Benchmark neutron fields established for both LWR-PV-SDIP and Little Boy have addressed specific real world issues. In so doing, these benchmarks have had to simulate the actual transport of fission spectrum neutrons through composite materials in complex geometries. While these elements were necessary to the basic purpose of these benchmarks, they present serious difficulties for the resolution of the observed discrepancy.

Indeed, it is difficult, if not impossible, to resolve this significant discrepancy in neutron dosimetry let alone attain more stringent accuracy goals required to implement PLEX or establish personnel radiation protection standards with a "business as usual" approach. Use of the same experimental and theoretical methods, whether in power reactor PV environments or LWR-PV benchmark field tests, will in all likelihood repeat past history rather than provide new insights. Results from the series of dedicated LWR-PV benchmarks at VENUS and NESDIP verify this conclusion. What is needed is a new and independent benchmark field that provides simpler and more ideal conditions for the comparison of theory and experiment, so that a higher plane of understanding of deep penetration neutron transport can be achieved.

To satisfy this need for a higher plane of understanding, a unique benchmark field has been set up at the Lawrence Livermore National Laboratory (LLNL). At LLNL, a tandem accelerator facility is used to study neutron transport from a monoenergetic source through a single material in a simple geometry.

Some of the more significant advantages of the Lawrence Tandem (LATAN) benchmark field are:

1. Simplified Geometry

- (a) Single Material
- (b) Point Source
- (c) Cylindrical Symmetry

2. Monoenergetic Neutron Source

- (a) Energy of the monoenergetic source neutrons can be varied
- (b) Independence of the fission neutron spectrum

The single material chosen for the first benchmark, LATAN-1, is a steel representative of LWR-PV. Because it has been demonstrated that active neutron detectors, such as fission chambers and proportional counters, produce non-negligible perturbations, measurements in LATAN-1 will initially emphasize passive dosimeters. Passive neutron dosimeters of high sensitivity and absolute accuracy will be used, such as SSFR and NRE. In contrast with conducting a sequence or series of irradiations, LATAN-1 irradiations have used a three-dimensional array of these passive dosimeters embedded at different mean-free-path locations from the point source. This approach reduces the need for normalization between irradiations with a concomitant reduction of systematic uncertainty.

4. The LATAN Benchmark Neutron Field

Monoenergetic neutrons for the irradiations are generated by nuclear reactions in a gas target system. The deuteron beam from the LLNL Tandem is incident on a newly designed gas cell located at the end of the 0 beam line. By filling the cell with various gases, such as deuterium or tritium, monoenergetic neutrons are produced with energies from 2 to 20 MeV.¹⁹ For a typical gas fill of 5 atm of deuterium, a neutron beam of 5×10^7 neutrons/sec, strongly peaked around zero degrees, is produced. For LATAN-1, these neutrons are then incident on the center of a cylindrically symmetric assembly of the representative steel with appropriately placed neutron dosimeters, such as SSRT, located throughout the assembly. The absolute magnitude of the neutron flux is measured by the associated particle technique. A solid state detector is used to count the number of charged particles produced in the gas cell and this result is used to determine the absolute number of emitted neutrons.

One of the most important limitations of this kind of benchmark neutron field can be the room return background, i.e., the neutrons which scatter in the material surrounding the experimental facility and then find their way back into the assembly. The experimental hall at the LLNL Tandem was designed to reduce this problem. The walls are thin and most of the neutrons are allowed to pass out of the experimental area and to interact at a large distance in an earthen berm, where their effect is reduced by $1/R^2$. However, the floor of the experimental hall is heavy concrete, and the hall contains heavy experimental equipment such as switching and quadrupoles magnets, which can act as effective neutron scattering sources. Consequently, a combination of experimental and computational methods are used to understand the magnitude of this room return effect.

Experimentally the magnitude of the room return can be studied by using a pulsed deuteron beam and active neutron detectors. A short pulse (~ 1 ns) of deuterons is incident on the gas cell and active neutron detectors located within the assembly are used to measure the return neutron intensity as a function of time. These results are compared with extensive Monte Carlo neutron transport calculations, which mock-up most of the significant neutron scattering sources. The agreement between measured and calculated values of the room return increases our confidence in the values assigned to this background effect.

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