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Burnup Monitoring for Pebble Bed Reactor Systems

Prepared for
US Department of Energy

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Nuclear Nonproliferation Division

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AGR	Advanced Gas Reactor (program)
AWCC	active well coincidence counter
BUM	burnup monitoring
D-D	deuterium–deuterium
DDA	differential die-away
DOE	US Department of Energy
D-T	deuterium–tritium
HKED	hybrid K-edge densitometry
HPGe	high-purity germanium
HV	high voltage
kcps	kilo counts per second
LWR	light water reactor
MCNP	Monte Carlo N-Particle (code)
NDA	nondestructive assay
NMC&A	nuclear material control and accounting
ORIGEN	Oak Ridge Isotope Generation (code)
ORNL	Oak Ridge National Laboratory
PBMR	pebble bed modular reactor
PBR	pebble bed reactor
PBUM	pebble burnup monitoring
PEEK	polyether ether ketone
SNM	special nuclear material
TRISO	tristructural isotropic

EXECUTIVE SUMMARY

A pebble burnup monitoring system is a required component for domestic reactor safety and safeguards applications associated with pebble bed reactors (PBRs). One of the main requirements of a PBR burnup monitoring system is that it needs to be capable of rapid measurements to assess the burnup of each individual pebble to determine whether to recirculate it in the reactor or discard it as spent fuel..

This report considers three different approaches for a burnup monitoring system for pebbles discharged from the reactor core in a pebble bed modular reactor-400:

- passive gamma spectrometry measurement,
- passive neutron coincidence measurement, and
- active neutron counter based on the differential die-away technique.

Conceptual designs have been created for each of these detectors, and preliminary analysis has been performed using Monte Carlo N-Particle and Oak Ridge Isotope Generation code simulations. The advantages and practical limitations (e.g., high radiation background) of each system were identified.

Simulations suggest that each of the three measurement techniques can be successfully employed to distinguish between pebbles based on their number of passes through the core and to quantify the burnup of pebbles.

1. INTRODUCTION

Burnup monitoring (BUM) systems have historically been used in support of international safeguards and criticality safety applications [1]. BUM systems provide a measured burnup value to confirm calculated values so that the reduced reactivity of an irradiated fuel element relative to its fresh condition can be properly accounted for. These measured values are then used to verify results from transport codes. Such verifications allow facility operators to take advantage of calculated postirradiation isotopic distributions in determining the reactivity of a fuel elementenabling more efficient and safe handling, storage, and processing of spent nuclear fuel. Deviations of measured burnup values from expected values may provide an indication of unexpected or possibly deliberate deviations from a nuclear facility's declared operating parameters in support of safeguards. For traditional light water reactors (LWRs), burnup measurements are performed on intact spent fuel assemblies months to years after the assemblies have been removed from the reactor. Burnup measurements for LWR fuel assemblies are challenging because of the highly attenuating nature of the assemblies, high neutron and gamma-ray emission rates from the assemblies, and the complex irradiation history of assemblies while in the core.

Application of the BUM concept to pebble bed reactors (PBRs) is more akin to process monitoring than it is to a traditional burnup measurement. Although an LWR fuel assembly may be moved within the core two or three times at well-established intervals (e.g., 12 to 18 months) during its useful life, fuel pebbles circulate through the reactor core several times, following unpredictable paths through the core. Burnup measurements are performed for an LWR fuel assemblies only after their permanent removal from a reactor, but the burnup of each pebble is examined after each pass through a PBR core. Pebbles exceeding a given burnup level are removed from circulation, and pebbles below the limit are returned to the core.

The operational requirements for pebble burnup measurement are more challenging than the corresponding fuel assembly assay. Because each pebble is measured individually and a reactor core may contain hundreds of thousands of pebbles, the measurement time must be very short (<60 s). Although the radiation emission rate from an individual pebble is low compared to an intact fuel assembly, pebble burnup measurements are performed in close proximity to the operating reactor, resulting in very high ambient background levels. Additionally, a pebble's burnup needs to be measured shortly (hours to days) after it is discharged from the core, and a PBUM system must operate in extreme environmental conditions.

In support of domestic reactor safety and safeguards goals associated with PBRs, we have examined the performance of potential neutron- and gamma ray–based BUM systems for a generic PBR through a series of Monte Carlo N-Particle (MCNP) simulations. A limited set of benchmark measurements of irradiated tristructural isotropic (TRISO) fuel materials, primarily performed by a separate National Nuclear Security Administration project, were available to validate the predicted performances.

2. PEBBLE BURNUP MONITOR APPLICATIONS

Pebble BUM (PBUM) systems can be used to quantify one or more aspects of irradiated nuclear fuel in support of the following application areas.

2.1 CRITICALITY SAFETY

Because the mass loading of a single pebble is not large (<10 g ^{235}U), the burnup of an individual pebble does not have a significant influence on criticality safety. However, the aggregated measurements of hundreds of pebbles could allow an increase within a given volume. For instance, reliable burnup values can be used to maximize the spent fuel pebbles loaded into a single waste container or enable the use of larger waste containers for spent pebbles.

2.2 NUCLEAR MATERIAL CONTROL AND ACCOUNTING

Most detection mechanisms considered for PBUM systems are gamma ray–based. Unfortunately, gamma-ray emission rates from U and Pu are small relative to emission rates from fission products. However, nondestructive assay (NDA) techniques are available that offer some capability for quantifying U and/or Pu mass content. The various quantitative methods are presented here with brief statements regarding potential hurdles in deployment.

- **Self-induced x-ray fluorescence—determination of the U:Pu ratio for a pebble:** Passive x-ray fluorescence measurement takes advantage of the high gamma-ray fluence of a pebble. The fission product gamma rays induce characteristic K-shell fluorescence x-rays from the U and Pu within the pebble. Although quantifying the absolute U and Pu mass content of a pebble using this technique is impossible, the count rate ratio of the characteristic x-rays from U and Pu can be used to calculate the U:Pu concentration ratio. The concept has been successfully demonstrated in measurements of irradiated TRISO materials with relatively long cooling time (e.g., 3 years); however, long measurement times were required, and a path forward to a practical measurement arrangement was not obvious.

- **Passive neutron measurement:** Passive neutron emission rate combined with a knowledge of the isotopic distribution within a pebble may be used to quantify Pu mass. However, the low Pu mass in a pebbble and high neutron background rates resulting from reactor operations require significant shielding and distance between the reactor and the passive neutron measurement. The distance and shielding requirements needed for a successful in-line measurement system suggest that such a measurement may not be achievable.

- **Active neutron interrogation:** The low fissile mass and consistency of the pebbles allows the use of the differential die-away (DDA) active neutron interrogation method for quantifying the fissile mass of a pebble. The technique provides a direct measurement of ^{235}U and ^{239}Pu content but requires knowledge of the U and Pu isotopic distributions to provide a total mass value for the pebble. The practicality of implementing an automated active neutron interrogation system in a pebble bed facility needs to be evaluated.

- **Hybrid K-edge densitometry (HKED):** HKED systems are routinely used for quantifying U and Pu concentrations in aqueous spent nuclear fuel reprocessing dissolver solutions. HKED uses a commercial x-ray generator to provide an intense x-ray interrogation source to overwhelm the fission product gamma-ray signal. Two measurements are performed simultaneously: a transmission measurement for determination of the concentration of the dominant actinide (i.e., U) and an active x-ray fluorescence measurement for determination of the concentrations of the minor actinides (e.g., Pu, Np, Am, Cm) relative to the dominant one. The HKED technique could be easily adapted to provide rapid measurements of irradiated pebbles, but the challenge would be developing a system robust enough to tolerate the PBR environment.

- **Gamma spectrometry:** Simulated and measured gamma spectra from a limited set of irradiated TRISO fuel samples and pebbles are also presented in this report because gamma spectrometry measurements are usually used to measure a pebble's burnup value.

2.3 INTERNATIONAL SAFEGUARDS

Fission product production varies based on the starting U and Pu isotopic distributions, the overall interrogating flux, and irradiation history to determine the burnup of a pebble. The ratios of various fission product activities are compared to predicted values, and deviations from expected values indicate that a non-normal operating conditions have taken place.

Particular characteristics of PBRs, such as online refueling and the use of fuel elements without unique identification, present a challenge for international safeguards verification. In online refueling scenarios, the need to verify the presence of all nuclear material can lead to difficulties in accounting for all pebbles within the reactor fuel handling system and core. However, because each pebble is measured individually and a reactor core may contain hundreds of thousands of pebbles, time available to measure will likely be less than a minute. This brief measurement window also adds unique difficulties and challenges for accounting and monitoring, which challenges the implementation of international safeguards.

2.4 PROCESS CONTROL

As pebbles pass through a reactor core, ^{235}U content diminishes through the fission process while various Pu isotopes are produced, primarily through neutron capture on ^{238}U. The overall reactivity of the pebbles decreases with each pass through the reactor. As passes through the core accumulate, a pebble becomes less valuable in terms of power production. Pebbles are also expected to age mechanically with each pass because of high temperatures, vibrations, wear, and radiation damage. To minimize the potential for mechanical failure and optimize overall reactor performance, a pebble is removed from the core when its burnup exceeds a predetermined value.

The most common burnup measurement technique relies on the ratio of characteristic gamma-ray lines from the decay of two or more fission product nuclides produced by fission of the U and Pu contained within a pebble. Alternative methods include passive neutron coincidence counting, but the low neutron emission rates from a single pebble would require impractically long measurement times with this technique.

3. SPECIAL CHALLENGES FOR PEBBLE BURNUP MONITORING

Application of BUM to PBRs introduces additional challenges compared to traditional burnup measurements.

3.1 SHORT COOLING TIMES

Traditional burnup measurements are performed 5–10 years after removal of a fuel item from a reactor, whereas pebbles are assayed within 100–200 h. The fission products in irradiated pebbles would still contain many short lived-fission product nuclides, so the irradiated pebble gamma-ray spectra are far more complex than those of the aged LWR fuels.

The short cooling time also means that variations in cooling times on the order of hours can affect measurement results. The overall gamma-ray emission rates and isotopic ratios would be different between measurements made at 99 or 101 h after irradiation of a pebble ends, potentially biasing measurement results.

3.2 VERY HIGH GAMMA-RAY EXPOSURE RATES

Because the measurements are expected to occur within 100–200 h of removal from the reactor core, exposure rates at the surface of an irradiated pebble may be as high as 10 Sv/h. Because a typical high-purity germanium (HPGe) detector becomes saturated under exposure rates of only a few tens of microsieverts per hour, a PBUM system would require a high degree of collimation and a long standoff distance of several meters.

The gamma-ray exposure rate from a single pebble is sufficiently high that any proposed neutron counting systems (whether proportional tube or scintillation systems) must also incorporate significant shielding (e.g., 7.5 cm Pb or more) to protect against the gamma rays.

3.3 LOW MASS LOADING (EFFECT ON NEUTRON MEASUREMENT)

The ranges of masses considered are from 2 to 7 g U per pebble. Traditional burnup measurements are performed on a fuel rod or fuel assembly containing many hundreds of grams of special nuclear material (SNM). Lower mass loadings mean that traditional ^{3}He-based passive neutron coincidence assays of individual pebbles are not practical.

3.4 HIGH THROUGHPUT

Unlike burnup measurements for LWRs, which are typically performed on a subset of fuel assemblies, each pebble in a PBR must be assayed. The throughput required limits measurement time to less than 60 s per pebble or requires multiple measurement systems operating in parallel.

3.5 DIFFERENCES FROM PASS TO PASS ARE SMALL

The incremental difference in burnup from one pass to the next can result in relatively small changes in the observable signal. Additionally, a pebble may take different paths through a reactor core from one pass to the next. Such a scenario results in a spread of expected distributions of burnup for a given pass through the reactor. This blurring of the expected burnup based on pass number requires a more precise measurement to resolve one pass from the next. Longer measurement times are required to accurately determine the passes associated with a given pebble.

3.6 HIGH AMBIENT BACKGROUND LEVELS IN MEASUREMENT AREA

The pebble measurement point is expected to be near the reactor core, where ambient gamma-ray and neutron background levels may be greater than 10 Sv/h. Gamma-ray systems would require both shielding and a substantial standoff distance from the reactor while making use of as much of the facility structure as possible to reduce gamma-ray exposure rate on the detector head.

Background neutrons can degrade a gamma-ray detector's energy resolution over time. A typical HPGe detector can tolerate a total fluence of approximately 1×10^8 n/cm^2 before degradation of the energy resolution becomes apparent, and after a fluence of 1×10^9 n/cm^2 most detectors become unusable and must be repaired or replaced. This sensitivity to neutron exposure suggests that gamma-ray detectors would need to be replaced on a regular basis and potentially multiple times per calendar year unless the detectors can be sufficiently shielded from the neutron flux.

Because of the harsh operating conditions expected for the PBUM system, any neutron detector deployed would likely be a ^{3}He or BF_3 proportional tube-based system. However, even with the optimal proportional tube, a neutron detector can only tolerate 0.5 Sv/h gamma-ray exposure rates before pileup gamma-ray events begin to be misidentified as neutron events. The neutron counting system would likely be located near the operating reactor core, where the neutron and gamma-ray background levels may exceed tens of sieverts per hour, necessitating the use of substantial external shielding.

3.7 ALIGNMENT

The long standoff distance between a collimated detector and a pebble requires precise alignment of the detector. Gross misalignment would result in a reduction of the observed counting rates for all peaks in the spectrum; so, in principle, it would have no effect on the measurement. However, misalignment would also increase the apparent thickness of the materials between the detector and pebble such that the attenuation as a function of energy would shift and introduce a bias into both overall and relative peak intensities. However, because a direct line of sight is unlikely to be available between a pebble and the detector face, traditional alignment methods, such as the use of a laser pointer, may not be effective, and a reliable alignment methodology must be developed and implemented for the measurement system.

3.8 HIGH AMBIENT TEMPERATURES

PBRs will operate at higher temperatures than LWRs. Temperatures in the regions where irradiated pebbles may be assayed are likely to be much greater than 100°C, requiring that detectors either be located remotely within a temperature-controlled environment or that their construction materials be able to withstand elevated temperatures. For reference, most commercial radiation detector systems require that the ambient temperature be less than 50°C. In HPGe-based BUM systems, the detector can be located hundreds of centimeters from the pebble under assay, allowing the detector to be isolated in a temperature-controlled environment. However, because the temperature in a reactor facility would change significantly depending on the operating state of the reactor, the effect of these changes on collimator diameter and alignment must be considered.

4. EXPECTED PERFORMANCE OF GAMMA RAY–BASED AND NEUTRON-BASED PBUM SYSTEMS

We examined the potential performance of both neutron- and gamma ray–based BUM systems for irradiated pebbles. Note that the detector arrangements examined in the following should be considered as proof of concept rather than as fully optimized measurement systems.

4.1 SIMPLIFIED GAMMA-RAY MEASUREMENT

The response from a simple gamma ray–based BUM was simulated using a combination of MCNP and In Situ Object Counting System (ISOCS) modeling. The simulated detection arrangement is shown in Figure 1. The modeled detector is a coaxial HPGe detector contained within a thick lead shield located 500 cm from a single irradiated pebble. The pebble is assumed to be transported to the detector assembly using a pneumatic transfer or gravity feed mechanism, and the pebble is assumed to be contained within a transfer pipe. The transfer pipe is assumed to be separated from the gamma-ray detection system by at least one containment barrier (e.g., a steel panel).

Without proper standoff distance, collimation, and attenuation, the incident gamma-ray flux can easily saturate the detection system, overwhelming its capacity to respond to individual photons. The current generation of digital signal processors can readily accommodate throughputs of 100 kilo counts per second (kcps) without significant performance degradation. Based on the simulated gamma-ray spectrum from pebbles irradiated to various burnups located 100 cm from an unshielded, uncollimated detector, we would expect count rates in excess of 2×10^9 cps. Thus, increasing the pebble-to-detector distance, adding attenuation, and introducing a narrow collimating aperture to reduce the incident gamma-ray fluence are necessary steps.

To reduce the overall count rate to an acceptable level, we first assume a transfer pipe wall thickness of 0.76 cm (0.3 in.), a containment barrier wall thickness of 0.16 cm (0.0625 in.), and that both are constructed from stainless steel. We next assume a circular collimating aperture through the detector shield with a radius (R_1) of 0.2 cm and an aperture through the collimator itself equal to the diameter of the pebble. We found that it was also necessary to increase the detector-to-pebble distance from 100 to 600 cm. In this configuration, we can expect an overall count rate of approximately 92 kcps for a pebble with a burnup of 53 GWd/MTU.

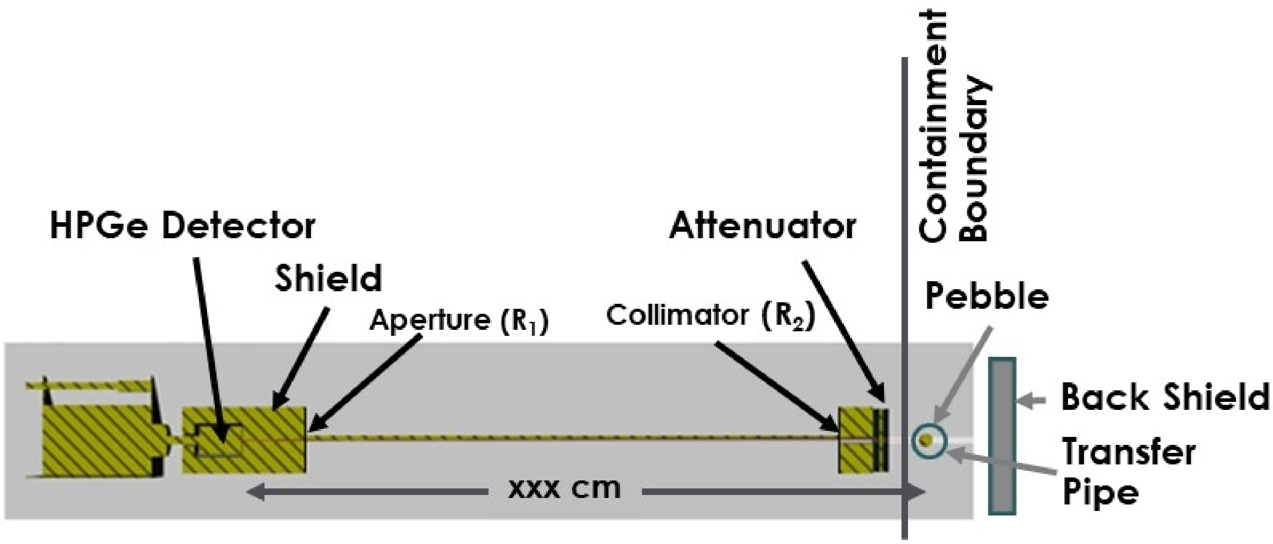

Figure 1. A simplified gamma-ray detection arrangement for irradiated pebbles. The separation between the pebble and the detector face is expected to be a minimum of 200 cm.

Simulated spectra were generated for pebbles for various routes through a pebble bed modular reactor (PBMR)-400 [2] for one to seven passes through the core. Figure 2 shows a pebble making three passes through the core with an approximate burnup of 53 GWd/MTU, and Figure 3 shows a similar spectrum, a pebble making six passes through the core with an approximate burnup of 88 GWd/MTU.

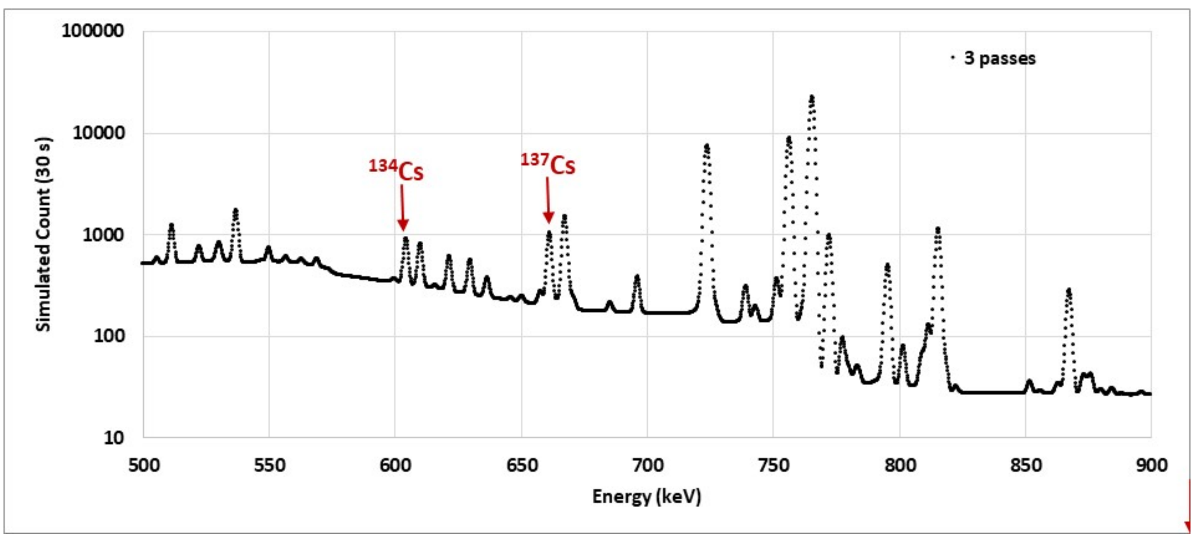

Figure 2. Simulated spectrum for a medium burnup pebble (53 GWd/MTU) showing the energy region of interest (100 h of cooling).

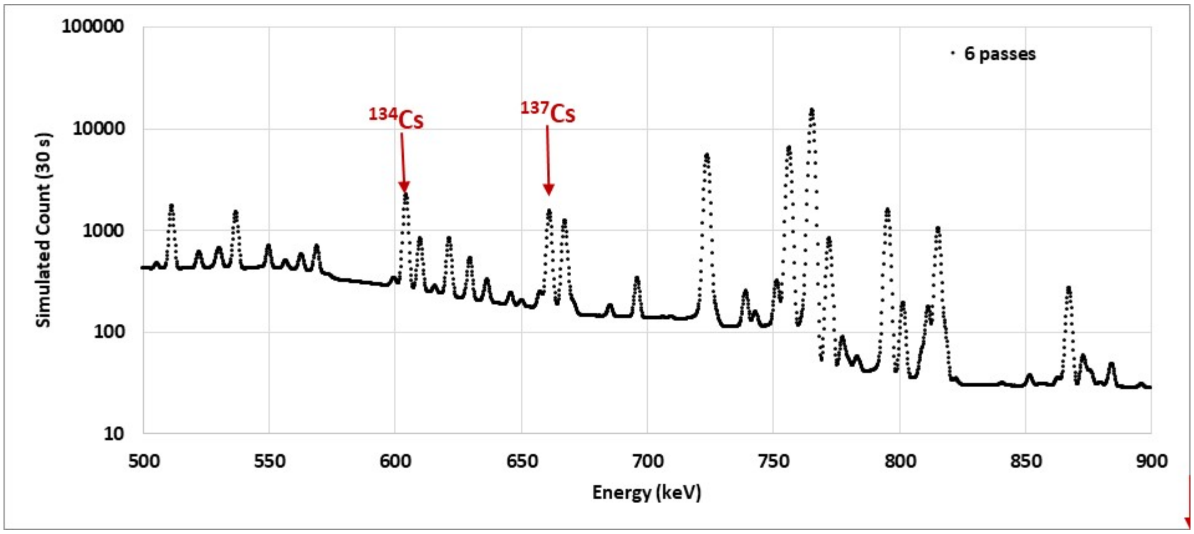

Figure 3. Simulated spectrum for a high burnup pebble (88 GWd/MTU) showing the energy region of interest (100 h of cooling).

Interfering gamma-ray peaks from ^{103}Ru and ^{132}I are separated by about 6 keV each from the ^{134}Cs and ^{137}Cs peaks, requiring that the gamma-ray detectors selected have an energy resolution of better than 0.25% in the 600–700 keV energy range to fully resolve and quantify the peak intensities accurately. The complexity of short cooling time spectra requires gamma-ray energy resolution provided by a (HPGe) detector. Although other gamma-ray detector types (e.g., cadmium zinc telluride detectors) are attractive because they do not require liquid nitrogen cooling, they do not provide the required energy resolution for the expected fission product distributions.

A laboratory-measured spectrum from a single irradiated TRISO particle extracted from an AGR-5 compact [3] (produced by the Advanced Gas Reactor [AGR] program) is shown in Figure 4 for comparison. The time from last irradiation to measurement was approximately 3 years, resulting in a spectrum that is much simpler than the simulated spectra. Most of the short-lived fission products (e.g., ^{103}Ru and ^{132}I) have decayed so that the 604 keV peak from ^{134}Cs and the 661 keV peak from ^{137}Cs are well resolved and suffer minimal interference from the gamma rays of other fission product nuclides.

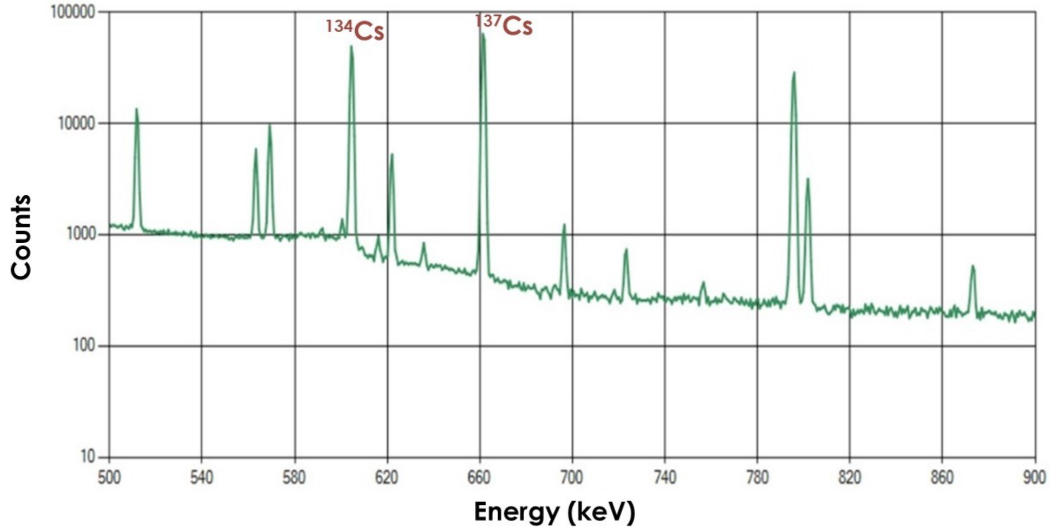

Figure 4. Measured spectrum for a single irradiated AGR-5 TRISO fuel particle showing the energy region of interest (3 years of cooling).

A plot of the decay-corrected measured and expected ^{137}Cs:^{134}Cs peak ratio as a function of burnup is shown in Figure 5. The response is also influenced by the mass and physical arrangement of the item under assay because of changes in the attenuation of emitted gamma rays. The simulated pebbles include more particles than the measured intact TRISO compacts and collections of loose TRISO particles from the AGR program [4] [3]. More details of these gamma measurements can be found in a recent Oak Ridge National Laboratory (ORNL) report [5] The differences in the attenuation of the 604 and 661 keV gamma-ray peaks result in the different slopes for each geometry. The physical arrangement of loose particles within their respective containers also affects assay results. However, these effects do not come into play for intact pebbles or TRISO compacts, so assays of these items result in greater linearity in response with burnup. From the measurements and simulations performed, the expected measurement precision for burnup determination is approximately 2% for a 30 s measurement time.

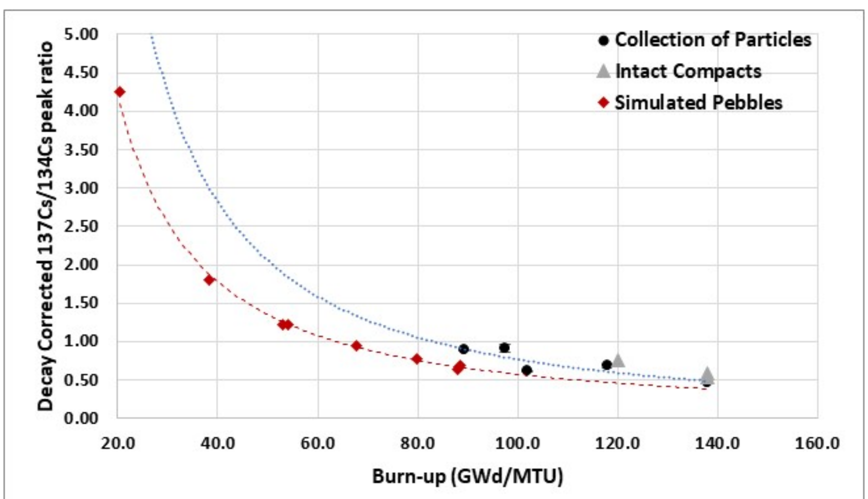

Figure 5. Simulated and measured peak rate ratios for ^{137}Cs and ^{134}Cs for a mix of measured and simulated TRISO fuel forms. The measured spectra were obtained from single TRISO particles, collections of particles, and intact TRISO compacts.

4.2 PASSIVE NEUTRON COUNTING SYSTEM

We considered the potential application of passive neutron counting for BUM purposes. The initial total mass of U is expected to be only a few grams per pebble, and after multiple passes through the reactor, the Pu content of a pebble increases to only approximately 100 mg, and the total buildup of Cm isotopes is approximately 1 mg. The passive neutron signal is dominated by the ^{242}Cm and ^{244}Cm content of a pebble. The simulated (α, n) and spontaneous fission neutron emission rates per gram of SNM within a pebble are shown in Table 1. The table also provides the expected reduction in total SNM mass (U + Pu + Cm) as a function of pass number.

Table 1. Specific neutron emission rates for a pebble completing successive passes through a simulated PBMR-400 core

	pass_1	pass_2	pass_3	pass_4	pass_5	pass_6	pass_7
Simulated burnup (GWd/MTU)	20.4	38.2	54.0	67.8	79.9	88.6	93.8
(α, n) (n/s/g SNM)	2.80	28.64	94.61	188.20	293.82	407.66	477.83
Spontaneous fission (n/s/g SNM)	14.5	188.5	744.7	1,802.3	3,429.3	5,678.5	7,264.4
Total emission (n/s/g SNM)	17.3	217.2	839.3	1,990.5	3,723.1	6,086.2	7,742.3
Relative mass (U + Pu + Cm)	0.95	0.91	0.88	0.86	0.84	0.82	0.81

Constructing a passive neutron coincidence counting system that can accurately characterize irradiated pebbles in a timely manner is relatively straightforward if the counter is installed in a low background environment (i.e., no nearby sources of radiation). The expected neutron count rates for a simple well counter system are presented in Table 2. The results suggest that such a counter would be able to reliably identify the number of passes through the core. However, the burnup monitor must necessarily be located near the operating reactor such that high gamma-ray and neutron background rates can be expected. For a passive neutron counter that measures the total passive neutron emissions (i.e., "Singles") from a pebble, high neutron count rates can be achieved, according to the results shown in Table 2, and they can be used to discern pebbles with different numbers of passes provided that the counter has a high detection efficiency and is well shielded from the high gamma-ray and neutron background.

Table 2. Expected singles and doubles rates for an irradiated TRISO pebble (initial total U mass 9 g) completing successive passes using an 18% efficient well counter design. Precision values are based on a 60 s assay time and a 150 h cooling time and assume a low background counting environment.

	pass_1	pass_2	pass_3	pass_4	pass_5	pass_6	pass_7
Total U Mass (g)	7.72	7.51	7.34	7.20	7.07	6.96	6.85
Singles (1/s)	4.17	35.18	135.97	322.46	603.14	985.96	1,254.25
Doubles (1/s)	0.22	2.58	11.19	29.52	60.10	104.35	136.14
Doubles precision	44%	8.7%	4.3%	2.9%	2.2%	1.9%	1.8%

To demonstrate the feasibility of neutron measurements of irradiated TRISO particles, we developed a small neutron counter for installation into the access port of the hot cells in Building 3525 at ORNL (Figure 6). The counter consisted of four short ^{3}He tubes embedded in a cylindrical high-density polyethylene moderator and provided a detection efficiency of 1% at the measurement location. The detector was inserted into the hot cell through a collimator port, and the irradiated TRISO items were placed on a spacer attached to the collimator port approximately 5 cm from the surface of the detector.

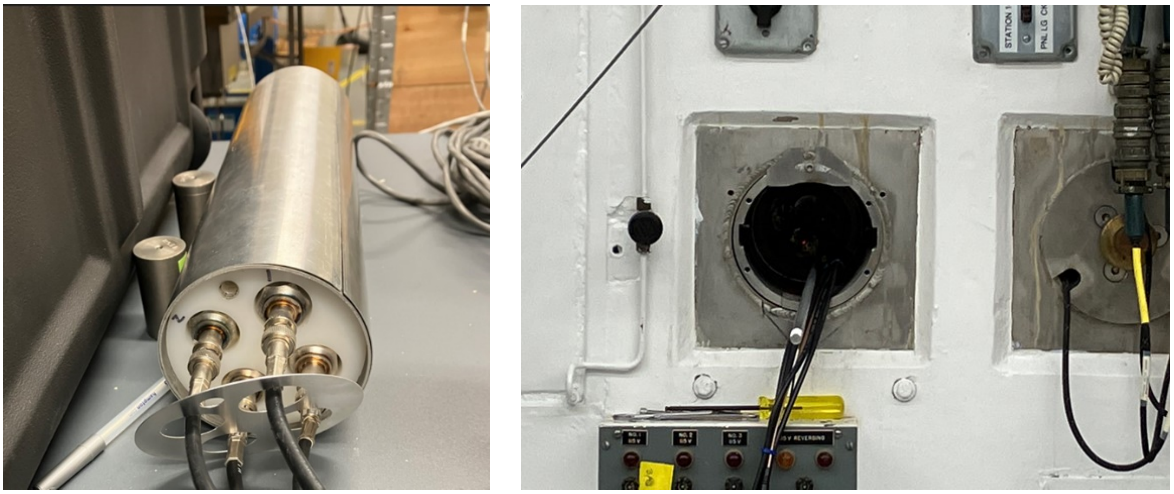

Figure 6. The proof-of-concept neutron detector (*left*) inserted through the hot cell wall (*right*) for measurement of irradiated TRISO compacts.

Our initial concerns were that the gamma-ray exposure rates within the cell would saturate the neutron detector. Instead, we found that the neutron background from the spent commercial nuclear fuel rods within the cell dominated the measurement. The plots in Figure 7 show the neutron detection rate as a function of high voltage (HV) bias setting for the detector located in a low background area with a ^{252}Cf source, for the detector located within the hot cell, and for the detector located within the hot cell with a full TRISO compact placed in the assay position within the hot cell. The pileup of gamma-ray events because of the high exposure rates within the hot cell and the irradiated compact can result in misidentification of gamma-ray events as neutron events. Estimated exposure rates at the neutron detector location were in excess of 100 R/h (1 Sv/h). Adding gamma-ray shielding around the neutron detector was not feasible in this situation, so to minimize the effect of gamma-ray pileup events, the amplification was decreased relative to a fixed detection threshold by reducing the HV bias setting. To ensure that the detector was operating below the breakdown region, we selected an operating voltage well below the normal HV setting for this counter, sacrificing 25% of the counter's detection efficiency.

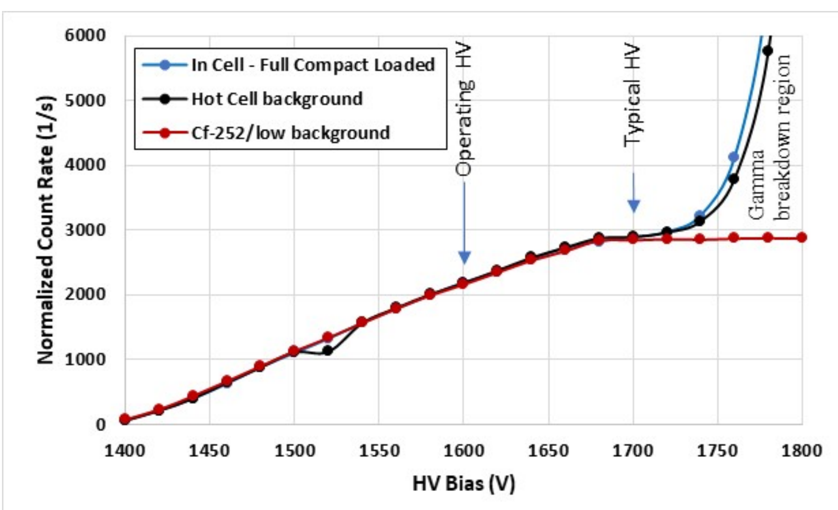

Figure 7. Measured HV plateaus illustrating the effect of high neutron and gamma-ray background on measurement (by operating at reduced HV bias, sensitivity to gamma rays is reduced).

The neutron backgrounds in the hot cell were high (2,200 cps) compared to the expected count rates (approximately 30 cps) from the irradiated compacts. We believe that in this case, placement of the packaged compacts close to the detector head shielded the detector from a portion of the neutron background in the cell. The smaller items were positioned closer to the detector and presented less shielding from the neutron background such that, although the full compacts contained much more material, the smaller items yielded greater net count rates. Ultimately, obtaining reliable data on neutron emission from these measurements was not possible.

An implementable neutron counting system is expected to have one of two general configurations. The first configuration is an in-line well counter design in which a pebble passes through a cylindrical ring of ^{3}He proportional tubes embedded in high-density polyethylene. In contrast, in the second configuration the pebble passes by an array of moderated ^{3}He proportional tubes. The choice between the two options will be driven by facility design requirements, such as physical diverters to sort viable from spent pebbles. An in-line arrangement affords greater detection efficiency and, to some extent, simpler external shielding design (Figure 8). Neutron and gamma-ray background may exceed 1,000 R/h (10 Sv/h), necessitating bulk shielding around the assay system to enable proper operation of the system. Examples of pass-by detector arrangements are shown in Figure 9. The slab style detector depicted includes both gamma-ray shielding and partial neutron shielding. These configurations would also require consideration of neutron and gamma-ray background levels during design. MCNP modeling of the detector arrangements suggests that both in-line and pass-by configurations can be developed to accommodate the potentially intense backgrounds and provide measurement precision sufficient to segregate pebbles by number of passes through the reactor.

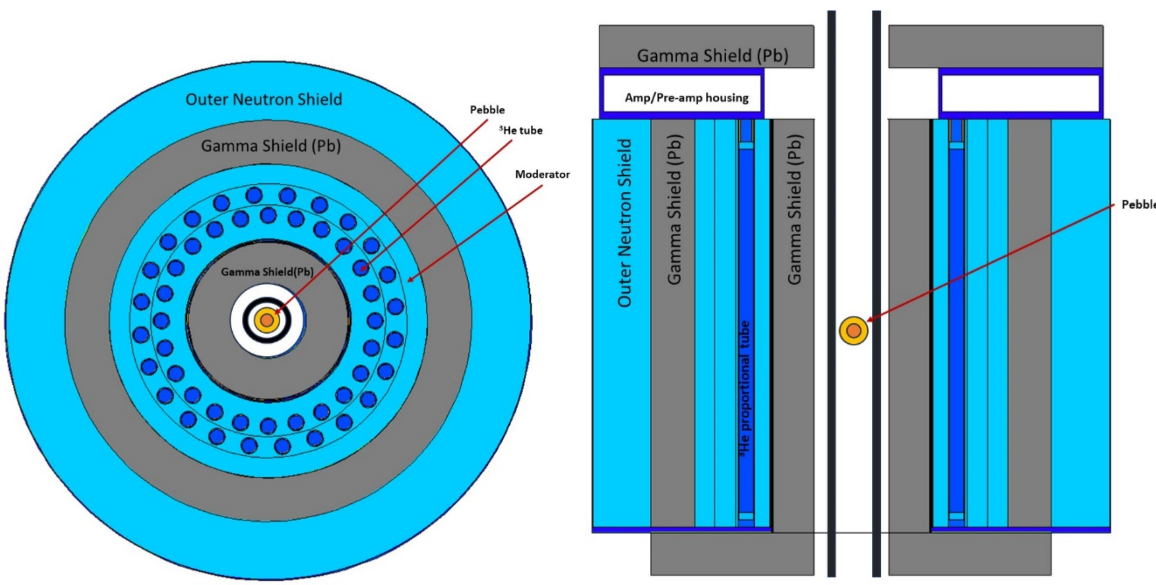

Figure 8. Notional in-line passive neutron counting system for pebble assay.

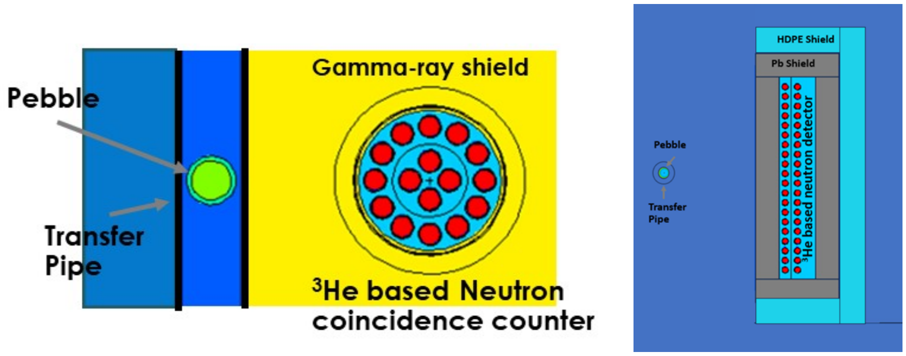

Figure 9. Notional pass-by passive neutron counter system.

Three basic types of active interrogation system are in use for assay of ^{235}U and ^{239}Pu: the ^{252}Cf shuffler, the active well coincidence counter (AWCC), and DDA. The total mass of U and Pu within a single pebble over its lifetime is no more than a few grams. AWCC and ^{252}Cf shuffler systems are typically employed when the total mass of fissionable materials is greater than 50 g, whereas the DDA technique is well suited to low mass assays. Large-scale, commercially available DDA assay systems routinely provide detection levels of less than 10 mg within 120 s of active interrogation. We examined the potential performance of the DDA technique for assays of pebbles after successive passes through a PBMR reactor using the ORIGEN code to predict the isotopic makeup of the pebbles and using the MCNP code to evaluate the measurement performance of a simple (and nonoptimized) DDA assay chamber (Figure 10). In this evaluation, we examined the performance assuming that the interrogating source was a 1×10^8 n/s pulsed deuterium–tritium (D-T) neutron generator.

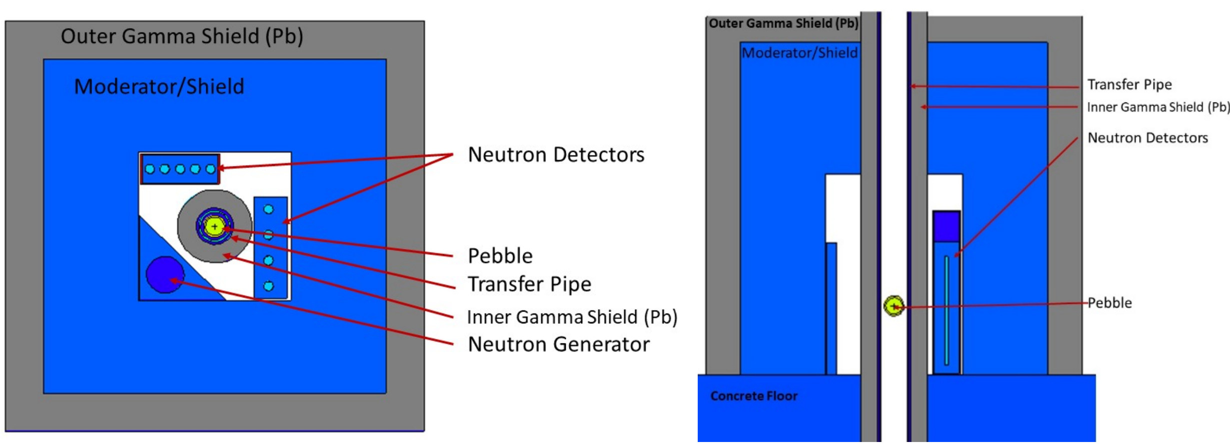

Figure 10. Notional active neutron interrogation system based on the DDA technique.

The DDA technique is based on the difference in the time required for the interrogating neutrons to thermalize and induce fissions and the time required for detection. The neutron detector bank is wrapped with Cd such that detected neutrons must have an energy of 1 eV or higher, whereas the majority of induced fission events are the result of slower thermal neutrons. The characteriestic die-away time for neutron detection tends to be short (approximately 40 µs in this example); the time to induce fission using thermalization is slower, with a characteristic die-away time of approximately 350 µs (Figure 11). The difference in these two characteristic times gives rise to the name “differential die-away.”

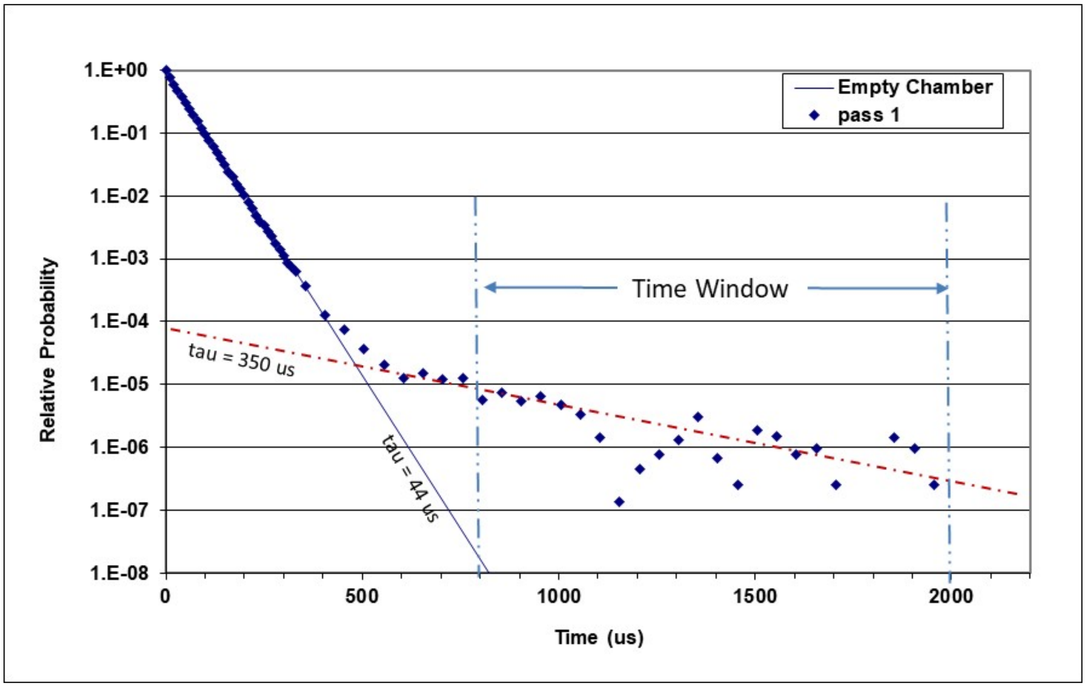

Figure 11. Simulated neutron detection rate as a function of time following the neutron generator pulse from a 1 × 10^8 n/s D-T generator with a single pebble with U + Pu mass of approximately 1 g.

The neutrons emitted by the D-T generator have a relatively high neutron energy, 14 MeV, and these neutrons have sufficient energy to induce fission in ^{238}U as well as ^{235}U and Pu isotopes. Neutrons emitted via the deuterium–deuterium (D-D) reaction have lower energy (2.5 MeV), so use of a D-D generator would reduce the contribution from ^{238}U, improving sensitivity to ^{235}U and Pu. However, historically, compact D-D generators have only been available with lower neutron yields of 1 × 10^6 to 2 × 10^6 n/s, so the decreased sensitivity to ^{238}U did not necessarily translate to improved measurement performance. Recently, compact D-D neutron generators have become available with yields of 1 × 10^8 n/s or greater, so considering possible use of a D-D generator for this application would be beneficial.

4.3 EFFECT OF EXTREME OPERATING TEMPERATURE ON NEUTRON DETECTION SYSTEMS

Because the neutron counting system may need to be placed near the operating reactor, ambient temperatures may be elevated compared to NDA system installations. Temperatures in practical locations for a BUM system neutron detector head may be well in excess of 100°C. The neutron detection systems discussed herein require neutron moderators to thermalize the neutrons for detection and to shield the detector against potentially high neutron background rates. Many plastics commonly used for moderation and shielding (e.g., high-density polyethylene) have melting points of 131°C and softening points as low as 50°C. Thus, common detector construction materials may not be suitable for use in these facilities. An alternate moderator material, polyether ether ketone (PEEK), is a semicrystalline thermoplastic with excellent strength and ductility, is a good moderator, and does not melt at 300°C. As a moderating material, PEEK is promising and could enable passive neutron NDA techniques to be used as part of a BUM system.

5. CONCLUSIONS

We considered three approaches to measuring the burnup of pebbles consumed by a PBMR-400 reactor. Simulations suggest that each of the three measurement techniques can be successfully employed to distinguish pebbles based on number of passes through the core and to quantify their burnup. Each technique can be designed to produce precise results with measurement times as short as 30 s. Consequently, more practical considerations will determine which technique is optimal for a given measurement scenario. These additional factors are cost, reliability, complexity, maintainability, safety, and survivability.

Adaptation of traditional gamma ray–based BUM techniques to address the nuclear material control and accounting (NMC&A), safeguards, and process monitoring needs of a PBR is feasible. These systems would be based on high-resolution gamma-ray spectroscopy to provide the necessary energy resolution and measurement precision required for these applications. Deployable systems would require heavy shielding, tight collimation, and large standoff distances between the detector and irradiated pebbles. The following list summarizes the primary challenges for gamma ray–based systems:

- **Neutron interactions**—HPGe detector lifetime is impacted due to the presence of neutrons. With adequate standoff distances and shielding, the impact of neutron interactions can be reduced. Detectors will need to be replaced regularly.

- **Extreme ambient temperatures**—High operating temperatures can degrade the measurement performance and operational life of detectors and electronics. Gamma-ray detectors and electronics must be contained within an environmentally controlled housing.

- **Extreme gamma-ray backgrounds**—Even with extended standoff distances, detectors and electronics must be protected against the effects of high gamma-ray exposure rates. The effects on detector performance and lifetime must be considered for each specific installation.

- **Detector alignment**—A simple, reliable detector alignment method must be developed based on facility design constraints.

Neutron NDA techniques could replace or augment gamma measurements to determine a pebble's burnup and fissile content. Neutron measurements can potentially provide more sensitive burnup measurements than gamma measurements can. Additionally, the measured coincidence neutron signal is usually linear with the fissile content of the spent fuel and can potentially be used to distinguish pebbles with different initial enrichments—that is, pebbles with same burnup but different enrichments are expected to have different fissile contents. Such distinctions can be useful for fuel management and NMC&A. One challenge is the high-heat environments where such instruments would be used—the challenge stems from the temperature limitations of the polyethylene moderator material, which would not withstand temperatures greater than 200°C. An alternate moderator material, PEEK, is a semicrystalline thermoplastic with excellent strength and ductility, is a good moderator, and does not melt at 300°C.This new moderating material is promising and could allow passive neutron NDA techniques to be used as part of a BUM system. Exploration of the use of passive neutron detectors is recommended to see if they can outperform gamma instrumentation for NMC&A purposes. They may be considered as confirmatory measurements for spent fuel as it exits the reactor system and is placed in spent fuel storage canisters.

Note, because a PBUM system must operate with high reliability, the key to a successful design is simplicity. This condition is true for both gamma ray–based and neutron-based systems. A full failure mode analysis study should be performed when determining the ultimate system configuration. Hot spare requirements and maintenance protocols must be developed before final system selection. This work was based on PBMR-400 pebbles; recommended future work is to perform similar analysis on X-energy pebbles (based on public design information), for which both initial enrichments and final burnups are significantly higher than those of PBMR-400 pebbles.

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