LLNL-CONF-560791

LAWRENCE LIVERMORE NATIONAL LABORATORY

Use of Antineutrino Detection for Assessment of Fuel Burnup

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June 11, 2012

INMM Annual Meeting
Orlando, FL, United States
July 16, 2012 through July 20, 2012

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1 Introduction

Burnup is a quantity that is widely used in nuclear engineering and nuclear non-proliferation. It describes the amount of energy extracted from, or almost equivalently, the number of atoms that have undergone fission within, nuclear fuel. As such, it is closely related to the integral neutron exposure, fissile inventory, and fission product inventories of that nuclear fuel. Estimation of burnup is therefore important for applications including reactor fuel management, spent fuel storage, and nuclear safeguards.

Since it is impractical to directly measure the total power released by a single fuel assembly within the extreme environment of an operating reactor core, indirect measurements or inferences of burnup are used. Most often, these involve the combined use of in-core and/or ex-core measurements of total power, temperature, and/or neutron flux and a reactor evolution code. Those measurements provide boundary conditions to the evolution code, allowing an inference of the burnup of each assembly through the cycle and at discharge.

Here, we describe a proposed burnup measurement methodology that is considerably less intrusive than the conventional method described above. The physical process underlying the concept of burnup - the number of nuclear fissions that has occurred in an assembly - also results in the emission of a large and well-known number of antineutrinos. A measurement of reactor antineutrino emissions can therefore be related to the power of a reactor core. Due to the highly penetrating nature of antineutrinos this measurement can be achieved without any connection to reactor plant systems. Used in conjunction with a reactor burnup code, such a measurement could be used to infer the burnup achieved by each assembly in a reactor core. If also combined with conventional Material Accountancy and Containment and Surveillance (C&S) techniques, such measurements could provide a burnup verification capability for safeguards or similar applications. We note that it can be applied to any reactor and/or fuel type including fast and thermal reactors fueled with any combination of Low Enriched Uranium (LEU) and Mixed Oxide (MOX) fuel. We will also use our past antineutrino detection demonstrations to discuss the precision with which individual assembly burnup could be assessed.

2 Relationship between Assembly Burnup and Total Reactor Power Output

As discussed above, the burnup of an assembly depends upon its neutron irradiation history: the neutron flux an assembly is exposed to determines the number of fissions that occur within that assembly and therefore the amount of energy released. Within a reactor core, this flux depends upon the assembly's location, the burnup/composition of the assembly in question and surrounding assemblies, the use of control rods or poisons, and the instantaneous reactor power.

Capturing the complicated interplay between these many variables requires the use of a reactor simulation code. Several benchmark collaborations have investigated reactor code performance, including for MOX fuels. For example, "Validation of Nuclear Data for High Burn-up MOX Fuels", or "VALMOX", a European collaboration used several codes to perform a benchmark study of MOX fuel irradiated up to 48 GWd/MTHM [1]. The results were generally satisfactory, with isotopic predictions within 1% for U, with a worst case result in one simulation of 4% error for ^{239}Pu. In another example [2] a nodal code was used to study the complexity of full core evolution, including transient calculations (rod ejection in a core with partially loaded MOX). Only nodal codes have the ability to model both neutronic and thermal hydraulic effects.

By definition, the average incremental burnup of a reactor core during a particular equilibrium cycle is directly proportional to the total power output of that reactor core during that cycle. While the incremental burnup of an individual assembly will differ from that average value, it too will be closely related to the total core power output. That relationship may deviate slightly from linearity, due for example to local control rod use or a change in the reactivity profile across the reactor core with time, but assembly burnup will increase monotonically with total core-wide power output. A reactor simulation can be used to determine the relationship between the incremental burnup of an individual assembly and total power output during a particular reactor cycle. **Figure 1** shows an example of the relation between individual assembly burnup and the integral power of a reactor core, as provided by a 2-D simulation of an LEU fueled Pressurized Water Reactor (PWR) core using the ORIGEN simulation package.

Therefore, a single core-wide power measurement could then be used to infer the burnup achieved by each of those assemblies during that cycle. A reactor simulation, requiring the initial composition and position of each assembly as an additional input, can be used to relate individual assembly burnup values to the total reactor power output throughout the cycle.

Enthalpy and flow rate measurements are typically used by reactor operators to measure thermal power. This measurement scheme is intrusive, since it requires direct connection, and in many cases penetrations into, plant feed water piping. In applications that seek to independently verify operator declarations of burnup, the addition of a second calorimetric measurement system to a plant may trigger relicensing, since it involves the installation of equipment on or near critical plant systems. With careful and frequent calibration and maintenance, systems of this type can achieve a precision on thermal power of about 0.5-2%. Note however that the precision with which burnup could be assessed in this way is also affected by the typically larger uncertainty of the necessary reactor simulation code. In contrast, an ongoing

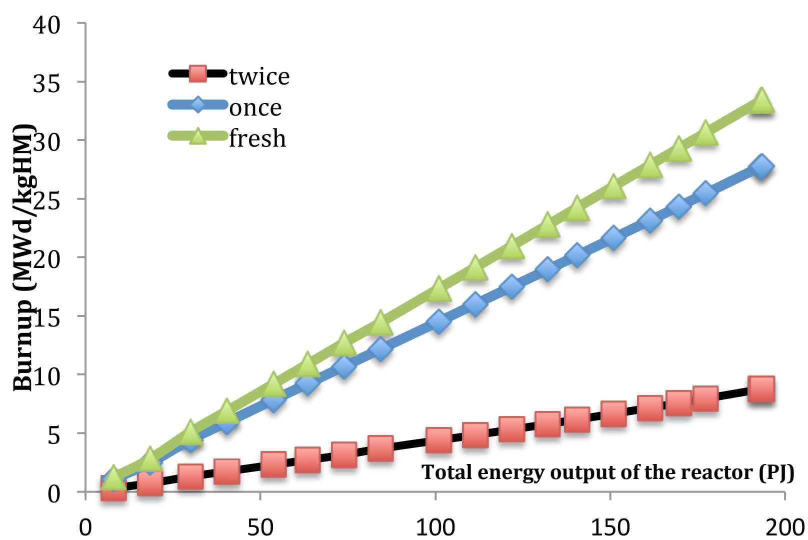

Figure 1 Curves displaying the relationship between incremental assembly burnup and total reactor power for three representative assemblies during a single cycle of an LEU fueled PWR equilibrium core. These assemblies are fresh (green), once-burnt (blue), and twice-burnt (black/red). The incremental burnup achieved by the assemblies that have previously been resident in the core (once and twice burnt) is less due to their position in the core and the depletion of their fissile worth due to the previous burning. Nonetheless, the burnup of all assemblies is a monotonically increasing function of the total power output of the reactor.

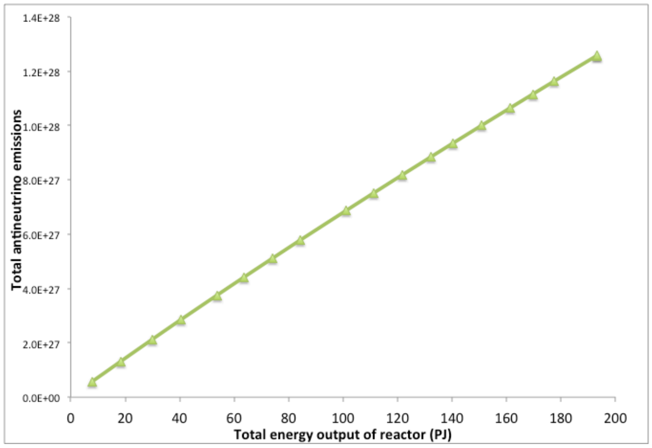

Figure 2. The relationship between total antineutrino emissions and total reactor power is shown for a PWR LEU equilibrium core.

measurement of the total antineutrino emissions from a core provides a non-intrusive means to infer the total power output of that core, and therefore the burnup of the assemblies in that core.

3. Relationship between Total Reactor Power Output and Total Reactor Antineutrino Emissions

Just as the average burnup of a reactor core is directly related to the total power output of a reactor, so too are the total antineutrino emissions from that reactor. This is because the physical process giving rise to each is the same: nuclear fissions in the core release energy, and result shortly thereafter in the emission of antineutrinos. The relationship between total power output and total antineutrino emissions is not linear, since fissions of different isotopes result in different antineutrino emissions and the isotopic composition of a typical core evolves throughout a reactor cycle. Nonetheless, total antineutrino emissions will increase monotonically with total core-wide power output (e.g. Figure 2).

As is familiar from our and others' past work [3-4], the antineutrino emissions of a particular reactor configuration can be calculated using a reactor simulation code. The assembly-level fission rates of each isotope, which are needed to calculate assembly-level burnup, are also required to calculate the antineutrino emissions from that assembly. Summing these emissions across the reactor core provides the total antineutrino flux that could be measured with a detector.

4. Relationship between Individual Assembly Burnup and Total Reactor Antineutrino Emissions

As noted above;

1. The burnup of each individual assembly in a reactor core is related to total reactor power output via a monotonically increasing (and almost linear) function
2. The total antineutrino emissions of a reactor are related to total reactor power output via a monotonically increasing function.

It therefore follows that:

The burnup of each individual assembly in a reactor core is related to the total antineutrino emissions of that reactor via a monotonically increasing function.

Alternately, we can write:

$$B_i(t) = F_i\big(R(t)\big), \tag{1}$$

where $B_i(t)$ is the burnup of the *i*th assembly at time *t*, $R(t) = \int_0^t r(t')dt'$ is the integral of the instantaneous antineutrino emissions from the core, *r*(*t*), from beginning of cycle until time *t*, and F_i is the monotonically increasing function that describes the relationship between those two quantities. A similar relationship holds between the average core burnup and the total antineutrino emissions of a core.

The set of functions F_i, one per assembly, is determined via a reactor simulation. At minimum, the initial enrichment, burnup, and position within the core of each assembly are required as inputs to that simulation. Operational data like control rod positions will also affect this relationship, especially if there are relative variations in them across the core. An example of these relationships for two MOX assemblies in a partial MOX PWR core is shown in Figure 3 .

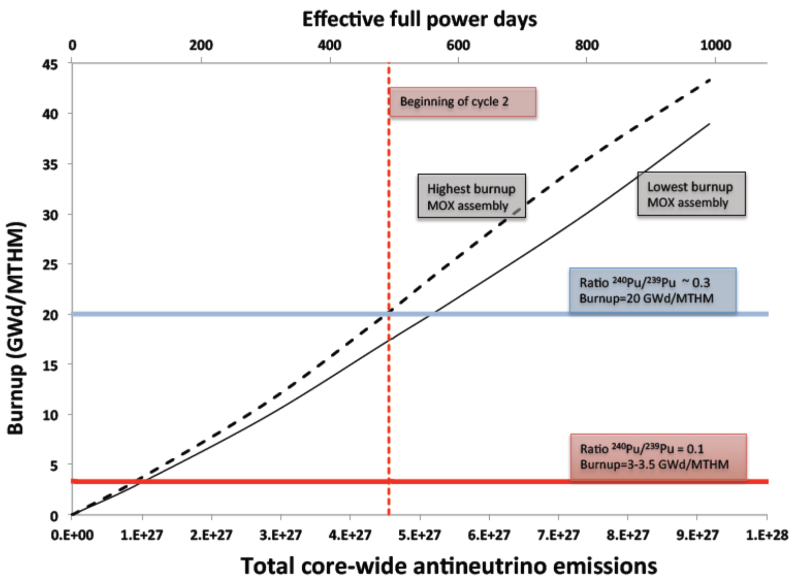

Figure 3. The results of a 3D simulation of a 1/3 MOX equilibrium PWR core. Shown are the assemblies with highest and lowest burnup over two complete fuel cycles as a function of time (top-axis) and total antineutrino emissions.

5. Precision with which Assembly Burnup can be determined from Total Reactor Antineutrino Emissions

Based upon Equation (1), it is clear that the precision with which the burnup of an assembly can be determined will depend upon:

1. the precision with which $R(t)$ can be measured by an antineutrino detector,
2. how accurately F_i describes the initial and evolved states of the reactor core.

We expect, and will demonstrate, that the F_i can be well represented by a quadratic approximation

$$B_i(t) = F_i\big(R(t)\big) \approx a_i R(t) + b_i R(t)^2, \qquad (2)$$

where a_i and b_i are constant coefficients specific to the *i*th assembly.

The precision, or relative error, with which the burnup can be determined can then be expressed as

$$\left(\frac{\sigma_{B_i}}{B_i}\right)^2 = \left(\frac{\sigma_R}{R}\right)^2 \left(\frac{1+2\rho_i}{1+\rho_i}\right)^2 + \left(\frac{\sigma_{a_i}}{a_i}\right)^2 \left(\frac{1}{1+\rho_i}\right)^2 + \left(\frac{\sigma_{b_i}}{b_i}\right)^2 \left(\frac{\rho_i}{1+\rho_i}\right)^2 , \qquad (3)$$

where $\rho_i = \frac{b_i R}{a_i}$ is a measure of the antineutrino rate's deviation from linearity as a function of burnup. To a good approximation, $\rho_i \sim .05$ or less, so the third term in Equation (3) will only have a sub-percent contribution to the overall precision and can safely be neglected. We then see that the relative (percentage) precision on burnup is simply the combination of the precision of the detector measurement $\left(\frac{\sigma_R}{R}\right)$ and the precision on the reactor simulation/evolution code $\left(\frac{\sigma_{a_i}}{a_i}\right)$. A reasonable simulation error is hard to state, as it depends significantly on the precision of the initial conditions. The underlying evolution has a similar precision to the burnup evolution (~2-3%). Considering our earlier discussion about simulation benchmarks, and assuming that the initial fuel isotopics are well-defined by independent inspection activities, it seems reasonable to assume that the overall simulation error could be maintained within 5%.

6. Precision with which Total Reactor Antineutrino Emissions can be Measured

The size and technology choices for an antineutrino detector can be optimized to meet the requirements for a particular task. The ultimate precision of antineutrino detection will not be limited by the statistics of antineutrino counts, but rather by the systematic errors of the detector technology and the measurement methodology. Based on our own deployment experiences and a survey of the experimental literature, we believe that an overall detection precision of 10% can be reasonably achieved using existing technology. The precision is dominated by two factors: the theoretical production rate of antineutrinos within a core and the overall selection efficiency for events within the detector.

The theoretical production rate is ultimately limited by our knowledge of the antineutrino spectra from all of the individual beta-decay branches within the reactor core. Many of these special isotopes are difficult to produce and have never been measured. As a result, the current state-of-the-art models [5] are only good to the 3-5% level. Systematic errors due to detector selection efficiencies can be constrained to below 2%. However, detectors which achieve those low selection efficiency errors require external background radiation to be lower than is likely achievable within an application environment. Most such high-precision neutrino detectors are very large and are placed deep underground with several meters of surrounding shielding. A more realistic, deployable detector can be constructed with a selection efficiency uncertainty of 5-7%.

Remaining systematic errors come from the influence of other external backgrounds and the choice of detector material. These errors can be constrained to less than 4%. As a result, we believe that a combined detector precision of 8-9% is possible with existing technology. We therefore choose a conservative detector precision of 10% for the rest of this discussion. We note that this holds for an absolute measurement. If a direct calibration of the detector can be accomplished using a well-known or otherwise validated reactor cycle, a relative precision of 1-2% would be possible. This was the approach taken during our previous experimental demonstrations [3-4].

7. A worked example demonstrating the relationship between average burnup and total antineutrino emissions

We can use the partial MOX core simulation produced by Hayes et al. [6] to complete a worked example. The question addressed in [6] is different than that considered here. There, the emphasis was on the effect different initial MOX core loadings would have on the evolution of the *instantaneous* antineutrino emission rate, and whether that observable could be used for an initial core loading verification. Nonetheless, we can use their simulation data which, in effect, reports instantaneous antineutrino emission rate versus average burnup for a 1/3 MOX core (Figure 4), here to demonstrate how detector and simulation precision affect the ability to assess burnup using the antineutrino measurement technique.

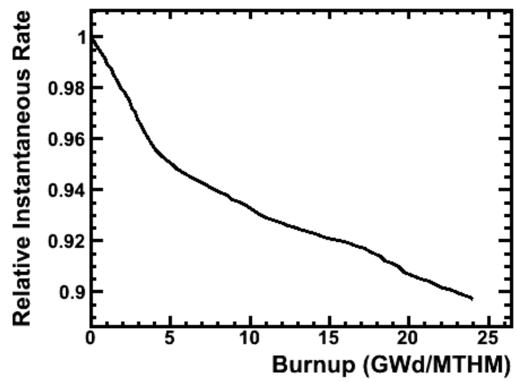

Figure 4. The instantaneous antineutrino emission rate relative to start of cycle as a function of average burnup for a 1/3 MOX core. From [6].

This simulation effort only reports a single burnup value, roughly equivalent to the core-wide average. The discussion that follows can be readily generalized to each assembly in a core, if an assembly-by-assembly core simulation, like that in , is completed. In this case, the relationship between core-wide average burnup and antineutrino emissions is replaced with that for each individual assembly.

It is straightforward to integrate the instantaneous emission rate to produce the total antineutrino emissions of this core, as a function of burnup (time). This is shown in **Figure 5**. Also shown as a dashed line is a linear function whose slope matches that of the beginning of the total antineutrino emissions vs average burnup curve. This reveals the small extent to which this curve deviates from a linear function and confirms that $a_i \gg b_i$ in Equation 2.

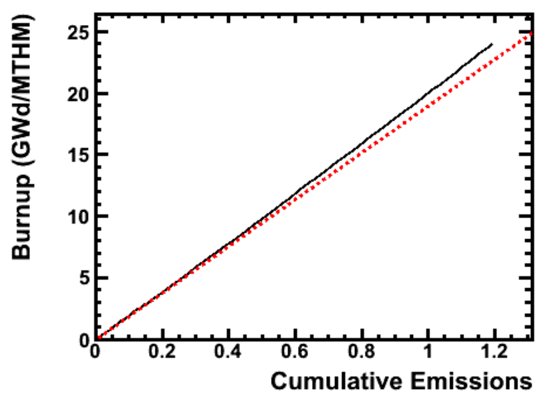

Figure 5. The average burnup of the 1/3 MOX core as a function of the total antineutrino emissions (the quantity that a detector can measure). Dashed line is a linear function whose slope matches that of the beginning of the total antineutrino emissions vs average burnup curve, showing small deviations of the curve from linearity.

Finally, we perform an approximate pictorial demonstration of how the detector and simulation precision determine how tightly the burnup value can be constrained. In Figure 6 we plot this same data, except here the red dashed lines represent a 5% error band about the simulation prediction of the relationship between total emissions and average burnup. The vertical green bands represent a detector precision of 10%. The intersection of those with the simulation error band determines the minimum and maximum possible burnup values.

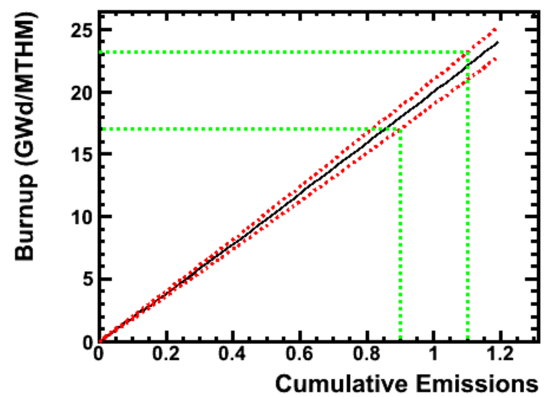

Figure 6. A pictorial representation of how detector precision (vertical green bands) and reactor simulation precision (red dashed bands) determine the precision with which burnup can be constrained (horizontal green bands).

As an example, we consider an application scenario in which an integrated antineutrino flux measurement of $R \geq R_{Thresh}$ was considered necessary to verify that a minimum burnup of 20 GWd/MTHM had been achieved. Given the previously stated uncertainty values for the detector (10%) and reactor simulation (5%), we can calculate the confidence level with which a minimum burnup of 20 GWd/MTHM had been verified as a function of R_{Thresh} (**Figure 7**).

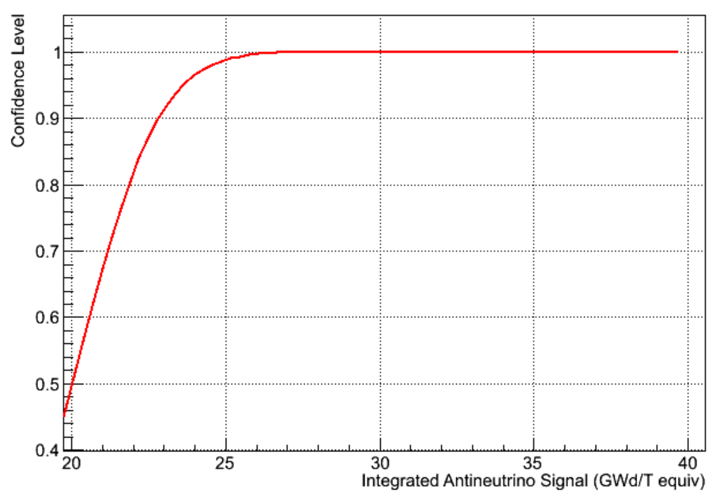

Figure 7 The confidence level for verifying that a burnup of 20 GWd/MTHM had been achieved as a function of the measured antineutrino flux. The integral antineutrino flux measurement is expressed in units of burnup (GWD/t), with the unit conversion occurring through the use of the relation expressed in Equation (2). A measurement of $\mathrm{R} \geq 25\ \mathrm{GWd/T}$ would ensure a 99% confidence that the minimum burnup had been achieved.

8. Previous Demonstrations of Antineutrino Power Monitoring

Our past work [3-4] has provided proof-of-principle demonstrations of the ability to monitor reactor power via antineutrino measurements. A compact, robust, and largely automated detector system (SONGS1) 25 m from the Unit 2 PWR of the San Onofre Nuclear Generating Station between 2003 and 2008. This device had an active volume of about $0.75m^3$ and a detection efficiency of 10%, yielding an expected detection rate of approximately 400 antineutrinos per day with the reactor at full power.

Figure 8 demonstrates the short-term instantaneous power monitoring ability of the SONGS1 detector. Here the number of antineutrinos detected is compared to the number predicted based upon the power history reported by the operator. We stress that the device had no connection to any plant system – it was positioned outside the reactor containment and simply counted the number of antineutrinos emitted by the reactor core. The transition from the reactor off state to full power over several days can be clearly observed. The measured detection rate does not fall to zero at zero reactor power due to cosmic ray induced background. However, since the cosmic ray flux is stable in time, this background can be reliably measured during reactor off periods and subtracted from reactor on periods. Analysis over shorter time scales determined that a reactor shutdown could be indicated to 99% confidence within just 5 hours using antineutrino measurements alone [4]. This ability to independently and remotely verify the state of the reactor core provides an additional Containment and Surveillance tool for off-load refueled designs like BWRs, PWRs, and many fast reactors.

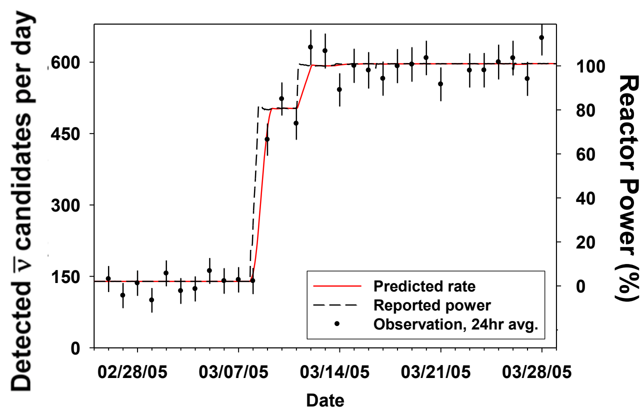

Figure 8. A short-term instantaneous power monitoring demonstration from the SONGS1 antineutrino detector. The measured data points (black) agree well with a prediction (red) based upon the power history reported by the operator (grey, right-hand axis).

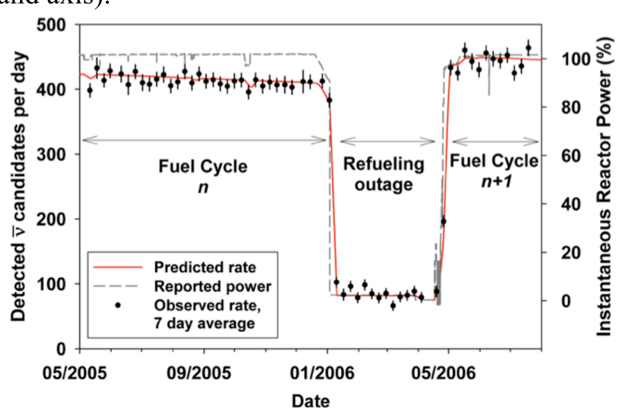

Figure 9 A long-term instantaneous power monitoring demonstration from the SONGS1 antineutrino detector. The measured data points (black) agree well with a prediction (red) based upon the power history reported by the operator (grey, right-hand axis).

Of more interest to this work is the ability to measure the total power output of a reactor during a particular operational cycle, since total reactor power output can be used to determine the burnup of individual assemblies via a reactor simulation code. Antineutrino measurements have also been demonstrated to provide this measurement capability – the total number of antineutrinos emitted by a reactor is related to the total power output of that reactor. When deriving the relationship between total antineutrino emissions and total power output, one must take into account the evolution of the reactor fuel isotopics, since fissions of different isotopic produce slightly different numbers of antineutrinos. This is relatively straightforward, since the reactor simulation code used to infer burnup from total power can also provide the fuel isotopics as a function of time.

This effect can be observed in **Figure 9**, which shows long-term power monitoring results from the SONGS1 detector. Here, the *instantaneous power* of the reactor is recorded. The measured antineutrino values agree very well with the expectation (red curve) that accounts for the evolution of the reactor core, given the preceding power history and knowledge of the reactor core map. The reduction in the expected antineutrino detection rate over time at full power is due to the ingrowth of ^{239}Pu in the core – ^{239}Pu fissions result in the emission of slightly fewer antineutrinos than do ^{235}U fissions. This demonstration was performed against an LEU fueled core. This so-called "burnup" effect would be less evident in a full or partial MOX core, since there is a smaller fractional change in the core composition in these cases.

The SONGS1 results can also be used to examine the total reactor power output (**Figure 10**) over the same measurement period presented in **Figure 9**. Here the total number of detected antineutrinos (black data points) is compared to a prediction (red curve) based upon the total reactor power output over that period (grey curve) and the expected reactor fuel evolution given the observed power history and reactor core map. The background measured during the reactor off period has been subtracted from the detector data to yield the number of reactor produced antineutrinos. Two important features are evident: (1) the total antineutrino measurement agrees very well with the prediction; and (2) the antineutrino measurement very closely follows the total power output of the reactor before, during, and after a reactor refueling outage.

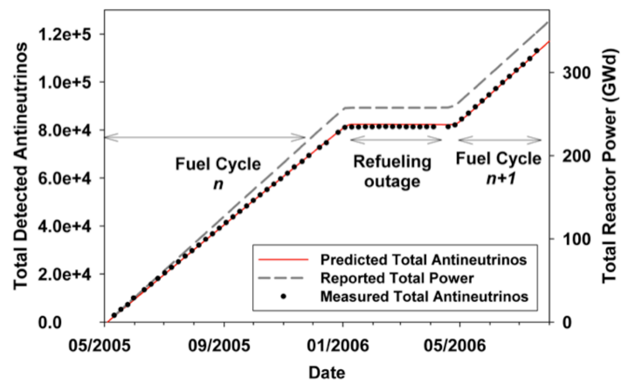

Figure 10 A long-term total power monitoring demonstration from the SONGS1 antineutrino detector. The measured data points (black) agree well with a prediction (red, left-hand axis) based upon the power history reported by the operator (grey, right-hand axis). The right-hand axis is scaled to separate the total power and total antineutrino curves for clarity

Finally, this data allows us to draw a direct correspondence between the total number of antineutrinos detected and the total power output of the San Onofre Unit 2 reactor (**Figure 11**). The measured data points, plotted as a function of total reactor power output, are in very good agreement with the predicted total, which is derived from the power history to date and the reactor core map using a reactor simulation. Such a simulation with these inputs also provides the burnup and isotopic content of each fuel assembly. Therefore, measurement of the total number of antineutrinos emitted from a reactor, used in conjunction with a verified reactor core map and a reactor core simulation, can determine the total reactor power output and the burnup and isotopics of each fuel assembly at any

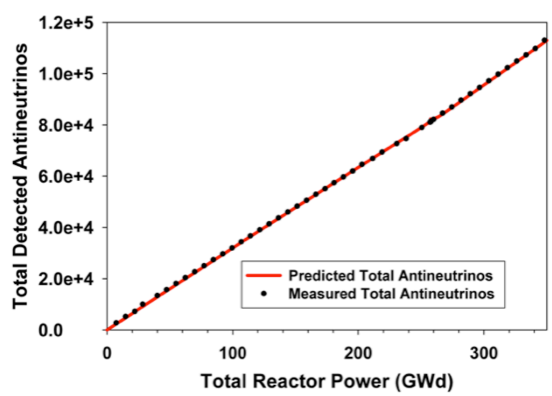

Figure 11 Data demonstrating the total power measurement capability of the SONGS1 antineutrino detector. The measured data points (black) agree very well with a prediction (red) based upon the observed power history of the reactor.

point in the reactor fuel cycle. For the results here, an uncertainty in our knowledge of the detection efficiency introduces an overall systematic shift in the prediction from the measurement. This appears as a scale factor, removed in **Figure 8** and **Figure 9** above by calibrating our initial antineutrino rate with the known reactor thermal power, provided by the operator. This is equivalent to the calibration against a well-known or otherwise validated reactor cycle discussed above. Using this strategy, the precision of the antineutrino measurement would be 1-2% and the precision with which burnup of individual assemblies could be constrained would be limited by uncertainties related to the reactor simulation code. These same reactor simulation code uncertainties are common to all other burnup assessment techniques based upon measurements during reactor operation (e.g. in-core and/or ex-core measurements of total power, temperature, and/or neutron flux).

9. Conclusion

Here we have described a potential measurement tool for the non-intrusive assessment of reactor fuel assembly burnup. Past experimental work demonstrates the fundamental principle of the technique – antineutrino measurements, when combined with a reactor simulation code, are analogous to a reactor thermal power measurement. The highly penetrating nature of the antineutrino emissions from a reactor allow great flexibility in the placement of a detector to measure them – no connection to any plant system would be required.

This technique can be applied to any reactor and/or fuel type including fast and thermal reactors fueled with any combination of LEU and MOX fuel, so long as an appropriate reactor simulation code is available. While this technique is unlikely to achieve sufficient precision to completely replace conventional power measurements that are currently used as inputs to reactor simulation codes, it provides a complementary and independent measurement. The non-intrusive and independent character of the technique make it especially suitable for applications where it is necessary to verify the power history and/or assembly-level burnup declared by a reactor operator.

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LLNL-CONF-560791
This research is supported by the U.S. Department of Energy National Nuclear Security Administration Office of Nonproliferation and Verification Research and Development.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000