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ABSTRACT:

As described in an earlier article [1], important information regarding reactor power and the amount and type of fissile material in reactor cores can be determined by measuring the antineutrino rate and energy spectrum, using a cubic meter scale antineutrino detector at tens of meters standoff from the core. Current International Atomic Energy Agency (IAEA) safeguards techniques do not provide such real-time quantitative information regarding core power levels and isotopic composition. The possible benefits of this approach are several and have been discussed in the earlier article. One key advantage is that the method gives the inspecting agency completely independent access to real-time information on the operational status and fissile content of the core. Furthermore, the unattended and non-intrusive nature of the technology may reduce the monitoring burden on the plant operator, even though more information is being provided than is available within the current IAEA safeguards regime.

Here we present a detailed analytical framework for measuring the impact that such a detector might have on IAEA safeguards, if implemented. To perform the analysis, we will use initial data from our operating detector and a standard analysis technique for safeguards regimes, developed at Lawrence Livermore National Laboratory. Because characterization of the prototype detector is still underway, and because improvements in the prototype could have important impact on safeguards performance, the results presented here should be understood to be preliminary, and not reflective of the ultimate performance of the system.

The structure of this paper is as follows. Reactor safeguards and the relevant properties of antineutrino detectors are briefly reviewed. A set of hypothetical diversion scenarios are then described, and one of these is analyzed using the Lawrence Livermore National Laboratory Integrated Safeguards System Analysis Tool (LISSAT) The probability of successful diversion is calculated for one specific scenario, for two cases:

1. Use of current IAEA safeguards methods

2. Use of current IAEA safeguards methods along with antineutrino detectors.

The relative improvement in IAEA safeguards are assessed by taking the ratio of the two probabilities (with and without antineutrino detectors).

INTRODUCTION

From a safeguards point of view, diversion of special nuclear material (SNM) from light water reactors such as plutonium is a concern to the IAEA, ref. [1]. IAEA safeguards monitoring systems are currently in place about half the world's power reactors and at hundreds of research reactors worldwide. In large part, these reactors are now safeguarded by indirect means that do not involve the direct measurement of the fissile isotopic content of the reactor, but instead consist of coded tags and seals placed on fuel assemblies, and measures such as video surveillance of spent fuel ponds and non-destructive assay.

Current IAEA safeguards techniques do not provide real-time quantitative information about the reactor core power level and isotopic composition. Important information regarding the amount of fissile material and its composition can be determined by measuring the antineutrino production rate and the antineutrino energy spectrum, here called antineutrino measurements for short. Depending on the antineutrino detector properties, these measurements can be used to derive estimates of reactor power, and of the relative or absolute amounts of U235 and Pu239 in the core whenever the reactor is operational.

The facility operator for off-load reactors makes declarations regarding the amount of fresh fuel received, the spent fuel that is shipped to the spent fuel pond from the reactor, spent fuel that is shipped to the reprocessing plant (if reprocessing is performed) and estimates of the burnup rate. These declarations can be confirmed by antineutrino measurements. Antineutrino measurements can also be used to detect changes in power levels and changes in fuel design.

We use the Lawrence Livermore National Laboratory Integrated Safeguards System Analysis Tool (LISSAT) method refs. [3,4,5,6] in this paper to generate and analyze diversion scenarios and to determine the impact of the antineutrino detection probability in reducing the scenario non-detection probability. This work provides an initial study of one of several diversion paths we are considering, and serves to illustrate the power of the LISSAT tool as a means for comparing reactor safeguards methods with and without antineutrino detectors. We have begun our comparative analysis with the conceptually simplest scenario, not the most realistic or advantageous. We may find that antineutrino detectors have more impact on other diversion scenarios as we continue our comparisons. We are using antineutrino data from a real prototype detector fielded by Lawrence Livermore National Laboratory and Sandia National Laboratory, ref [6]. A follow-on detector, now being designed, will have improved systematic and statistical precision which will also impact the comparison.

DIVERSION SCENARIOS IDENTIFIED FOR ANTINEUTRINO DETECTORS

We identified five scenarios involving diversion of fissile material from reactor sites that antineutrino detectors could be used. We limit our discussion to off-load reactors that are refueled at intervals, typically 18 months. Other reactor types will also be considered using this same framework. These scenarios are identified in table 1. The method and removal node (physical location for SNM removal) for each scenario is shown in column 3. The anti neutrino detection strategy is shown in column 4 for each diversion scenario. The strategy is based upon the following observations. If a higher (lower) fission rate occurs in the reactor, the antineutrino production rate will increase (decrease). If more (less) uranium is fissioned compared to plutonium, the antineutrino production rate will increase (decrease) and a higher (lower) antineutrino energy spectrum will be generated. Higher (hardening) and lower (softening) are synonymous. Approximately, the natural evolution of the reactor fissile isotopics over the normal fuel cycle induces a 5-10% reduction in the rate of antineutrinos measured in a standard detector, with the percentage depending on the details of the core design and fuel loading. Deviations from this normal behavior may signal illicit operation of the reactor.

Figure 1 shows three facilities considered in the five diversion scenarios – 1) Fuel fabrication plant, 2) reactor site that consists of a fresh fuel storage area, the reactor and spent fuel cooling pond and 3) the reprocessing plant.

Scenario 1 entails diversion of Mixed Oxide (MOX) Fresh Fuel in the fresh fuel storage area and replacement with LEU fresh fuel assemblies. Scenario 2 involves diversion of partially burnt fuel from the reactor during refueling with the substitution of fresh fuel. Scenario 3 involves unreported Pu production by substituting fertile fuel with fresh fuel. Scenario 4 involves running the reactor at full power and diversion at the reprocessing plant and misdeclaring lower fuel burnup rate at the reactor. Scenario 5 involves running the above nominal full power level, declaring full power and diversion at the reprocessing plant.

DETAILED ANALYSIS OF SCENARIO 5 – RUNNING REACTOR AT HIGHER POWER

To demonstrate the LLNL safeguards modeling approach, LISSAT, and the impact of antineutrino detectors on IAEA safeguards, we chose diversion Scenario No. 5 -- Unreported Pu Production at a PWR Reactor by

Running a Reactor at a Higher Power Level and Subsequent Diversion at a Reprocessing Plant. This scenario is similar in concept to undeclared feed at a uranium enrichment plant.

This diversion scenario involves running a light water at a higher power level than declared to produce an extra 8 kg of Pu that it is diverted at a reprocessing plant. We assume that the reactor operator is in collusion with the reprocessing plant operator. Specifics of this diversion scenario are described below.

We will assume a 3400 MWT PWR. The time line for the loading and unloading of fuel assemblies and storage in the spent fuel cooling pond is shown in figure 2. When fully loaded, the reactor contains 249 fuel assemblies. We assume that the refueling cycle occurs every 18 months and that one-third of the core is removed (83 fuel assemblies) during refueling. These fuel assemblies have undergone a total of 54 months of irradiation. When running at normal power (100%), we assume that the 83 spent fuel assemblies contain 383 kg of Pu at the end of the refueling cycle. To divert an additional 8 kg of Pu, we need to run the reactor at 5% higher power for two 18 month refueling cycles. The reactor operator makes a misdeclaration to the IAEA that the reactor burnup corresponds to 100% power when in fact the reactor has been running at 105% of power during the two 18 month intervals. We assume that these 83 spent fuel assemblies are stored in the spent fuel cooling pond for five years. At the end of the five year cooling period, we assume that the spent fuel assemblies are sent to the reprocessing plant and that the 8 kg of Pu is diverted at the reprocessing plant. How the 8 kg of Pu is removed at the reprocessing plant is beyond the scope of this paper.

At the reprocessing plant, we assume that the spent fuel assemblies are dissolved and measured in 10 separate batches at the accountability tank with a measurement accuracy of 0.85%. Since there are a total of 391 kg of Pu, each batch will contain approximately 39.1 kg of Pu. There is a concealed amount of 8/391 = 2.0%. We assume that the reprocessing plant operator introduces a bias of 1.0% in each measurement and leaves 1.0% as an imbalance in the Material Unaccounted For (MUF).

Three potential anomalies could be produced.

1. Fuel Burnup Anomaly -- Reactor Operator Burnup declarations are not consistent with IAEA's estimate.
2. Shipper Receiver Difference between reactor and reprocessing plant – Estimates of Pu according to fuel burnup calculations do not agree with estimates of Pu according to measurements made at the accountability tank located at the reprocessing plant
3. Difference Statistic Anomaly or MUF Statistic Anomaly -- Reprocessing Plant facility declarations regarding Pu content in spent fuel are not consistent with IAEA's estimate. Estimates regarding Pu content are based upon accountability measurements. The accountability measurement has three elements: volume measurement, taking a sample by remote control from the actively mixed tank, and laboratory measurement of Pu concentration. We assume that the inspector observes the volume measurement and the taking of a sample, and the concentration measurements are done by both the operator and the inspector's home lab. We assume the operator can bias his concentration measurement but cannot bias the volume measurement or the sampling procedure.

We assume that if the IAEA does not detect these anomalies, then the reprocessing plant operator will be successful in diverting 8 kg of Pu downstream of the accountability tank at the reprocessing plant. Figure 3 depicts the digraph generated for this scenario. The purpose of the digraph is to depict the flow of material, measurements and information as diversion occurs and provides the basis for the logic for generating the fault tree. Dashed lines in the digraph represent detection of anomalies. Events in the digraph indicated by N: indicates events that nullify information flow so that anomalies are detected by the IAEA.

The fault tree for successful diversion is shown in figure 4 and consists of all AND gates. For successful diversion to occur (i.e., diversion is not detected by the IAEA) – all detection paths must fail, i.e., all of the three anomalies described above will not be produced. There is one diversion path to this fault tree that consists of five basic events described below –

A. Diversion of 8 kg of Pu downstream at accountability tank
B. Reactor operator runs reactor at 5% higher power than declared for 36 months
C. IAEA accepts reactor operator burnup declaration corresponding to 100% reactor power
D. Reprocessing plant operator introduces a bias of 1.0% in each measurement and leaves 1.0% as an imbalance in the Material Unaccounted For (MUF)
E. IAEA does not detect a bias of 1.0% in each measurement and a 1.0% imbalance in the MUF

Events B, C and D are replicated twice in the fault tree in figure 4. We assume that each of the basic events described above occur with probability one except for event E. Event E involves reporting a measurement bias of 1.0% for each of the 10 tanks that are measured for Pu content and an undetected shift of 1.0% of the input stratum in the MUF. Given a 0.4% measurement accuracy for one series of ten measurements of concentration by the operator or the inspector, the probability that D-statistic will not produce a 2 σ warning signal (one of the components of event E) is 0.59. The probability that the MUF anomaly will not be detected to a statistically significant degree depends on measurement accuracy for the output stratum, in-process inventory, and holdup strata. The probability of non-detection may be greater than 0.5. As a first bounding value, we assume a probability of non-detection of 1. We have not investigated the probability of triggering the MUF – D statistic. Hence the probability of successful diversion is the event E probability, 0.59.

The above analysis assumes that antineutrino detectors are not employed. If antineutrino detectors are employed, event C will have a lower non-detection probability. Assuming the current detector efficiency described in [5], the probability that the detector will not detect a 5% reactor power increase during 36 months is 0.33. With antineutrino detectors employed, the probability of successful diversion probability is Prob(Event C) x Prob (Event E) = 0.19. The reduction in the nondetection probability is then 1/Prob(Event E) = 3.

SIMULATION AND DATA INPUTS FOR THE ANTINEUTRINO DETECTOR

For the analysis above we relied on data taken with the LLNL/SNL antineutrino detector at San Onofre, and on a simulation of the reactor core using the ORIGEN code provided by Oregon State University. The simulation confirms that operating the reactor at 105% power causes the antineutrino count rate to rise by approximately 5%, as shown in Figure 5. Data from the San Onofre detector as currently operated allows an estimate of the power that is accurate to 4.5%, or approximately 1 standard deviation for the power shift described in scenario 5. Based on an initial analysis of the detector performance, we find that the power estimate can be reproduced monthly with this precision. Systematic drifts that may arise from temperature or other fluctuations in the detector response may prevent a more precise measurement with the current detector. We estimate that these systematic uncertainties can be reduced by one half in a follow-on detector, leading to a 2 standard deviation detection of a 5% shift in reactor power. More information can be found in the accompanying paper ref [6].

CONCLUSIONS

The LLNL LISSAT method provides a systematic approach to generate and analyze diversion scenarios and demonstrates the impact of antineutrino detectors in reducing the scenario non-detection probability. The scenario analyzed for this paper was running the reactor at a higher power level than declared and than diverting at the reprocessing plant. The scenario is intended to illustrate the technique – other scenarios may prove to be more sensitive to the introduction of an antineutrino detector. Even for this scenario, chosen for its simplicity, the introduction of an antineutrino detector showed a factor 3 in reducing the non-detection probability. Further reduction in the probability of non-detection can be anticipated from improvements in the antineutrino detector, and possibly through examination of other diversion scenarios. The remaining four scenarios will analyzed by LISSAT to determine the impact in reducing the non-detection probability when antineutrino detectors are used. In addition, a cost benefit analysis will be generated for all five scenarios.

Diversion Scenario Number	Diversion or Anomaly	Method/ Removal Node (Physical point for removal)	Anti neutrino detection strategy
1	MOX FF Diversion/Replacement	LEU Assembly substituted for FF assembly/ Fresh fuel storage area	detect *increase* in rate or *hardening* of high energy spectrum
2	Partially Burnt Fuel Diversion/Replacement	FF assembly substituted for partially burnt assembly/ 1.Reactor during refueling 2.Spent fuel storage area 3.Reprocessing facility	detect *increase* in rate or *hardening* of high energy spectrum
3	Unreported Production	Fertile Assembly substituted for FF/ 1.Reactor during refueling 2.Spent fuel storage area 3.Reprocessing facility	Detect *decrease* in rate or *softening* of high energy spectrum
4	Run Reactor at Full Power, Diversion at Reprocessing Facility	Misdeclare lower burnup/ Removal of Material at reprocessing Plant	Detect *decrease* in rate or *softening* of high energy spectrum
5	Run Reactor at greater power than declared	Misdeclare reactor power/ 1.Reactor during refueling 2.Spent fuel storage area 3.Reprocessing facility	Detect increased rate

Table 1 -- Five Diversion Scenarios Considered for a Light Water Reactor

FF = Fresh Fuel
SF = Spent Fuel

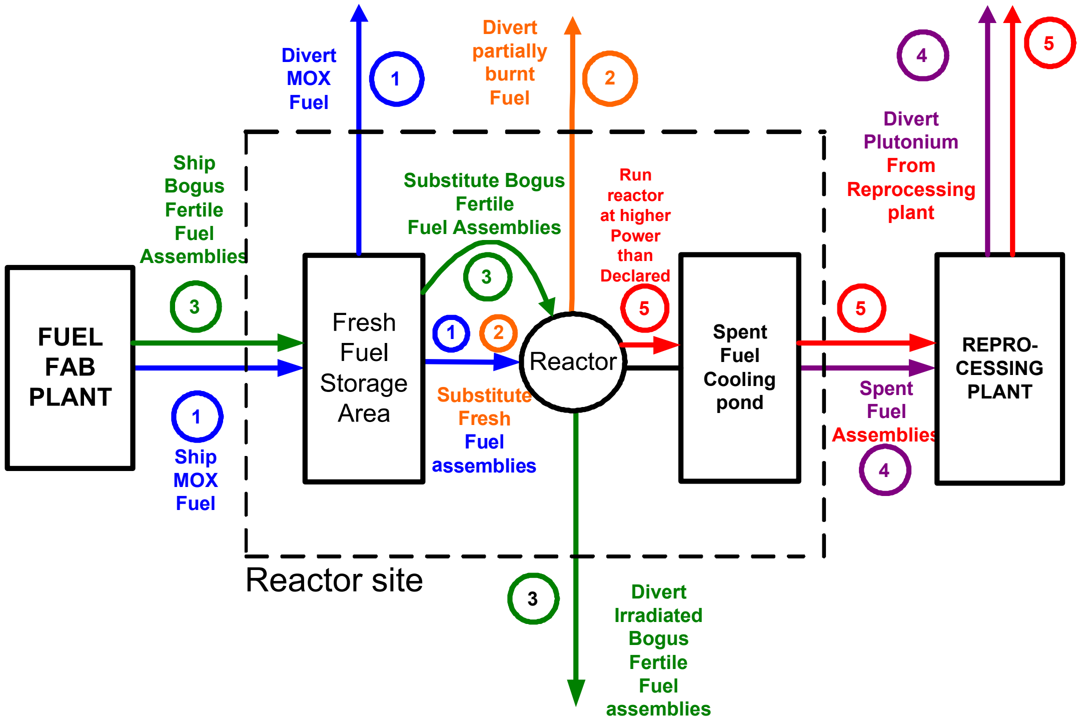


Figure 1 – Five Diversion Scenarios Considered for Light Water Reactor

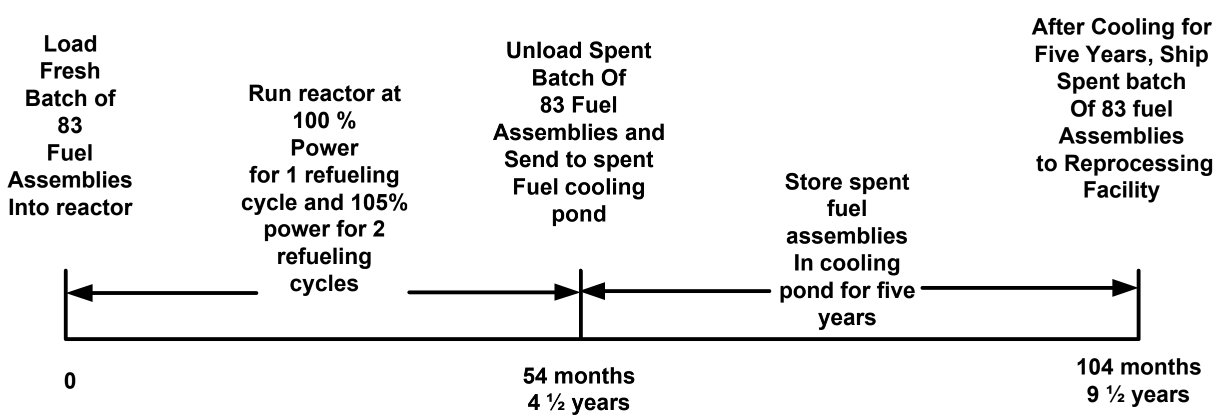


Fig. 2 -- Time Line for Unreported Plutonium Production by Running Reactor at 105% for one Refueling Cycle

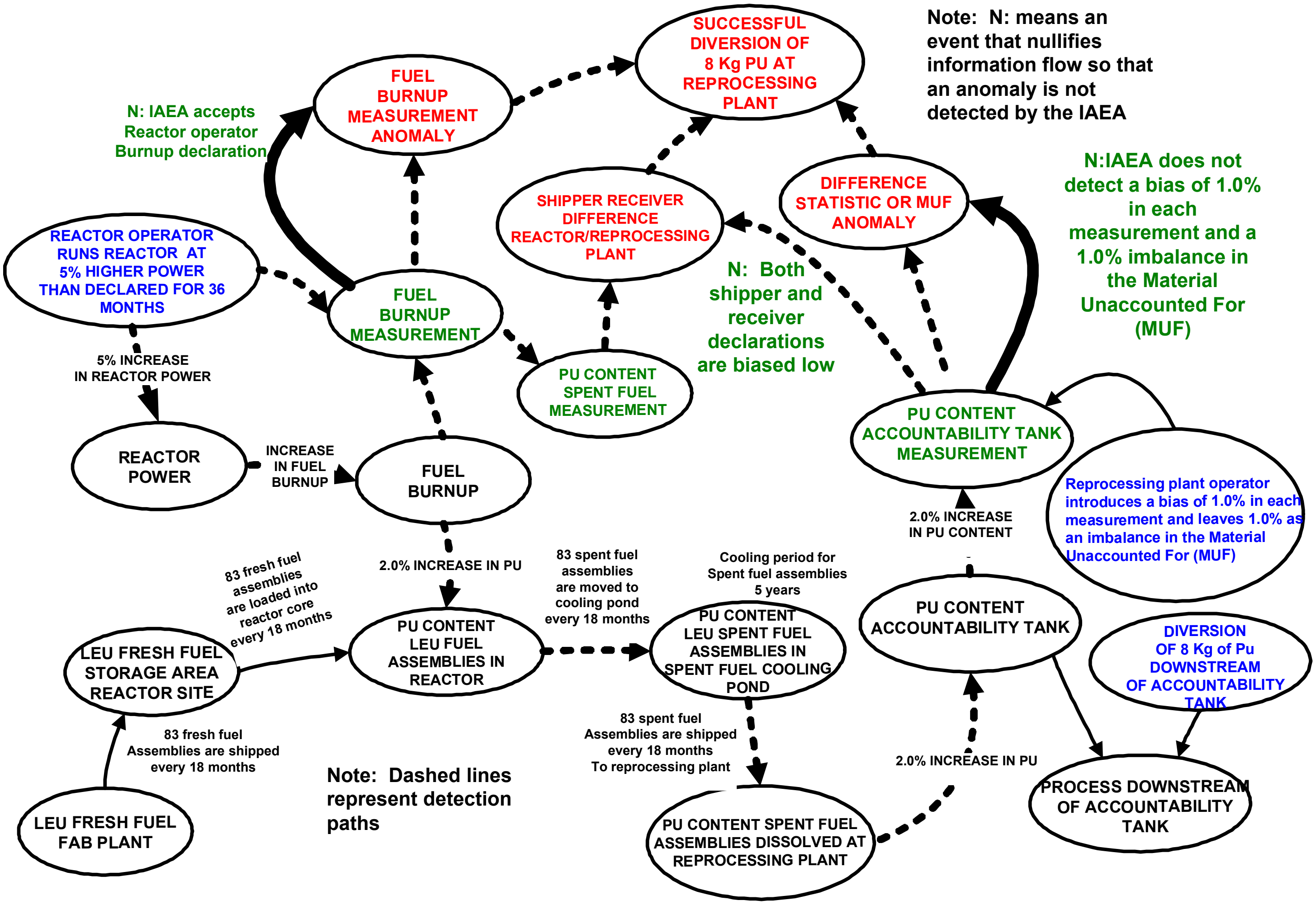
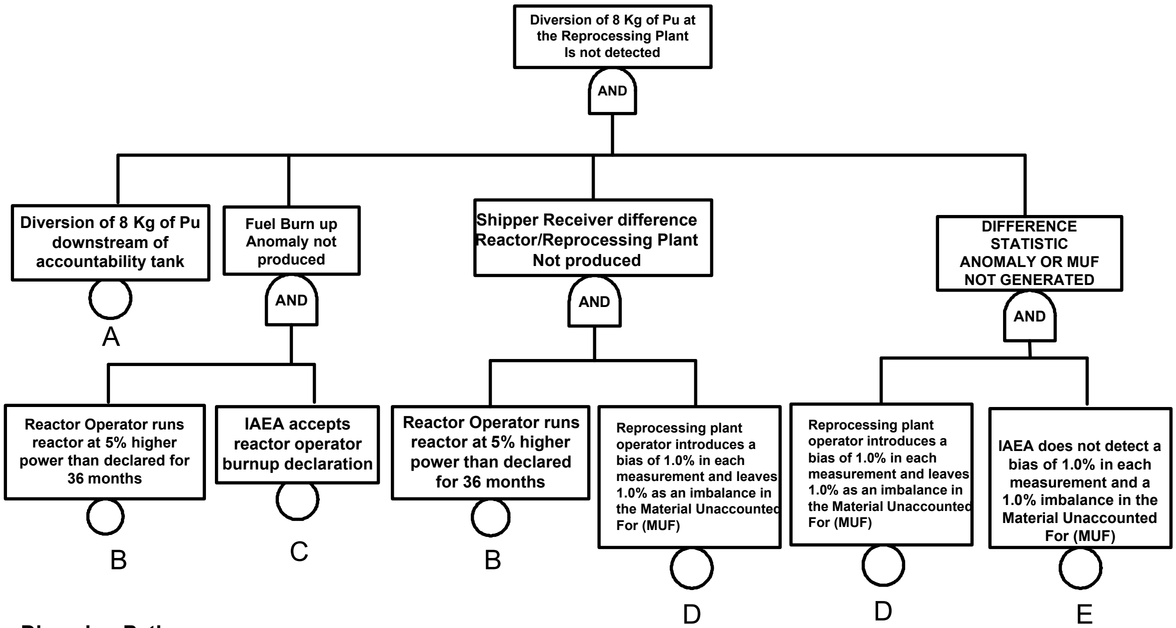


Figure 3 – Digraph for unreported Pu production at a PWR reactor by running the reactor at a higher power level than declared and subsequent diversion at a reprocessing plant



Diversion Path

A. Diversion of 8 Kg of Pu downstream of accountability tank
B. Reactor Operator runs reactor at 5% higher power than declared for 18 months
C. IAEA accepts reactor operator burnup declaration
D. Reprocessing plant operator introduces a bias of 1.0% in each measurement and leaves 1.0% as an imbalance in the Material Unaccounted For (MUF)
E. IAEA does not detect a bias of 1.0% in each measurement and a 1.0% imbalance in the Material Unaccounted For (MUF)

Figure 4 – Fault Tree For Unreported Pu Production at a PWR Reactor By Running the Reactor at a Higher Power Level then Declared and Subsequent Diversion at a Reprocessing Plant

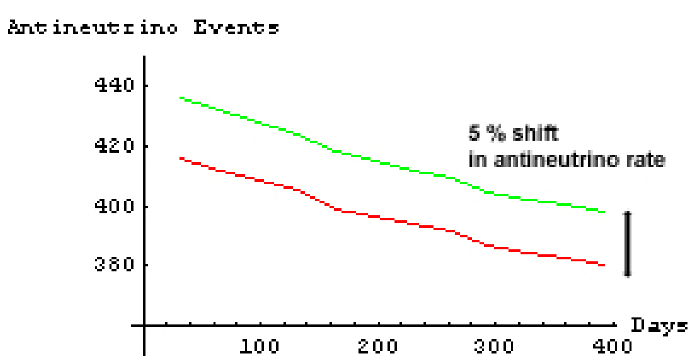


Figure 5 – Simulation of the SONGS reactor demonstrating the 5% upward shift in antineutrino rate cause by a 5% increase in reactor power. The upper (green) line is the antineutrino rate assuming operation at a 105% power level, the lower (red line) is for a baseline 100% power operation. The number of events is normalized to correspond to the approximate efficiency of the current detector, which counts approximately 400 net antineutrino events per day at full power. The slow downward drift in antineutrino rate is due to the ingrowth of plutonium in the core. This known drift is removed in order to extract the estimate of the reactor power.

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