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Submitted to:

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ABSTRACT

A safeguards system has been developed since 1993 in the course of supporting a fuel cycle process to fabricate CANDU fuel with spent PWR fuel(known as Direct Use of PWR spent fuel In CANDU, DUPIC). The major safeguards technology involved here was to design and fabricate a neutron coincidence counting system for process accountability, and also an unattended continuous monitoring system in association with independent verification by the IAEA. This combined technology was to produce information of nuclear material content and to maintain knowledge of the continuity of nuclear material flow. In addition to hardware development, diagnosis software is being developed to assist data acquisition, data review, and data evaluation based on a neural network system on the IAEA C/S system.

INTRODUCTION

The DUPIC fuel cycle, which stands for direct use of spent pressurized water reactor (PWR) fuel in Canada deuterium uranium (CANDU) reactors, has been developed [1 and 2] as an alternative to conventional spent fuel management options of direct disposal or plutonium recycle. Spent light water reactor (LWR) fuel can be burned again in a heavy water reactor (HWR) by direct refabrication into CANDU-compatible DUPIC fuel bundles. This technical feasibility indicates that the DUPIC fuel cycle could be considered as a prospective fuel cycle, since LWRs and HWRs are expected to dominate the world market in the foreseeable future.

Korea, with both PWR and CANDU reactors, initiated a feasibility study on the DUPIC fuel cycle concept in the early 1990's as a joint evaluation program with Canada and the United States (US). The conclusion of the earlier study has led to a subsequent program on experimental verification of the DUPIC concept. DUPIC technology, now in experimental development at KAERI under international cooperation (Canada, U.S.A, IAEA) seems to draw mounting attention not only from national, but also from international nuclear communities.

The R&D efforts for the current stage are directed to fuel re-fabrication and verification of compatibility with the CANDU design. In addition to this, the DUPIC safeguards system which has been recommended to embed safeguards considerations from the earliest possible stage of research and development, is being developed to support DUPIC fuel cycle development. They include two basic items : a material accounting system which has been used as a major measure of safeguarding by the IAEA, and its complimentary measure, containment and surveillance(C/S) system. For the material accounting system, a set of remotely operable instruments for non-destructive assay have been developed under strong support of LANL experts[3]. For the C/S system, an unattended continuous surveillance system using advanced diagnosis is being developed[4].

This paper addresses the main features of DUPIC safeguards and the development status of DUPIC safeguards system, which has been developed since the early nineties.

DUPIC FUEL MANUFACTURING PROCESS AND ITS FACILITY

The spent LWR fuel assemblies are transformed into the HWR fuel bundles by way of the DUPIC fuel fabrication process. This removes the metallic components, including cladding, from the spent LWR assembly. Almost all the spent LWR fuel material flows along with the bulk stream through the DUPIC fuel fabrication processes and scrap recovery, except for a small amount of irrecoverable discards. The waste stream from the DUPIC fuel fabrication processes would therefore mainly consist of the metallic components from spent LWR fuel, and the gases and semi-volatile fission products released from the bulk fuel material treatment, in addition to measurable discards and losses. There is no liquid waste arising from the DUPIC fuel fabrication processes which depend entirely on dry method, in contrast to wet processes from which liquid waste as effluent can arise. Once fabricated, the DUPIC fuel pellets are loaded into the metallic components of an (CANDU-type) HWR fuel bundle.

KAERI(Korea Atomic Energy Research Institute) has prepared a hot cell, the so-called DUPIC Fuel Development Facility(DFDF), for experimental manufacturing of DUPIC fuel. The installation and in-cell performance test of the equipment at the IMEF(Irradiated Material Examination Facility) M6 hot cell at KAERI was completed at the end of 1999. The main experiment using the IMEF M6 hot cell started in January 2000. Based on the results of a DUPIC powder/pellet characterization study at PIEF(Post-Irradiation Examination Facility) hot cell, the reference fabrication process conditions were established. Until now, about fifty DUPIC pellets have been successfully fabricated from spent PWR fuel, and fifteen pellets of them have already been loaded into the Hanaro research reactor for a performance evaluation.

MAIN FEATURES OF DUPIC SAFEGUARDS

A key feature of the DUPIC fuel cycle concept is its unique proliferation resistance[5 and 6]. The DUPIC fuel cycle concept has technical characteristics that naturally comply with the SFS(Spent Fuel Standards)[7] since the fuel is never chemically separated in any step along the DUPIC linkage between LWRs and HWRs. In addition to the absence of any separation of SNM involved in DUPIC fuel fabrication, the inherently hostile conditions of spent fuel material during re-fabrication require a heavily shielded enclosure around the fuel fabrication processes, linked with safeguards surveillance systems, which constitute multiple layers of security. DUPIC processing is self-contained, and there is no transport of intermediate materials outside of the facility: spent LWR fuel enters the facility, and fresh CANDU-DUPIC fuel leaves.

The proliferation resistance inherent in the DUPIC fuel cycle has to be paired with commensurate safeguards systems for the assurance of nonproliferation compliance. It was pointed out that the deterrent nature of radioactive fuel materials to human access, as proliferation resistance in the sense of spent fuel standards, can also be a hindrance to measurements for nuclear material accountability, and thus construed as a negative factor for safeguards. This is a technical question that could be solved with the development of an adequate measurement system.

The characteristics of the DUPIC process from a safeguards aspects are (1) that major part of the process contains the bulk form of spent fuel material, thus, Material Unaccounted For(MUF) is inevitably generated and the MUF has to be periodically evaluated, (2) there is no IAEA safeguards criteria available for use as a reference in establishing a facility safeguards system, (3) that there is no known NDA measurement technology for DUPIC material accounting.

As a strategy for nuclear material accounting in DUPIC process, the neutron inventory verification concept was introduced. The rationale of the concept can explain as follows; All spent LWR fuel for manufacturing DUPIC fuel has 10 years of cooling time. Most neutrons(~ 99%) generated from that spent fuel originate from spontaneous fission of Cm-244. The spontaneous fission neutrons can be selectively measured by the use of a shift resister. Therefore, the Cm mass can be estimated from measuring the coincidence neutrons and it is then possible to set up a mass balance of the Cm within a specific material balance period. The diversion of the SNM can be also inferred from the Cm mass balance. In addition, SNM(Special Nuclear Material) such as plutonium and uranium can be indirectly estimated from the Curium ratio(Pu/Cm or U/Cm) in which the ratios in a specific batch can come from a burnup simulation code like ORIGEN2 or destructive analysis. With this concept, KAERI and LANL have been jointly pursuing the development of an appropriate nuclear material verification system, named DSNC(DUPIC Safeguards Neutron Counter), by introducing neutron coincidence measurement technology.

When structuring a nuclear safeguards system for the DUPIC facility, the secondary concern is the containment and surveillance system. It is important to continuously monitor the flow of fuel transport casks in these areas. However, inspection of the resulting safeguards data requires much time and effort. Therefore, it is necessary to develop software that automatically pinpoints and diagnoses the anomalies of the data. This will greatly alleviate the inspection time and effort required in the operation of safeguards systems. Furthermore, by automating the integral analysis of camera and radiation monitoring data, a more precise diagnostics of nuclear material inventory can be achieved. The R&D effort for the surveillance system of a DUPIC facility is directed into a time synchronized unattended continuous monitoring system. The monitoring system hardware integrates the sensory unit of CCD cameras and neutron monitors, which records the visual history of the material transport and the radiation level at the reception areas. This system can recognize the anomalies of the monitored data and identifies the path and type of the transported nuclear material. The surveillance system being developed as well as the neutron coincidence counter for SNM accounting are described in the following subsection in more detail.

STATUS OF DSNC DEVELOPMENT

Hardware Description and its Installation

The DSNC, which is a well-type neutron coincidence counter, is for inferring the amount of Curium from measuring spontaneous fission neutrons at various process stages in the DUPIC fuel cycle. The DSNC design was done jointly at KAERI and LANL and its concept was described well in a previous paper[3]. The DSNC design focused on all types of DUPIC process material that are remotely measurable(CANDU type bundle, powder, rod-cut, hulls, and wastes) in a hot cell during lab scale operation. A total of 18 ^{3}He tubes with nitrogen quenching were symmetrically located in a high density polyethylene moderator and each of the ^{3}He tubes was connected to an individual preamplifier to reduced the gamma-ray pileup problem. A preamplifier status lamp was attached to each tube in order to visually monitor its normal operation in the hot cell. Another unique feature of the DSNC, compared to other conventional coincidence counters, is that substantial shielding is added to protect the ^{3}He tube/electronics from the intense gamma-rays of the DUPIC process material with a maximum surface dose of ~10^{4} R/h.

The DSNC manufactured by KAERI was installed in the M6b hot-cell of DFDF for DUPIC material safeguards. Lead bricks for gamma shielding and boron lined high-density polyethylene bricks for neutron shielding were installed outside of the DSNC to reduce background signals from the processing hot materials remaining in the M6 hot-cell. Stainless steel plates were also covered shielding materials. In order to commonly use the data from the DSNC, an IAEA safeguards instrument cabinet for monitoring the DSNC data was installed near KAERI's measurement system located outside the hot cell. All related cabling work was done in the operation area of the M6 hot-cell during from Oct. 4th to Oct. 8th, 1999.

Figure 1 shows the connection of cabling DSNC as well as IAEA's and KAERI's instruments related to the DSNC. In this figure, the neutron signal from DSNC was split into 3 neutron signals through a splitter that was inside the IAEA cabinet. Two signals from the splitter connected to two JSR-12s of the IAEA system, respectively, of course one of them is for backup, and the remaining one was connected to the PSR-B of the KAERI system.

In addition, the IAEA neutron source, K-868 (Cf-252 activity 2.022E+04 n/s as of Dec. 19th, 1999), which was received in March, 1999, was located under the VACOSS seal near the DSNC in the M6 hot-cell to determine the detector characteristics in advance of DUPIC material measurement.

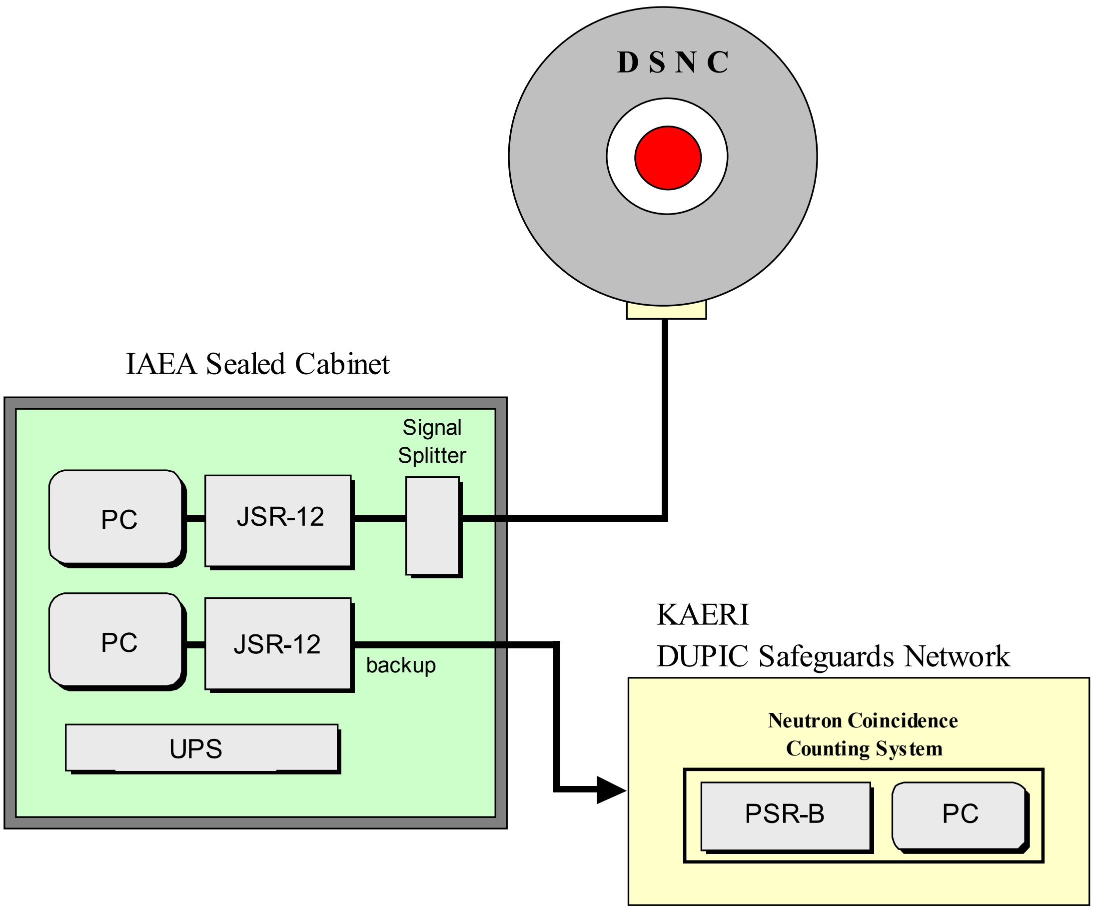

Fig. 1 Connection of the DSNC under IAEA Safeguards

Software Setup

Collect and analysis programs, MIC (Multi-Instrument Collect, Version 1.652), RAD (Radiation Review, version 2.05) and INCC (IAEA Neutron Coincidence Counter, version 4.04) for a neutron multiplicity counter developed by LANL for IAEA safeguards were transferred to KAERI for DSNC operation and installed not only on a PC in the IAEA cabinet, but also on a KAERI PC during from Oct. 4th to Oct. 8th, 1999. The revised INCC program includes the calculation function of Pu, U and U-235 isotope contents from measured Cm-244 content and the Curium ratio.

Performance and IAEA Authentication Tests

To officially use the DSNC for DUPIC safeguards, the authentication from the IAEA is needed. For this, the DSNC was calibrated and authenticated two times at the DFDF by the IAEA with assistance from the KAERI and LANL safeguards teams on Oct. 8, 1999 and Dec. 9, 1999.

From the hot experiment of the DSNC with IAEA standard source and Spent Fuel Standards (SFS) major setup parameters including operating high voltage under a high-level gamma-ray background, detection efficiency and a calibration constant were determined. The DSNC detection efficiency was 13.48% using the IAEA neutron source(K868) and verified its constancy within +/- 0.02% during one month. The Cm-244 calibration constant of DSNC, which means the slope of a straight line between the curium mass and measured double, was also derived from the singles rate of K868 combined with the singles/doubles ratio from the SFSs by LANL as shown in Figure 2. The Slope, 1.19E+05 cps/g Cm-244, will be used to convert the measured Doubles rate to Cm-244 content.

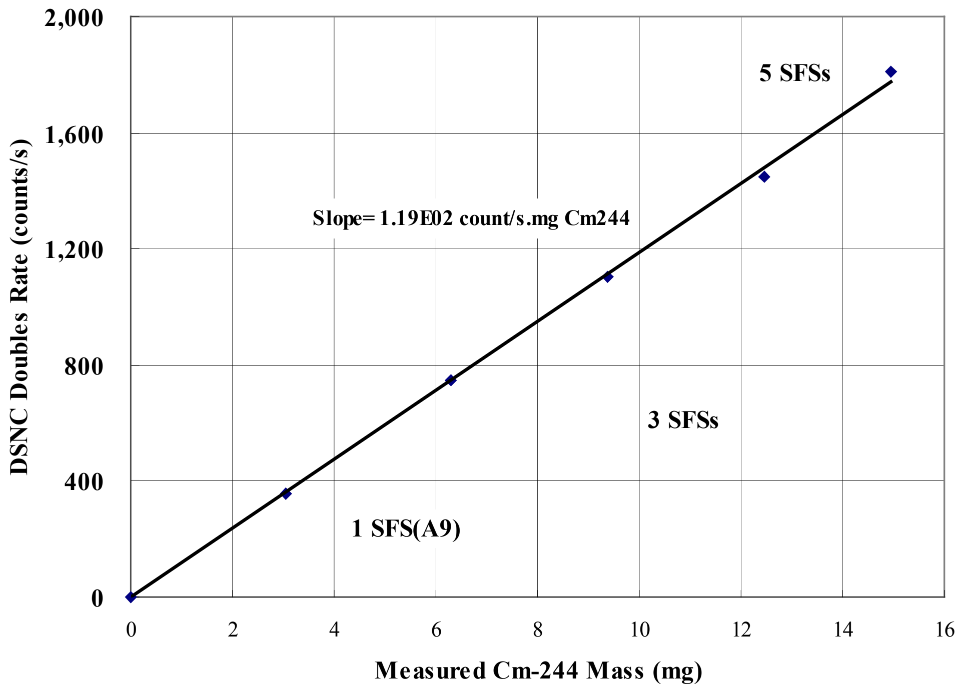

Fig. 2 Calibration slope for DSNC Cm-244 Measurements

After calibration, the performance verification test of DSNC by 12 SFSs showed that the declared Cm-244 contents from ORIGEN2 calculations for the SFSs are almost the same as the measured Cm-244 by the DSNC. It was indicated that the declared mass (ORIGEN2 code value) in the SFSs have an average difference of about 4% compared to the measured mass by DSNC. Part of this difference can be attributed to the uncertainty in DSNC calibration for Cm-244. However, the major source of the difference is probably caused by the ORIGEN2 calculation of the Cm-244 mass that has an uncertainty greater than 10%.

Based on the hot test and authentication experiment results with hot materials, it was concluded that the DSNC was reliable enough to be used for the measurement of DUPIC process materials. With this reliable confidence, this neutron measurement system is being used for nuclear material accounting of the DUPIC process by the IAEA as well as the domestic safeguards body. Eventually, this system will be integrated with the C/S system in the near future.

THE STATUS OF DUPIC CONTAINMENT & SURVEILLANCE SYSTEM

R&D efforts in the C/S area are directed to an unattended, continuous, integrated surveillance system to meet and improve the basic functionality of other unattended continuous surveillance systems. In system development, particular effort is made for digital analysis of events by incorporating an advanced diagnosis mechanism to selectively draw a conclusion on only the significant events throughout the monitoring period. This was done by integrating the video and radiation sensors in a common time dimension through image processing, and designing a computer interface for the neutron counting sensor. This system is able to alert spent fuel material movement to and from a typical hot cell system.

Hardware Description

Figure 3 shows the Containment and Surveillance(C/S) system for the safeguards of the DUPIC Fuel Development Facility(DFDF) under development.

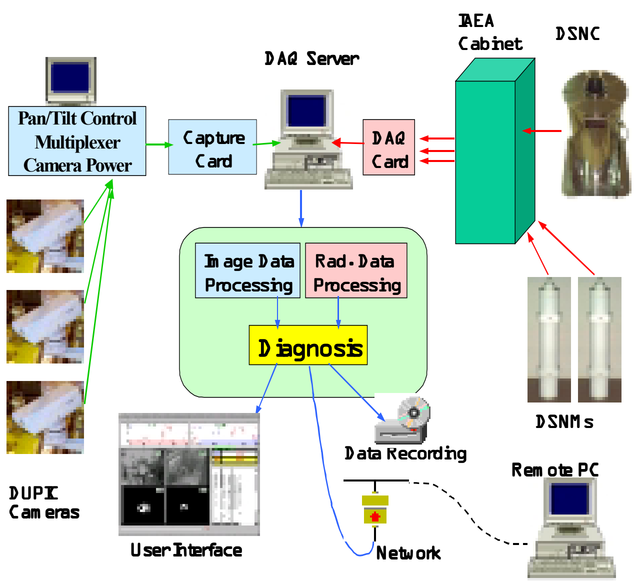

Fig 3 Configuration of the DUPIC C/S System

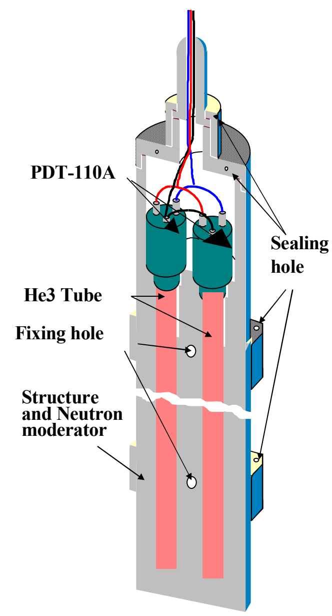

Fig 4 DUPIC Safeguards Neutron Monitor

There are two unsealed doors and one sealed door on the DFDF. Three CCD cameras are positioned at each door in order to monitor some activities related to the SNM movement to and from the doors. Two DSNMs(DUPIC Safeguards Neutron Monitor), as shown in Figure 4, are located near the unsealed doors to detect any transportation of nuclear material through the doors. The cameras and DSNMs installed on the outside surface of the DFDF are cabled to the surveillance server (a personal computer) located in the working area of the DFDF. The personal computer takes the image signal and the radiation signal periodically, analyzes them, and diagnoses the transportation status to report the result to the remote client as shown in Figure 3. The signals of DSNC and DSNMs are shared with the cabinet of the IAEA.

Each neutron monitor(DSNM) installed at the DFDF includes two pairs of He-3 gas proportional counter tubes and a preamp to increase efficiency and reliability. They have no gamma shielding because they are located outside of the hot cell, and their structures are constructed with high density polyethylene, which also has the function of neutron moderation. The signals from the DSNMs are acquired with a DAQ, card which has four input channels and simply counts the number of neutrons detected.

Software Description

The data periodically acquired is processed to be fed to the transportation diagnosis routine, where the level and the variance of the radiation data and the position and the size of the objects in the image data are evaluated by the data processing software. Image processing, based on the differentiation of images and the comparison of objects size, is still very preliminary.

The transportation diagnosis program has two stages of the individual mode and the overall mode. In the individual mode, the radiation transportation status based on the radiation data and the object transportation status based on the image data are determined separately, and in the overall mode the two results are unified to make an overall diagnosis about transportation. In the individual mode, the diagnosis routines of both radiation and image determine the transportation status to one of the four cases of 'No Detection', 'Fade In', 'Rest', and 'Fade Out'. In the overall mode, a more sophisticated diagnosis based on the results of the individual mode and the raw data will be performed.

Preliminary Hot Test of the Surveillance System

Since the overall mode diagnosis is under development, only an example of the individual mode diagnosis is presented here as shown in Figure 4.

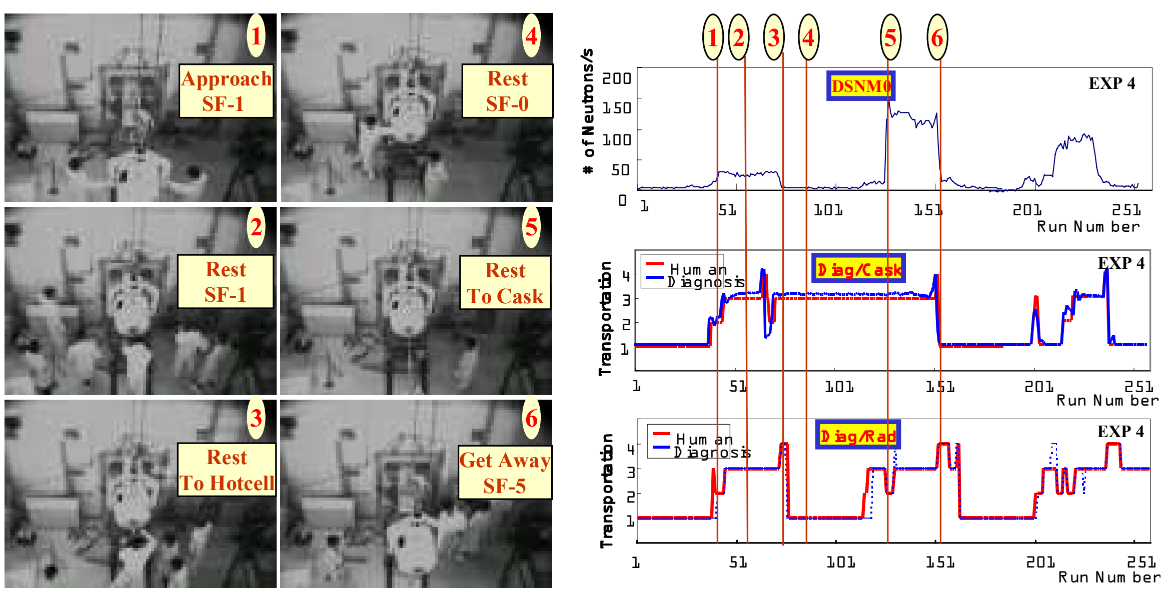

Fig. 4 Hot Test of the Surveillance System Using a Cask with one Spent Fuel Rod-cut

In this experiment, 10cm spent fuel rod-cuts were transported into the hot cell. (1) A cask containing one spent fuel rod-cut is approaching to the hot cell door(Cask Fade In, Rad Fade In), (2) the cask with one rod-cut in it is at rest(Cask Rest, Rad Rest), (3) the one rod-cut in the cask is being brought into the hot cell(Cask Rest, Rad Fade Out), (4) the empty cask is at rest(Cask Rest, Rad Rest), (5) five rod-cuts are being brought into the cask from the hot cell(Cask Rest, Rad Fade In), (6) the cask with five rod-cuts in it is going away(Cask Fade Out, Rad Fade Out). As shown in the above graphs, the diagnosis results well describe the transportation status. The top graph shows the radiation level, the middle one is object diagnosis, and the bottom one means radiation diagnosis. The blue lines in the middle and bottom plots are the diagnosis results by software and the red plots are by a human. The axis values in the middle and bottom plots mean that 1 is no detection, 2 is fade in, 3 is rest, and 4 is fade out.

CONCLUSION

A safeguards system has been developed since 1993 to support the DUPIC fuel cycle development. The development focused on a material accounting system and C/S system. For the material accounting system, a set of remotely operable instruments for a non-destructive assay have been developed under the strong support of LANL experts. For the C/S system, an unattended continuous surveillance system by adopting a neural network is being developed. Both of DSNC and C/S system under development were already installed in the DFDF and have been calibrated and tested at the DFDF hot-cell.

Based on the cold test and authentication experiment results with hot materials, it concluded that the DSNC was reliable enough to be used for the measurement of DUPIC process materials. From the preliminary hot test of the surveillance system under development, it was indicated that the surveillance system by use of the neural network would be helpful for unattended continuous monitoring of the DUPIC facility. If the system is appropriately set up with further hot test, it could be contributed to reducing of the inspection time and effort required in the operation of safeguards systems in the future.

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