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DESIGN, DEVELOPMENT AND TESTING OF AN AUTOMATED MEASUREMENT SYSTEM FOR THE ASSAY OF PLUTONIUM IN 3013 CONTAINERS

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ABSTRACT

Plutonium in a variety of forms stored in 3013 containers is one of two main input materials to the MOX facility being constructed at the Savannah River Site by Shaw AREVA MOX Services, LLC. The purpose of the MOX facility is to fabricate Mixed Oxide (MOX) reactor fuel from plutonium and uranium derived from decommissioned nuclear weapons. This paper describes the design, development and testing of an automated and integrated non-destructive assay (NDA) system consisting of a Gantry Robot crane, a sample weigh station, two gamma ray isotopic ratio spectrometry instruments, four calorimeter temperature pre-conditioners and four calorimeters. The purpose of the system is to assay and thus characterise all of the plutonium, which is an input to the fuel fabrication process. At the highest level the MOX facility Normal PLC (NPLC) system controls the movement of a sample by directing the Gantry Robot crane to move 3013 containers from an input conveyor to the various conditioning and measurement stations and then into storage positions. After the weight measurement, the 3013-containers are moved to temporary storage or one of the temperature pre-conditioning stations. The second stage of the measurement process is to load the 3013-container into one of the isothermal calorimeters. Following the completion of a calorimeter measurement of the container thermal power, the Gantry Robot crane moves the container to one of the plutonium gamma ray spectrometers to determine the plutonium isotopic ratios. Measurement data from the assay stations is combined in a Measurement Control Computer (MCC) and the assay result for each 3013-container of plutonium is transmitted to the MOX facility Normal PLC system. The paper describes the design and testing of the Gantry Robot crane with bar code reading and including the gripper designed to handle 3013-container with a misaligned lifting feature. Novel multimode calorimeters, thermal pre-conditioners and shielded plutonium isotopic ratio gamma ray spectrometers designed to measure fissile material in 3013 containers are described.

INTRODUCTION

A comprehensive automated system for measuring the fissile content of 3013 containers has been designed, built and tested by ANTECH for deployment at the Mixed Oxide Fuel Fabrication Plant being constructed by Shaw AREVA MOX Services, LLC (MOX Services) at the Savannah River Site. Fissile material (plutonium) in 3013 containers is handled by a 3-Axis Gantry Robot and measured in sequence by a weigh station, a calorimeter (to determine sample thermal power), a gamma ray spectrometer (to determine isotopic ratio data) and placed in temporary storage.

The MOX Services Normal PLC (programmable logic controller) provides supervisory control of the complete integrated NDA system as well as direct control of the Gantry Robot. A Measurement Control Computer (MCC) provides control and data analysis for the assay instruments and pre-conditioners. A Process Personal Computer (PPC) provides the link between the NPLC and the MCC. The PPC also communicates with the MOX Services network computers to upload assay result data files to MOX Services file servers.

Figure 1. 3013 container

All measurements are made and all sample handling is of material in 3013 product containers. Calibration and test samples are also contained in modified 3013 containers. The containers hold up to 4.5 kg of plutonium and have a total mass of up to 12 kg. In order to permit automatic handling by the Gantry Robot, a pintle or lifting feature is integrated within the lid of each 3013 container and it is also incorporated into the top of the thermally insulating and shielded plug units of the different pre-conditioning and assay instruments. A standard 3013 container is shown in Figure 1, in which the bar codes can also be seen.

The automated NDA System is located in a dedicated restricted access room accessed by input and output conveyors; see Figure 2. The 3-Axis Gantry Robot is at the top of the image with the Y-axis Bridge and the Z-axis vertical “ram” and End Effector in the top left corner of Figure 2.

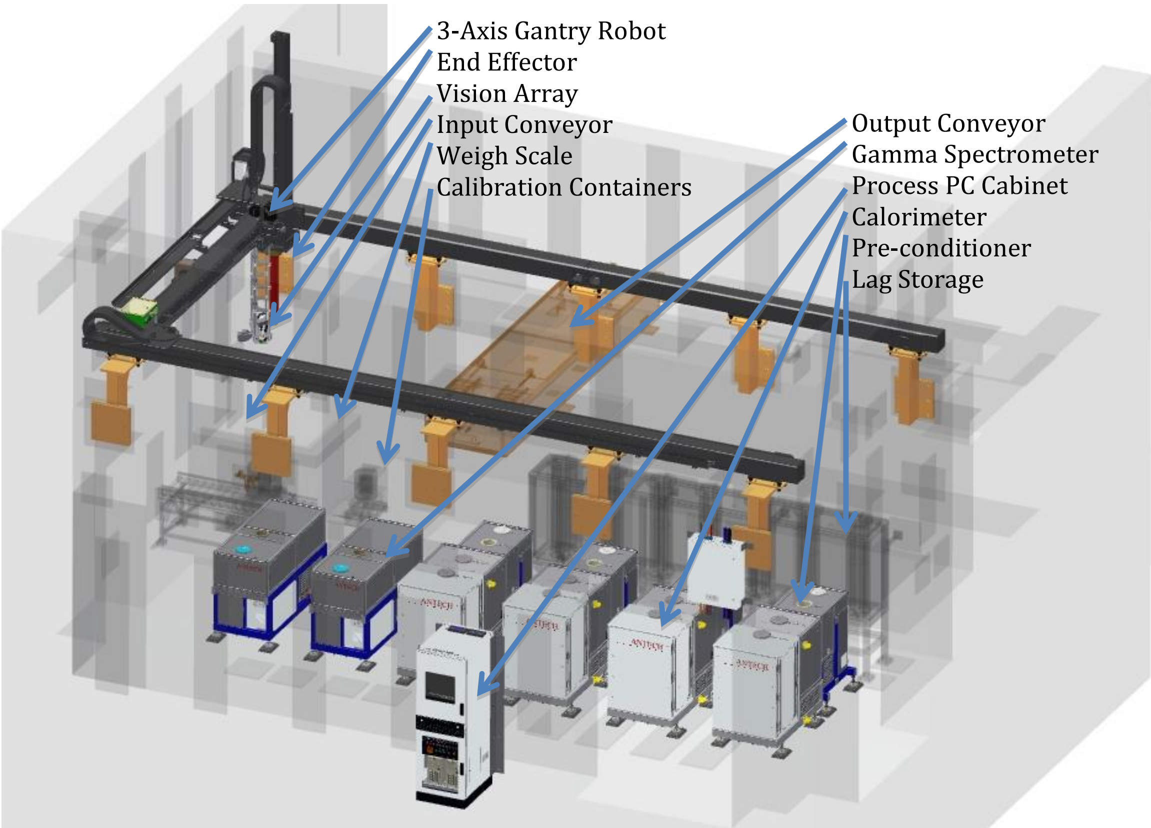

Figure 2. Three-dimensional view of the Automated Non-destructive Assay and Measurement System.

The two Gamma ray Isotopic Ratio Spectrometers are located in the left foreground and the shielded Input Conveyor is located to the rear and left of the Gamma Spectrometers on the raised surface. The Weigh Station is also behind the Gamma Spectrometers and to the right of the Input Conveyor. In the foreground to the right of the Gamma Spectrometers are 4 Calorimeters and to their rear are 4 Pre-conditioners. Although the original system design called for 4 Calorimeters and Pre-conditioners the initial delivered configuration has three of each instrument. The Lag Storage racks are to the rear of the Pre-conditioners and the Output Conveyor is located in an elevated position in the middle of the room below the 3-Axis Gantry Robot. Calibration and test 3013 containers are positioned behind the Gamma Spectrometers. Finally, the PPC cabinet (containing both PPC and MCC) is located externally outside of the assay room and is shown positioned in front of the Calorimeters. The assay instrument layout is also indicated in Figure 9. Figures 3 and 10 show some of the NDA instruments during testing.

NON-DESTRUCTIVE ASSAY AND MEASUREMENT INSTRUMENTS

Calorimetry for the thermal power measurement of plutonium [1] combined with gamma ray isotopic ratio measurement is the basis of the measurement and assay process employed by the MOX facility for determining the fissile content of 3013 containers in which the input material is supplied to the facility. The measurement system is made up of three component instrument types, consisting of calorimeter pre-conditioners, calorimeters and gamma ray isotopic ratio spectrometers. These three instrument types provide all of the measurement capability to quantify the fissile material input to the MOX facility. The measurement system design made provision for a total of four pre-conditioners and calorimeters and two gamma spectrometers. All the NDA instruments are mounted in a manner to facilitate quick removal of the instruments for maintenance outside the measurement facility. A custom designed location system has been developed to ensure accurate positioning of the instruments post maintenance thus alleviating the requirement of re-establishing their position.

Figure 3. Pre-conditioner, Calorimeter and Gamma ray Isotopic Ratio Spectrometer positioned below the 3-Axis Gantry Robot during testing. The support pillars are only used for factory testing.

The functionality of the process incorporates sample pre-conditioning or temperature adjustment, sample thermal power measurement and the measurement of isotopic ratio data by gamma ray spectroscopy. For the measurement of input plutonium samples in 3013 containers, it is necessary to combine the results of more than one measurement technique. The plutonium mass is determined by combining the calorimeter thermal power measurement with the isotopic ratio data from the gamma spectrometry measurement with standard plutonium specific power data. The measured data results, which are passed to the MCC and subsequently the PPC, include plutonium isotopic ratios, total plutonium mass, total americium mass, total mass of U-235 and the total uranium mass.

As the operation of the Non-destructive Assay (NDA) and Measurement System is automated, each of the individual instruments is designed to operate autonomously, without operator interaction but under the direction of the MOX facility NPLC. Commands are relayed to the NDA instruments through the PPC and MCC. Automated operation includes sample measurement and assay as well as calibration and performance checking or verification. Loading and unloading of all samples and calibration and check standards is conducted automatically by the 3-Axis Gantry Robot, which is described in detail later in this paper. The operation of each individual instrument type is described in the following sections.

Both the pre-conditioner and calorimeter are equipped with thermally insulated plugs to close the chamber when the unit is not in use or when a 3013 container is present in the chamber. All of the plug units have a lifting feature or pintle identical to the lifting feature on each 3013 container. During the loading and unloading process the plugs are removed by the Gantry Robot and placed in a storage location on the top of the instrument. The loading of the chamber includes the removal of the chamber plug unit prior to positioning the container in the chamber and the subsequent replacement of the plug unit to close the chamber by the Gantry Robot. All of these actions by the Gantry Robot are part of the sample loading and subsequent unloading process. In a similar manner, containers are placed in the measurement chambers of the two gamma ray spectrometers. These chambers are equipped with shielded top plugs. The loading and unloading of containers into the gamma ray spectrometers involves similar handling of the shielded plugs.

Calorimeter Pre-conditioners

During storage and shipment, thermally insulated 3013 containers of plutonium can reach elevated temperatures in excess of 100 degrees C. As calorimetry is a thermal measurement process it is necessary to pre-condition such containers before measurement by the calorimeters. Ordinarily, calorimeter sample pre-conditioning or pre-heating as it is often known, is required to raise the sample surface temperature to match the calorimeter measurement chamber operating temperature, typically 25-30 degree C. For most of the samples that will be measured by the MOX calorimeters, the function of the pre-conditioners will be to reduce the surface temperature of the 3013 containers of plutonium.

Figure 4. Thermal Pre-conditioner Unit

Each of the pre-conditioners consists of an internal cylindrical chamber similar in internal dimensions to the calorimeter measurement chambers. During pre-conditioning a 3013 container is placed in the internal chamber by the Gantry Robot. The process of container temperature modification is accomplished by controlling the internal chamber surface temperature of the pre-conditioner units at the same internal surface temperature as the calorimeters. This is achieved by a combination of both heating and cooling. A pre-conditioner unit is shown in Figure 4.

Should heating of the container be required to adjust its surface temperature, a heating coil is built into the outer surface of the pre-conditioner cylindrical chamber. In the more usual situation where a product container is at an elevated temperature, a closed loop air circulation system, similar to that used in ANTECH isothermal calorimeters, provides a means of cooling and heat removal. A Peltier cooling unit located in the base of the pre-conditioner controls the air temperature. Once a 3013 product container is loaded into an available pre-conditioner, the process of 3013-container temperature conditioning takes place. Temperature sensors imbedded in the wall of the pre-conditioner cylindrical chamber detect the container surface temperature and the pre-conditioner applies heat or more usually cooling to bring the container temperature to a level appropriate for a calorimeter measurement. The cooling process is very efficient at heat removal and the pre-conditioners are designed to adjust 3013 product container surface temperatures in as short a time as possible, typically less than an hour.

Calorimeters

The heat or thermal energy produced by plutonium samples in 3013 containers is measured by calorimeters of novel design operated in the "Isothermal Mode". The calorimeter design and operating characteristics have been described in detail in an earlier paper [2] so an abbreviated description of their operation is included in this section. One of the calorimeters is shown in Figure 5. Each Isothermal calorimeter consists of three concentric cylinders manufactured from aluminium alloy. Copper heater and nickel sense coils are wound around the outer surface of the middle and outer cylinders for electrical heating and temperature control.

Figure 5. Model CD285-3013 Isothermal Calorimeter.

The average cylinder temperature is determined by measuring the electrical resistance of the nickel sense winding. A copper heater coil is also included on the inner cylinder. Thermopile sensors for heat-flow measurement are located in positions in the gap between the inner and middle cylinders. The calorimeter inner cylinders (or measurement chambers) are controlled to a constant inner surface temperature through the application of a known and precisely measured quantity of electrical power. Once a 3013-product container is loaded into the measurement chamber and the Gantry Robot has replaced the plug unit, the calorimeter measurement begins. The calorimeter heat-flow sensors detect a temperature rise of the inner cylinder as heat or thermal power is released from the 3013-product container. In response, the calorimeter control system reduces the electrical power applied to maintain the inner cylinder constant temperature. When the calorimeter and 3013-product container reach thermal equilibrium, the difference in the calorimeter applied electrical power is a measure of the thermal power generated by the 3013-product container. With knowledge of the sample thermal power and the isotopic ratios data it is possible to determine not only the total mass of a plutonium sample but also the masses of the individual plutonium isotopes and the mass of Am-241.

Gamma ray Isotopic Ratio Measurement System

Isotopic ratios for plutonium (and uranium where appropriate) are measured using a high-resolution "safeguards quality" high purity Germanium (HPGe) gamma ray spectroscopy system. One of the Gamma ray Isotopic Ratio Measurement Systems is shown in Figure 6. The systems employ an

ORTEC SGD-GEM-5050P4 HPGe electro-mechanically cooled detector with high resolution and a detection efficiency of about 25%. The system incorporates ORTEC DSPEC® digital signal processing spectroscopy analysis electronics.

A 3013-product container is placed by the Gantry Robot on a rotation platform in the lead shielded cylindrical chamber of the instrument. The lead chamber and the lead shielding plug unit have a graded liner of tin and copper to supress the emission of lead X-rays. The HPGe detector views the fissile material (plutonium) in the product container through a variable aperture-shutter such that the full height of the container is in the detector crystal field of view. The width of the shutter is automatically adjusted to produce a count rate in the detector so as to optimise the HPGe detector dead time.

Figure 6. Gamma ray Isotopic Ratio Measurement System

Gamma ray spectral analysis to determine isotopic ratio data is performed by a version of the PC/FRAM isotopic ratio analysis computer code [3] written at the Los Alamos National Laboratory (LANL). Once a measurement is completed the gamma ray spectrum is analysed by PC/FRAM and the results data, consisting of the isotopic ratio information is transmitted to the MOX Services file server via the MCC and PPC.

MEASUREMENT AUTOMATION

The measurement automation system comprises a number of components in addition to the 3-Axis Gantry Robot. Some are located in the NDA measurement room and some are located externally. 3013 containers arrive on the Input Shuttle Conveyor into the Receiving Vestibule (provided by MOX Services) in a lidless transfer box. The Gantry Robot reaches into the lidless shielded transfer box to collect the 3013 containers for transfer to the weigh scale (also provided by MOX Services) and subsequently to the Lag Storage or directly to the NDA instruments. The overall system showing the NDA instruments and the Gantry Robot can be seen in Figures 2, 3, 9 and 10.

The Lag Storage rack (provided by MOX Services) has a capacity to store up to 28, 3013 containers in 7 columns each able to receive 4 stacked 3013 containers. Spacing of the columns is such as to avoid criticality. The containers are received in batches. If NDA equipment is fully utilised the containers are stored in the Lag Storage awaiting measurement.

3-Axis Gantry Robot

At the centre of the automation process is a 3-Axis Gantry Robot, which is used to move plutonium samples in 3013 containers between the Input Shuttle Conveyor Station, Weigh Station, Lag Storage rack, the different pre-conditioning and assay instruments, and the Output Conveyor Station. The design of the Gantry Robot is based on the use of gantry automation systems and components manufactured by Güdel AG based in Switzerland. The specific configuration of Gantry Robot for the Non-destructive Assay and Measurement System for MOX Services was designed to meet the demands of an exacting requirement specification associated with systems designed for handling plutonium in 3013 containers. The entire system has been designed and seismically qualified to meet MOX Services requirements. All of the design and manufacture of the system has been carried out under the control of the ANTECH ISO9001:2008 Quality Assurance System.

The MOX Services Normal PLC, which controls the 3-Axis Gantry Robot is a Siemens programmable logic controller (PLC) and utilizes Siemens closed loop-positioning servomotors for motion control. The MOX Services NPLC and the motor drives are housed external to the NDA room. The Gantry Robot provides all of the necessary functions to move the both the 3013 sample containers and 3013 based calibration and test containers through the measurement and calibration processes. The twin rails of the longitudinal X-axis will be mounted to the walls of the assay room utilising adjustable brackets. The robot has a total movement along the longitudinal X-Axis of 7.275 m. Spanning the X-axis is a bridge running on precision V rollers and rack. The bridge provides the Y-axis lateral motion of 2.3 m to gain access to the instruments positioned below. The vertical "ram" providing 1.8 m of Z-axis travel for the End Effector is located upon the Y-axis Bridge. The drive for all axes is provided by rack and pinion mechanisms through precision reduction gearboxes with motion provided by closed loop servomotors with absolute position encoders.

Safety interlocks ensure that the X and Y-axes are only permitted to move when the End Effector on the vertical Z-axis is in the elevated position to protect the sensitive assay equipment and the 3013 containers from damage and enhance criticality control. In addition to movement of the 3013 product containers, the gantry system manipulates isotopic and electric calibration samples in 3013 containers as well as removing and replacing the insulating and shielding plugs on the instruments.

Compensating End Effector

A Compensating End Effector (Figure 7) was designed by ANTECH for the 3-Axis Gantry Robot to automatically process the 3013 containers with geometric tolerances greater than the original design limits for 3013 containers and also process the instrument plug units. A novel design approach was required to pick up containers with the pintle feature positioned at up to 1.5 degrees from true and to accommodate containers stacked 4 high within the lag storage racks with a build-up of tolerance in the height of the containers. For both the input conveyor and lag storage there is a lack of close fit location when the 3013 containers are collected. These factors necessitated a design that incorporates a long reach and an integral degree of movement in the X, Y and Z planes as well as pitch and yaw movement.

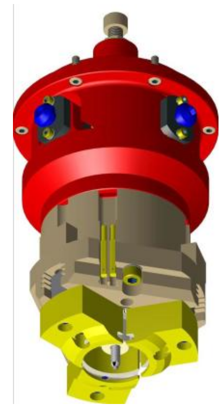

Figure 8. Gripper

Attached to the end of the Gantry vertical axis is a Schunk® pneumatically operated compensator permitting a limited amount of low friction travel in the X-Y plane when collecting containers specifically from the Input Conveyor and Lag Storage Racks. The compensator is locked centrally when depositing or receiving containers from other areas. Vertical movement is permitted at all times to ensure a positive location of the gripper.

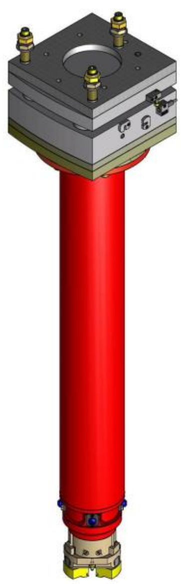

Figure 7. End Effector

The gripper (Figure 8) consists of a Schunk pneumatic 3-jaw gripper head fitted with proximity detection of the open and closed position and X and Y axis gimbals to provide 2 degrees of freedom in both pitch & yaw. In order that in the open position the gripper jaws provide precise alignment with the 3013-container lid, the nitride treated steel jaws have been machined to match the profile of the pintle, which is encased once the jaws are closed. Given the potential height tolerance for stacked 3013-containers, a linear transducer is positioned in the centre of the gripper jaws to provide feedback of the vertical can position to the NPLC control system. The data permits adaptive positioning of the gantry vertical axis to compensate for the stacking tolerance.

Container Identification System

The 3013 containers have both a machine-readable bar code and man-readable unique etched identifiers on their circumference. When a container is gripped the details are verified to ensure correct processing and routeing. A scanning bar code reader is mounted on the gantry such that the bar code characters are read when the 3013 container is raised to the upper vertical position. In the event that the bar code cannot be read, two high definition video cameras are positioned such that the man-readable characters can be read by staff in the system control room as an alternative method of 3013 container identification.

PROCESS OPERATION

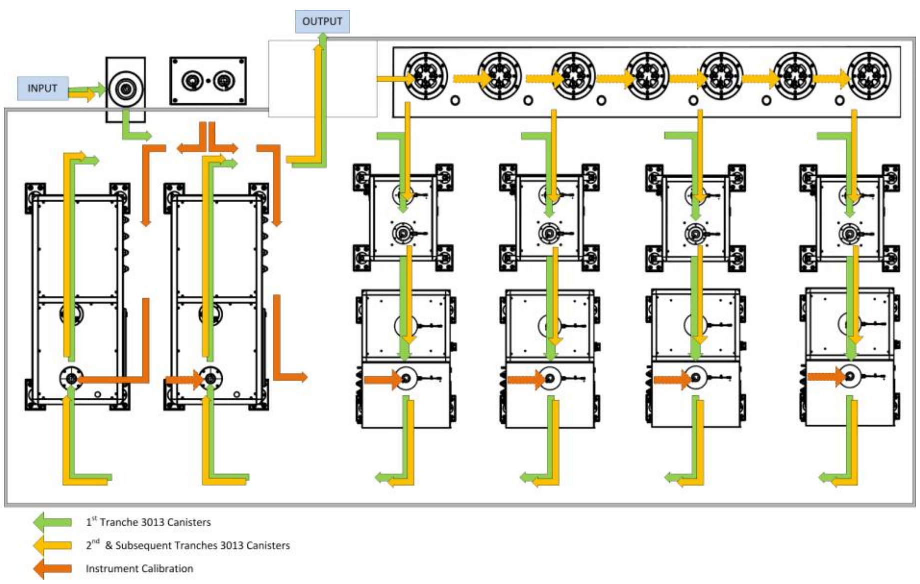

Figure 9. The process flow of 3013 product, calibration and test containers is shown in this figure. In this figure the Lag Storage is shown at the top and to the right and the Gamma ray Spectrometers are on the left of the image. See also Figure 2.

Three main process flows for 3013 containers in the NDA system are illustrated in Figure 9. Product 3013 containers are delivered on an Input Conveyor and, following measurement, they are delivered to an Output Conveyor. Both conveyors were supplied by MOX Services.

A total of four process flow sequences have been identified for 3013 containers moving through the NDA system. Initially containers are processed in a sequence involving arrival at the input, weight measurement, pre-conditioning, calorimeter measurement, gamma spectroscopy measurement and finally delivery to the output conveyor. However, 3013 product containers will be delivered in batches or tranches, and with all calorimeters occupied, temporary storage will be required. It is for this reason that the lag storage has been provided with a capacity of up to 28, 3013 containers. The three main sequences are shown in orange, green and yellow in Figure 9. The orange-labelled route shows the path followed by 3013 calibration and check source containers. The green-labelled route shows the process route without passing through the lag storage. The yellow-labelled route shows an intermediate phase of storage in the lag storage area prior to NDA measurements. The process route is defined as:

a. Pick 3013-container from Input Shuttle Conveyor
b. Weigh 3013-container on Weigh-scale
c. Store in Lag Storage (until pre-conditioner is available) as required
d. Condition in Pre-conditioner (to achieve calorimeter operating temperature)
e. Measure in Calorimeter to determine thermal power of 3013 containers
f. Measure in Gamma ray Spectroscopy System to determine isotopic ratio data
g. Place 3013-container on Output Shuttle Conveyor

A fourth process sequence is not shown in Figure 9. Upon receipt of a request from a downstream process unit to the NPLC, a 3013 container is retrieved from storage and delivered to the Output Shuttle Conveyor and brought back into the NDA room. The Gantry Robot then transfers this 3013 container from the Output Shuttle Conveyor to the Input Shuttle Conveyor for further transfer to the requesting process unit. As part of the management of the movement process for 3013-containers, every time a 3013-container is picked the end effector is raised to the top position of vertical movement and the barcode is read to verify the identity of the container. Movements of the Gantry Robot X & Y axis are only made with end effector raised to the top position.

TESTING AND CALIBRATION OF THE MEASUREMENT AND AUTOMATION SYSTEMS

Figure 10. This photograph shows the testing installation of the MOX facility automated NDA system. In this test configuration the Gantry Robot is supported on four pillars. A thermal pre-conditioner (left) and a calorimeter (right) are positioned below the Gantry Robot. Note that the End Effector is moving a plug unit on a pre-conditioning unit.

All pre-conditioning units were tested using simulated 3013 product containers, which were heated externally to a range of different temperatures before pre-conditioning. The units were commissioned to operate at temperatures slightly above the calorimeter set point temperature to compensate for heat-loss during the transfer from the pre-conditioner to an available calorimeter. Calorimeter testing and the electrical calibration process have been described elsewhere, [2]. The absence of fissile material necessitated an alternative scheme for the testing of the Gamma ray Isotopic Ratio Measurement Systems. The HPGe detectors and data acquisition electronics were calibrated and commissioned with calibrated point sources including Am-241, Co-60 and Cs-137. The operation of the software analysis algorithms was tested using archived gamma ray spectra from fissile material measurements. In operation, two calibration, validation and test standards in modified 3013 containers are stored in a rack near the Input Conveyor. The electrical heat standard obtains electrical power from a calibrated power supply built into each calorimeter. The gamma calibration standard with Am-241, Co-60 and Cs-137 calibrated sources provides a means of checking and calibrating the Gamma ray Isotopic Ratio Measurement Systems.

The 3-Axis Gantry Robot, Compensating End Effector (including pneumatic gripper) and Container Identification System have been subjected to an extended factory commissioning and testing process. The entire automation system is shown in the testing mock-up configuration in Figure 10. The instrument cabinets visible at the far end of Figure 10 contain the control electronics including the MOX Services Siemens NPLC. Some of the controlling electronics, the Siemens PLCs and the motion control software was provided by MOX Services and integrated into the system for testing and factory commissioning. All operations of the Gantry Robot have been extensively tested by a team from MOX Services supported by ANTECH over a period of several weeks.

CONCLUSION

The work reported in this paper includes the design, development, manufacture and successful testing of a fully automated assay and handling system for the determination of the fissile content of 3013 containers which constitute the input material for the Savannah River MOX facility being constructed by MOX Services. The constituent technologies includes a novel calorimeter design, automation of the sample pre-conditioning process and gamma ray spectroscopy measurement process as well as the implementation of an innovative 3-Axis Gantry Robot including a novel End Effector for robust handling of 3013 product containers from diverse sources and with variable mechanical tolerances. The design incorporates a high degree of criticality safety, necessary for the automated handling of 3013 containers used for the storage and transport of fissile material.

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