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DEVELOPMENT OF AN ENRICHMENT MONITOR FOR THE PORTSMOUTH GCEP[a]

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ABSTRACT

We have developed a gas-phase UF_6 enrichment monitor for use by the International Atomic Energy Agency at the Portsmouth Gas Centrifuge Enrichment Plant. The enrichment monitoring system provides a method for effective nuclear materials accountability verification while reducing the effort for both the facility operator and the inspector. The experience with an in-plant prototype monitor, the facility and operational constraints, and the constraints related to international safeguards inspection are described in terms of the impact on the monitor design.

I. INTRODUCTION

The Portsmouth Gas Centrifuge Enrichment Plant (GCEP) has been selected by the International Atomic Energy Agency (IAEA) for international safeguards inspection. An enrichment monitoring system, which is integral to a proposed IAEA nuclear materials accountability verification plan for GCEP, is to be installed at GCEP to provide the IAEA with continuous, verifiable, attributes measurements of the gas-phase feed, product, and tails UF_6 streams.[1] The enrichment monitors designed for GCEP are based on previous in-plant experience with a prototype monitor, on GCEP operational and facility design constraints, and on constraints related to IAEA international inspection. The enrichment monitoring system provides a method for effective nuclear materials accountability verification, while reducing the effort for both the facility operator and the IAEA inspector. The experience gained during test and evaluation of the prototype gas-phase enrichment monitor installed in the Paducah-product feed station of the Oak Ridge Gaseous Diffusion Plant (ORGDP) and specific GCEP operational and facility design constraints are discussed in terms of the impact on the GCEP enrichment monitor design.

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II. ASSAY METHOD

The gas-phase enrichment is determined by combining measurements of ^{235}U and total uranium concentrations. The ^{235}U concentration is determined from a measurement of the 185.7-keV gamma rays emitted from the decay of ^{235}U, and the total uranium concentration is determined by measuring the transmission through the UF_6 gas of 60-keV gamma rays from an external ^{241}Am source.

Accuracy of the measurement technique was first demonstrated using a laboratory prototype system based on an NaI(Tl) detector and static UF_6 samples.[2] The laboratory prototype produced results with an assay accuracy of better than 1% over the range of UF_6 enrichments of 0.72-5.4 at.% and over a range of UF_6 pressures from 5.33×10^4 to 1.076×10^5 Pa (7.7-15 psia). For 1.0%-enriched UF_6 at 9.31×10^4 Pa (13.5 psia), a 0.39% relative precision was measured for a 1-h counting time. As a result of these measurements, an in-line gas-phase enrichment monitor designed for in-plant use was installed in the Paducah-product feed line of ORGDP for field test and evaluation.

At the Paducah-product feed station, UF_6 from the Paducah Gaseous Diffusion Plant having enrichments near 0.9% is fed into the Oak Ridge plant. The UF_6 pressure at the monitor location varies between 6.89×10^4 and 1.11×10^5 Pa (10 and 16 psia) with flow rates of 0.057-0.126 kg UF_6/s (450-1000 lb UF_6/h). The most important aspect of the test was the observation of high levels of gamma-ray continuum background associated with high concentrations of ^{238}U daughter products. Because these background levels were unacceptably high for the desired assay accuracy of 1% using an NaI(Tl) detector, a high-purity germanium (HPGe) detector was installed in the monitor.

Subsequent measurements in several operating enrichment facilities have shown that under conditions of high UF_6 flow rates, a transport and plating on pipe walls of nonvolatile thorium compounds can be expected. The concentrations of these ^{238}U daughter products strongly depend on the operating conditions and design details of the facility.

In the current prototype at ORGDP, gamma rays are detected using standard high-resolution gamma-ray spectroscopy techniques based on a HPGe detector. The enrichment I is related to the measured count rate of 185.7-keV gamma rays R by

$$I = R/(C * \ln T60) \quad , \qquad (1)$$

where R is corrected for deadtime losses and attenuation in the gas, T60 is the transmission of 60-keV gamma rays through the UF_6, and C is the calibration constant. Determination of the enrichment from Eq. (1) is composed of two parts: measurement of R, yielding the ^{235}U concentration in the sample chamber, and measurement of T60, yielding the total uranium concentration in the sample chamber. Because the measurement accounts for variations in UF_6 density, the measured assay is independent of UF_6 pressure.

Using the germanium-detector-based monitor, assay accuracies of ~1% have been achieved for flowing UF_6 at an enrichment of 0.9% in the operating plant environment. A comparison of enrichments determined by the monitor to tag enrichments determined from gas mass spectroscopy is presented on a cylinder basis in Table I. The enrichment monitor values are the averages of all measurements made during the feeding of the respective cylinders. Mass spectroscopy results are based on gas samples withdrawn downstream from the enrichment monitor and are representative of the entire contents of the homogenized feed cylinders. The average bias of 14 cylinder measurements performed over the 2-wk period was 0.2%, and the relative standard deviation of the sample population was 1.3%. The expected precision for an average cylinder assay based on the monitor counting statistics is 0.5%. Slight fluctuations of the detector position probably were responsible for the larger standard deviation shown in Table I.

TABLE I

COMPARISON OF ENRICHMENT MONITOR AND TAG VALUES OF ^{235}U ASSAY

Cylinder	Tag (T) ^{235}U Assay (%)	Enrichment Monitor (EM) ^{235}U Assay (%)	$\frac{EM - T}{T}$
1	0.9494	0.9553	+0.0062
2	0.9544	0.9646	+0.0106
3	0.9498	0.9441	-0.0060
4	0.9515	0.9668	+0.0161
5	0.9500	0.9432	-0.0072
6	0.9490	0.9626	+0.0144
7	0.9503	0.9320	-0.0193
8	0.9482	0.9351	-0.0138
9	0.9496	0.9293	-0.0213
10	0.9493	0.9333	-0.0168
11	0.9495	0.9432	-0.0066
12	0.9516	0.9549	+0.0035
13	0.9440	0.9429	-0.0012
14	0.8865	0.9047	+0.0205

III. DESIGN CONSIDERATIONS

During the design phase of the enrichment monitoring system for GCEP, it was realized that enrichment monitors designed for measuring liquid UF_6, like those used routinely at the Portsmouth Gaseous Diffusion Plant, could not be used at GCEP because of a lack of single-phase liquid flow at the product-withdrawal station.[3,4] High flow rates associated with batch dumping of product desublimation cold-traps create a two-phase flow of UF_6 to the withdrawal cylinders, and methods to remove a single-phase liquid flow for measurement purposes were not practical because of facility operational and design constraints. Also, because of space limitations in the feed and withdrawal building and a desire to separate the IAEA design and construction activities from the ongoing process design activities, it was decided to put the enrichment monitors in a separate IAEA inspector facility.

In the inspector facility adjacent to the feed-and-withdrawal building, four enrichment monitors are connected to the interconnecting process pipeway (IPP). One monitor is connected to each of the feed, product, tails, and spare tails lines composing the IPP 1. IPP 1 provides the UF_6 connection between the feed-and-withdrawal building and process buildings 1 and 2. Because the assay accuracy required by the proposed IAEA nuclear-materials-balance verification plan cannot be achieved at the UF_6 gas pressures in the IPP, a sampling line incorporating compressor pumps has been designed to provide a gas pressure of 4.3×10^4 Pa (6 psia) at the monitor. Flow rates in the sample lines will be in the 200- to 1100-standard-cm^3/min range.

Use of in-plant instrumentation for IAEA inspection activities places unique and stringent requirements on the instrumentation design. A primary concern of the IAEA is that measurement results be verifiable, that is, the inspector must be able to authenticate the sample, assay procedure, and assay data transmission.

Also, the inspector is expected to be at the facility for accountancy verification 12-15 times a year for 2- to 3-day intervals. Consequently, the instrumentation must operate reliably, in an unattended mode, and must be easy to operate and maintain.

IV. MONITOR DESIGN DETAILS

Detailed layout of the monitor is shown in Fig. 1. The instrument electronics are in the front cabinet, which also houses the detector dewar, line-power conditioner, and interface junction boxes. The rear cabinet is heated and houses the measurement chamber, gamma-ray shielding, radioactive sources, measurement control shutter devices, UF_6 piping, flow meter, and heater elements. An insulated port in the heated enclosure accepts the detector snout, which is kept at room temperature. The two cabinets are thermally isolated from each other to keep the electronics at room temperature and the heated enclosure above 60°C.

The nuclear electronics provide the power, high-voltage bias, and signal processing required for high-resolution gamma-ray spectroscopy. All nuclear electronics used in the monitor are standard commercial NIM modules. The use of modular electronics allows on-site maintenance to be performed by the replacement of defective modules.

The detector is a 51-mm-diam, 15-mm-thick, HPGe planar type with an integrally mounted 3.5-cm-thick lead back shield. Cooling for the detector, required during operation but not during storage, is supplied by liquid nitrogen

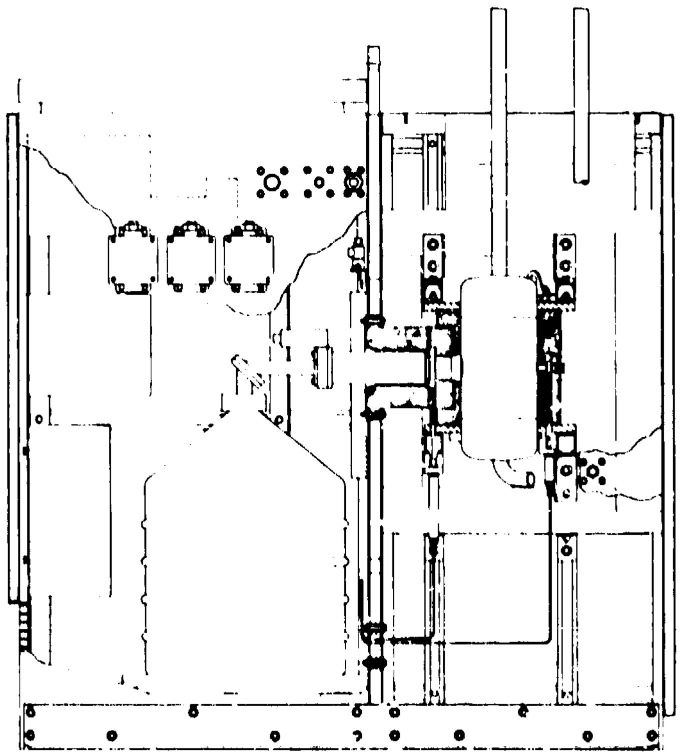

Fig. 1. GCEP gas-phase UF_6 enrichment monitor. The front cabinet houses the nuclear electronics, data acquisition device, line-power conditioner, detector dewar, and interface junction boxes. The rear cabinet is heated to 60°C and contains the UF_6 piping, measurement chamber, shielding, radioactive sources, measurement control shutter devices, and flow meter.

contained in a 30-ℓ dewar. The liquid nitrogen level is maintained by an automatic supply system. The detector high-voltage bias supply is coupled to a low-level liquid nitrogen sensor that protects the detector electronics by shutting off the bias if the liquid nitrogen level drops too low.

Signals from the detector are first conditioned by a preamplifier integrally mounted to the detector. The spectroscopy amplifier processes the preamplifier signal before the analog signal is converted to a digital signal by the analog-to-digital converter.

The programmable data acquisition and control (PDAC) module provides for automated data acquisition, data analysis, control, and data transmission functions. The data acquisition system includes a commercial analog-to-digital converter and digital stabilizer. The digital stabilizer corrects for drifts in the system gain by tracking the location of an 88-keV gamma-ray peak from ^{109}Cd and adjusting the digital signal before it is received by the PDAC.

A flow meter is included in the monitor to provide an indication to the IAEA inspector that flow through the monitor is continuous. It is therefore used as a flow switch and high accuracy is not required. The flow meter is a commercial mass flow meter using a heated tube thermal design. A flange connection of the flow meter to the UF_6 piping will be used to facilitate maintenance of the flow meter.

The chamber is constructed of 6-in., schedule 10, monel pipe. To allow for a reasonable transmission of 60-keV gamma rays through the chamber walls, the chamber wall thickness is reduced to 1.5 mm adjacent to the detector and to the ^{241}Am source. This design does not compromise the system design pressure range of full vacuum to 2.0 x 10^5 Pa (29.7 psia) at 74°C. The remaining piping is constructed with 1-in., schedule 10, monel pipe.

Two 2-position shutter devices are used for measurement control and calibration. One shutter device contains a uranium check source that is controlled automatically by the PDAC daily. The uranium source shutter is located between the measurement chamber and the detector face. The uranium source is put in the detector's view and an assay is performed. The result of the measurement is then compared with an expected value stored in the PDAC memory. During normal assays the uranium source is shielded from the detector. The second shutter device is a shield that can be inserted in front of the ^{241}Am source for background measurements. The shield shutter is controlled on demand from the PDAC front-panel keypad. The shield shutter and uranium source shutter are constructed of 0.635- and 0.965-cm tungsten plates, respectively. Each shutter is positioned by an air-driven piston. The positions of the shutter devices are monitored by the PDAC.

The main structural frame, major components, connections, and foundation anchorage of the enrichment monitors are designed for structural integrity and stability considering lateral earthquake forces for seismic class II components.

Interfaces between the monitors, the facility, and the enrichment monitoring system are closely controlled by design basis documents and interface control drawings, which were generated as a cooperative effort between the facility architect engineer and the development community. In the case of the enrichment monitors, a partial list of these interfaces includes the UF_6 process piping, electrical power, liquid nitrogen inlet and vent, instrument air, electrical signals, physical location, and the facility environment specifications.

Operation of the enrichment monitor is controlled by FORTRAN and assembly language programs stored in the PDAC read-only memory. The software provides all functions necessary to automatically acquire, analyze, and report data. The procedures for operating the monitor are designed to be as simple as possible under normal operation, yet provide the flexibility to perform functions necessary for calibration or diagnostics. After powering up or rebooting the system, the normal assay procedure is initiated automatically. All parameters required to perform the assay are retrieved from memory, and no user action or input is necessary.

Operating and maintenance procedures, which require an interface with the GCEP process system, will be the responsibility of GCEP operator personnel. Other than those procedures required for normal operation and maintenance of the slipstream loop and delivery of utilities, these procedures are limited to calibration, set-up, and maintenance activities for the monitors, which will be controlled by or performed by an IAEA inspector or by an authorized IAEA representative. When an interface with the GCEP process system is required, it will be performed by GCEP operator personnel under the observation of the inspector or his authorized representative.

Calibration procedures will include valving off of the monitors from the slipstream using manual block valves. The process gas will be removed using a portable purge and evacuation cart and a UF_6 sample will be put into the measurement chamber. The UF_6 sample will be contained in a standard 2S or smaller approved cylinder attached to an evacuation connection located downstream from the measurement chamber. A warm water bath or similar heating mechanism will be applied to the sample cylinder to reach a nominal pressure of 4.1×10^4 Pa (6 psia) in the chamber. An assay will be performed and the sample gas will be removed from the chamber. This procedure may be performed several times to cover the anticipated range of UF_6 assays. Measurements will also be performed on the evacuated chamber with the monitor shutters in various positions to determine gamma-ray backgrounds. After final evacuation of the chamber, the manual block valves are reopened and the monitor is returned to normal operation. Sampling of process UF_6 may also be used to verify the monitor calibration. Samples can be withdrawn using a pinch-tube system, or gas samples may be collected in 2S or smaller approved cylinders attached to the same evacuation connection used to introduce UF_6 samples. Calibration procedures are expected to be performed one to four times a year.

No maintenance on the measurement chamber is anticipated, and maintenance of the UF_6 process interface should be limited to that required for the flow meter.

V. SUMMARY

Evolution of the gas-phase enrichment monitors--from demonstration of the measurement technique in a laboratory environment through evaluation of a prototype instrument in a production facility to the final GCEP enrichment monitor design for IAEA safeguards--has illustrated the stages involved in transforming a measurement concept to an operational installation. The importance of testing measurement techniques in operating facilities became evident during this experience. Also, an effective safeguards system must be more than an effective measurement technique. It must be designed to satisfy the operational and facility constraints specific to the intended use. This design process involves a cooperative effort among plant designers, plant operators, and instrument developers. Through this process an effective enrichment monitoring system has been designed for the Portsmouth GCEP.

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