Modernization of the Gamma Box Measurement System at the Y-12 National Security Complex - 24461

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ABSTRACT

Mirion Technologies was commissioned to perform a major modernization of the gamma Box Measurement System (BMS) and Transmission Measurement System (TMS) located in Building 9720-32 at the Y-12 National Security Complex in Oak Ridge, Tennessee [1]. Some of the many benefits of this modernization include the simplification of systems, reduction in equipment footprint and maintenance, automated integration of transmission and emission measurements, automated combination of neutron and gamma measurements, implementation of a new data management database, ability to integrate new software algorithms such as enrichment or self-absorption corrections, ability to expand the system to other container types, elimination of obsolete hardware and software, and elimination of liquid nitrogen.

The BMS/TMS has been in operation since 1996 and is used primarily to characterize uranium-contaminated LLW packaged in B25 boxes for disposal to the DOE Environmental Management Waste Management Facility (EMWMF). The BMS consisted of twelve large NaI detectors for detecting and quantifying U-235 and U-238 in the boxes along with four 25% HPGe detectors for detecting other radionuclides of concern. The TMS consisted of three NaI detectors placed on one side of the box with three collimated uranium sources placed on the opposite side. The transmission values measured with TMS were used to correct the grams of U-235 and U-238 reported by BMS. The modern design integrates both emission and transmission measurements into a single system. Four large ~150% efficient electrically-cooled HPGe detectors with digital LYNX® MCA's were mounted on two towers, one on each side of the original BMS conveyor. Four collimated ~5.55E8 Bq Eu-152 transmission sources with shutters were positioned on the same towers opposite of each detector. Gamma emission is measured with the shutters closed and transmission with the shutters open. The conveyor was programmed for five static box positions yielding 16 independent emission measurements and 16 associated transmission measurements. The large degree of segmentation and overlap of the measurements ensure that activity hotspots are not missed and transmission corrections are accurate even for very inhomogeneous materials. Gamma efficiencies for each detector/segment combination were calculated using Mirion ISOCS™ mathematical efficiency calibration software. The segment data were acquired, combined, and analyzed using Mirion NDA2000™ software. A custom Data Management System was implemented to integrate BMS results with U-235 measurements obtained from the active neutron Crated Waste Assay Monitor (CWAM) system [2].

Validation measurements, including calibration verification, precision and accuracy, source distribution inhomogeneity, and detection limits were performed according to the Y-12 Performance Testing and Validation Plan (PTVP). Independent commissioning measurements were also performed. All performance requirements were met.

Results from the PTVP and commissioning studies will be presented. Quality Assurance measurements were established to monitor the performance of individual detectors as well as the total system daily. The upgraded BMS was put into production in July 2023.

INTRODUCTION

The Nondestructive Assay Facility (NDAF) at the Y-12 National Security Complex in Oak Ridge, Tennessee, began LLW characterization operations in 1996. The primary purpose of the facility is to quantify uranium concentrations in plant-generated LLW packaged in steel B-25 boxes. In 1997 the gamma-based Box Measurement System (BMS) – Transmission Measurement System (TMS) was approved by the Tennessee Department of Environmental Conservation (TDEC) to certify waste with total U < 35pCi/g (= 1.3Bq/g) for disposal to the DOE Environmental Management Waste Management Facility (EMWMF) in Oak Ridge [1]. The designed measurement throughput of the NDAF was 700 boxes per year.

In 2019 the BMS consisted of two sets of detectors with associated electronics and analysis algorithms:

- Twelve 12.7cm x 12.7cm shielded NaI detectors: the spectra were combined and analyzed using the Generalized Geometry Holdup (GGH) model [3] to generate an initial estimate of U-235 and U-238 masses.
- Four 25% HPGe detectors: these spectra were analyzed to identify and quantify nuclides other than U-235 and U-238. These measurements also provided the opportunity in some cases to generate an independent uranium enrichment value using the MGAU isotopics code.

The TMS was a separate gamma transmission measurement station that was comprised of three 7.6cm x 7.7cm NaI detectors positioned on one side of the box and three U235 plus three U238 sources placed on the opposite side. The TMS results were used to correct the initial BMS gU235 and gU238 estimates for gamma attenuation in the box.

Mirion Technologies was contracted in 2019 to perform a major modernization campaign on BMS/TMS. After the system upgrades the system is now simply referred to as the Box Measurement System (BMS). Some of the elements of this modernization included:

- Consolidation of a 19-detector 3-station system into a single 4-detector 1-station system. This resulted in a smaller system footprint, higher measurement throughput, and emission and transmission measurement, analysis, and reporting functions integrated into one system.
- Replacement of older low-resolution unstabilized NaI detectors with large (150%) modern high-resolution germanium detectors. Some of the advantages of this include lower detection limits and the ability to analyze all spectra for both uranium and non-uranium radionuclides.
- Replacement of LN2 cooling with electrical cooling. All LN2 was eliminated from the system.
- Replacement of obsolete software and analysis algorithms with commercial off-the-shelf software and improved analysis engines.
- Implementation of new analysis engines.
- Replacement of obsolete electronics.
- Installation of Eu-152 transmission sources with electronically controlled shutters.
- Implementation of ISOCS efficiency calibrations.

- Configuration and deployment of NDA-2000 software to manage and integrate all data acquisitions and analyses.
- Implementation of the XML-based Data Management System (DMS) for integration and management of BMS and neutron-based Crated Waste Assay monitor (CWAM) data.

DESCRIPTION OF THE MODERNIZED BMS

Hardware

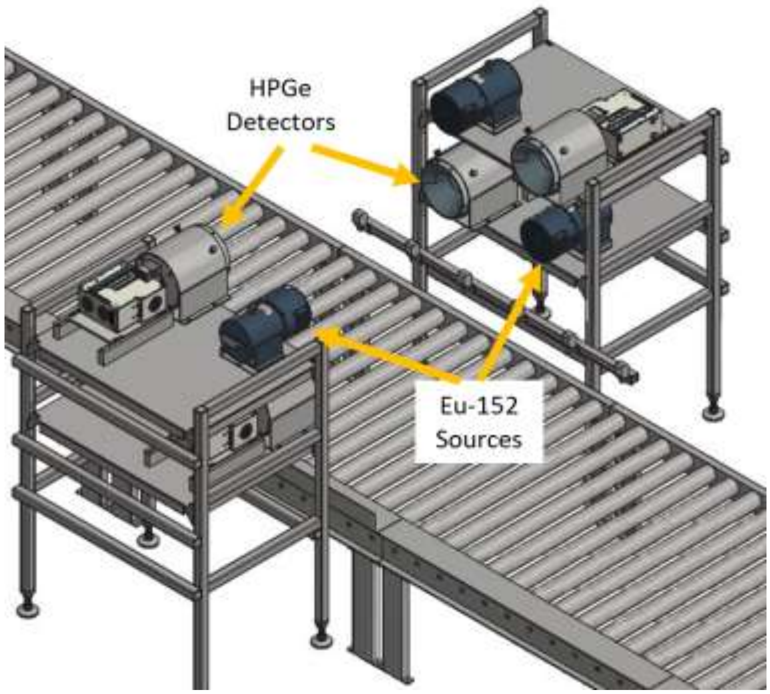

Figure 1 BMS detectors (4) and Transmission sources (4)

Figure 1 shows the central gamma detection hardware of the BMS. There are four very large (~150%) GC15024 germanium detectors, two mounted on each tower in a staggered pattern. The sensitive germanium volume of each detector is ~550 cm^3. Each detector has Pb side and back shields and a wide-angle (82º) front collimator. Each detector is attached to a CP5-Plus electronically controlled cryostat. A digital LYNX MCA is used with each detector for high-throughput data acquisition and control.

A 5.55E8 Bq Eu-152 transmission source is mounted opposite of and aligned with the axis of each detector. Each source is surrounded by more than 10.2cm of lead shielding and fitted with an electrically-controlled 12.7cm-thick tungsten shutter. When the shutter is open the transmission beam is defined by a 4.8 mm diameter aperture.

The only original elements are the box conveyers and conveyor motors. A Programmable Logic Controller (PLC) manages all mechanical controls. The PLC in conjunction with NDA 2000 controls the movement of the loaded box to specific load, unload, and measurement positions, the opening and closing of the transmission shutters, data acquisition, and all system checks, warnings, and alarms.

Two-Pass (Emission + Transmission) Measurement Sequence

The primary box measurement sequence for the BMS involves stepping the box through five fixed horizontal measurement positions, similar to vertical scanning in fixed segments of a drum in a Segmented Gamma Scanner (SGS) [4,5] system. This is illustrated in Figure 2, a top view of the system showing the five evenly spaced fixed positions for the leading edge of the box. One major difference between the BMS and traditional SGS is that each measurement measures the entire waste volume rather than a segment/slice of the waste volume. The BMS uses wide-angle collimators while the SGS uses slit collimators. The box moves sequentially from right to left. This measurement mode yields the lowest detection limits and best accuracy and precision performance at the cost of lowest throughput. Typical count times are 50 minutes.

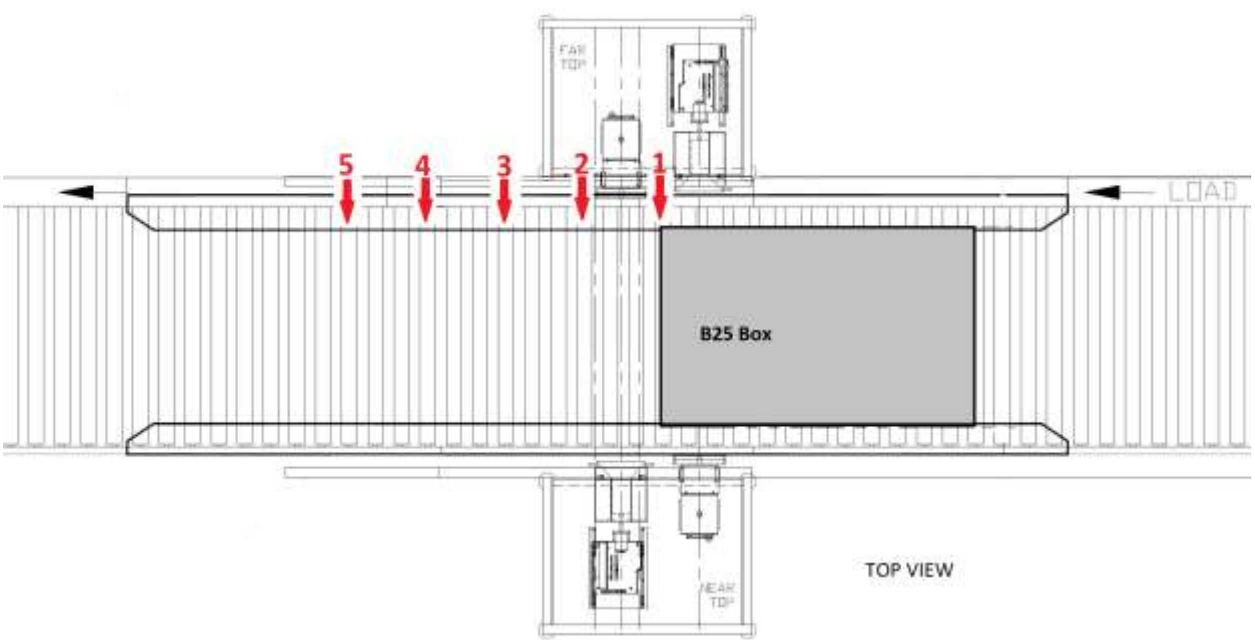

Figure 2 Overhead view of the five box positions for the two-pass count type.

The detector designations are: Near/Left/Top = Detector 1, Far/Left/Bottom = Detector 2, Near/Right/Bottom = Detector 3, Far/Right/Top = Detector 4. At each position spectra are acquired with the shutters open (Transmission) and shutters closed (Emission). In this mode there are 32 independent gamma measurements performed on the box, these are summarized in Table 1.

Table 1. Data acquisitions for the two-pass count type.

Box Position	Detectors	NDA2000 Report Segments	# Emission Measurements (shutters closed)	# Transmission Measurements (shutters open)	Total
1	3,4	1, 2	2	2	4
2	ALL	3,4,5,6	4	4	8
3	ALL	7,8,9,10	4	4	8
4	ALL	11, 12, 13, 14	4	4	8
5	1, 2	15, 16	2	2	4
				TOTAL	32

Other BMS Count Types

One-Pass (Transmission) Measurement

An alternate fixed-position waste box measurement sequence was configured for the BMS. For this count, the box is placed at Position 3 and data is acquired only with the shutters open. In this position the detectors have the highest whole-box detection efficiencies and the detectors are symmetric around the center of the box. This count yields four independent gamma measurements, one for each detector. This count type has a higher throughput at the expense of reduced precision and higher detection limits. Typical count times are 20 minutes.

Quality Control (QC) Calibration Check

This a one-pass measurement performed on a control waste box with well-established characteristics. Specifics of the QC measurements will be discussed below.

QC Background Count

The purpose of this no-box measurement is to monitor the ambient gamma background in the vicinity of the BMS. Separate spectra are acquired for each detector and the four total gamma count rates are monitored. Gamma background subtractions are not performed.

Empty Box Transmission Calibration

This is a two-pass measurement performed on a representative empty waste box. The data obtained from this count are used to correct for gamma absorption in the walls of the box.

Software and Analysis Algorithms

Expanded ISOCS

The primary purpose of Expanded ISOCS as implemented on the BMS is to run ISOCS efficiency calibration calculations in real time during the data analysis phase to create zero-matrix efficiency calibrations for each segment in the container measurement plus a summed efficiency calibration. These are referred to as geometrical efficiencies. The advantages of this approach are:

- New container types and geometries can readily be added to the system without having to go through the traditional ISOCS multicurve process.
- If a detector is repaired or replaced, only the two ISOCS files for that detector need to be updated on the system.

Below is a summary of the Expanded ISOCS process as implemented on the BMS:

1. Prior to box measurements, default ISOCS parameters were configured on the system for each container type to be measured.
2. Expanded ISOCS was configured in silent mode, so no user input is required for the ISOCS On-The-Fly calculations to run.
3. The box is loaded.
4. In NDA Operations, the operator selects the Count Type, starts the count, and enters container-specific details.
5. After data for all segments have been acquired without error, zero-matrix GIS files are generated for each segment and the sum.
6. The ISOCSwin.exe engine then runs and creates a zero-matrix ECC file for each segment and the sum. A progress bar is displayed during each calculation.
7. The measurement-specific GIS and ECC files are stored in the NDA2000 Data folder. The file names use the count sequence naming format.
8. Dual/Linear/Empirical/Interpolated efficiency curves are created and stored as CAM parameters in the segment and sum spectrum (.cnf) files.
9. In the Report file, for each segment and the sum the zero-matrix “Original Efficiencies” and the transmission-measured Attenuation factors are tabulated, and finally the transmission-corrected efficiencies are listed.

Differential Self-Absorption Correction (DSAC)

The purpose of the Differential Self-Attenuation Correction (DSAC) is to correct for significant gamma attenuation in lumps of U_3O_8 material that may be missed or under-corrected in the transmission correction analysis [6].

A reliable means of estimating the lump “thickness” or physical dimension is necessary. This method must have a means for validating that the computed “thickness” is indeed representative of the material. This is accomplished by using a close cousin of the differential peak method called differential self-attenuation. DSAC exploits the physical properties of a range of peak pairs for a given nuclide. DSAC is performed after the transmission corrections have been applied.

DSAC analysis solves for the factor rho*t (density x thickness) using peak-pair ratios, the ISOCS efficiencies, branching ratios, and the mass attenuation curve for the lump material. The rho*t returned from a DSAC analysis can then be utilized to make assessments based on the corrections for a given nuclide.

Features of the DSAC analysis as implemented on the BMS include:

- The engine will attempt to provide lump corrections to all nuclides included in the TMU that have three or more identified lines.
- The default mass attenuation coefficient is for U_3O_8.
- Corrected line efficiencies use standard Genie 2000 format.
- The rho*t derived for one nuclide can be applied to other nuclides if they are co-located.
- Spherical, cylindrical, and rectangular lump shapes are supported. The default shape is spherical.
- LACE analysis can be used to evaluate the effectiveness of the DSAC corrections.

SYSTEM PERFORMANCE

To test and document the BMS system performance, Mirion duplicated to the extent possible validation measurements performed on the original BMS by Babcock & Wilcox Technical Services Y12, LLC, in 2013 [7]. These measurements were published in the BMS Performance Test and Validation Plan (PTVP) [8] and are summarized here. Standard count times were used for all measurements.

Efficiency Calibration Verification

The BMS efficiency calibration was verified for U235 by placing four large-area (22.9cm x 45.7cm) low-density uranium sources vertically inside a test B25 box filled with clean plywood sheets. The average matrix density was 0.22 g/cm^3. The results for three replicate measurements are shown in Table 2. The Pass criterion was 70% ≤ %R ≤ 130%. The measured %R was 95.8%.

Table 2. Results of Efficiency Calibration Verification Tests

Measured gU235 Replicate 1	Measured gU235 Replicate 2	Measured gU235 Replicate 3	Average Measured gU235	Reference gU235	%Recovery =100% x $M_{measured}/M_{reference}$
50.79 g	49.94 g	50.11 g	50.28 g	52.50 g	95.8%

BMS Precision Test

To measure the precision of the BMS system, six 500mL uranium solution sources and five 50mL uranium solution sources were placed symmetrically within the plywood test box at three different heights. Six replicate measurements were performed. The total reference uranium masses were 4.06 gU235 and 45.9 gU238. The results are listed in Table 3. The Pass criterion for the percent relative standard deviation (%RSD) was %RSD ≤ 14%. The measured %RSD's were 1.20% for U235 and 8.7% for U238.

Table 3. BMS Precision Tests

Replicate	1	2	3	4	5	6	Measured Average	Measured Standard Deviation	Measured %RSD
Measured gU235	3.30	3.28	3.27	3.28	3.34	3.37	3.31	0.04	1.20%
Measured gU238	28.5	31.2	35.5	33.5	34.5	36.0	33.2	2.89	8.7%

Control Box Comparison Test

To make a direct comparison between the upgraded BMS performance and that of the original system, a designated ‘control box’ was measured. This box #N8708 is a LLW box selected by Y-12 in 1997 to be measured daily in the system for quality assurance purposes. The box contains uranium-contaminated air filters with an average bulk density of 0.089 g/cm^3. The comparison of 2022 [8] and 2013 [7] assays is shown in Table 4. The results are in very good agreement.

Table 4. Comparison of 2022 and 2013 Control Box Measurements

	Upgraded BMS (2022)	Original BMS/TMS (2013)
Measured gU235	4.218 ± 0.067	4.25
Measured gU238	2106 ± 29	2107

Commissioning Measurements

To further document the performance of the BMS, a set of independent commissioning measurements were performed on test boxes containing uncontaminated bailed waste, mixed metals, and concrete. The respective average bulk densities were 0.46, 0.48, and 1.33 g/cm^3. The baled waste and metals boxes are considered to be intermediate density while the concrete box is quite a high density in the context of LLW measurements using passive methods. The measured gamma transmission for the concrete box was only in the range of 0.07% – 1%. A combination of 8-12 50mL, 500mL, and planar uranium sources were distributed in the boxes.

The results are summarized in Table 5. The %Recovery for U235 ranged from 80% to 134% and the %Recovery for U238 ranged from 70% to 107%. These results were acceptable.

Table 5. Commissioning Measurements Results

Matrix	Bulk Density g/cm^3	Measured gU235	Reference gU235	U235 %R	Measured gU238	Reference gU238	U2358 %R
Metals	0.46	49.4	41.6	118.6%	16.9	16.6	101.8%
Baled Waste	0.48	35.3	44.0	80.1%	18.5	17.3	106.8%
Concrete	1.33	59.2	44.1	134.2%	17.4	24.8	70.1%

Minimum Detectable Activity

Standard two-pass BMS measurements were performed on four test B25 boxes with no radioactive sources present to quantify the U235 and U238 MDA's for a range of matrix materials and densities. The results are summarized in Table 6. The performance criteria were U235 MDA ≤ 0.02g and U238 ≤ 10g. The criteria were met for all materials and densities evaluated.

Table 6. Minimum Detectable gU235 and gU238 – Two Pass Count

Matrix:	Poly	Plywood	Metals	Concrete
Matrix Density (g/cc)	0.16	0.22	0.46	1.33
U235 MDA (g)	0.0071	0.0076	0.0069	0.0072
U238 MDA (g)	5.03	1.79	7.49	4.02

Daily Quality Control Measurements

For continuity with the original BMS system, daily QC measurements are performed on the Y-12 NDA 'control box' discussed above that contains uranium-contaminated air filters. The measurements are performed at the start and end of each shift using the shorter one-pass count type. The measurements are designed to monitor both individual HPGe detector performance and whole system performance. 28 different QC parameters were defined for the system using a combination of transmission-source peaks and uranium peaks:

- Each detector: Low-Energy (122 keV) FWHM, Hi-Energy (1408 keV) FWHM, Hi-Energy (1408 keV) peak centroid, U235 (185.7 keV) net count rate, U238 (1001 keV) net count rate
- SumSegmentSpectrum: U235 (185.7 keV) peak energy, U238 (1001 keV) peak energy, gU235, gU238
- SumSegmentNID: gU235, gU238

- Ratio of SumSegNID/SumSegmentSpectrum gU235
- Ratio of SumSegNID/SumSegmentSpectrum gU238

All raw data and 28 parameter values are documented in a detailed QC Report. The data are also transferred to QC charts to monitor for trends. 18 of the parameters have 2-sigma Investigate and 3-sigma Action limits defined so that flags are generated immediately to the Operator's attention if any measurement is outside of established nominal mean and variance performance.

Production Measurements

Daily BMS production waste box measurements started at the Y-12 NDA facility in July 2023. About 90% of the measurements used the shorter one-pass count type. Selection of the two-pass count type is based on higher net box weight, ≥1500 kgs, and/or a higher-Z material type. Figure 3 shows the daily throughput of the system for the first three months of operation. The facility throughput target is 10 boxes per day. A total of 397 boxes were measured with an average of 9.02/day and a maximum of 13 per day. Throughput has been limited by onsite waste transportation logistics and not by the BMS. The production throughput for the first quarter of operations exceeded the original 1997 BMS design performance of 700 boxes per year by 226%.

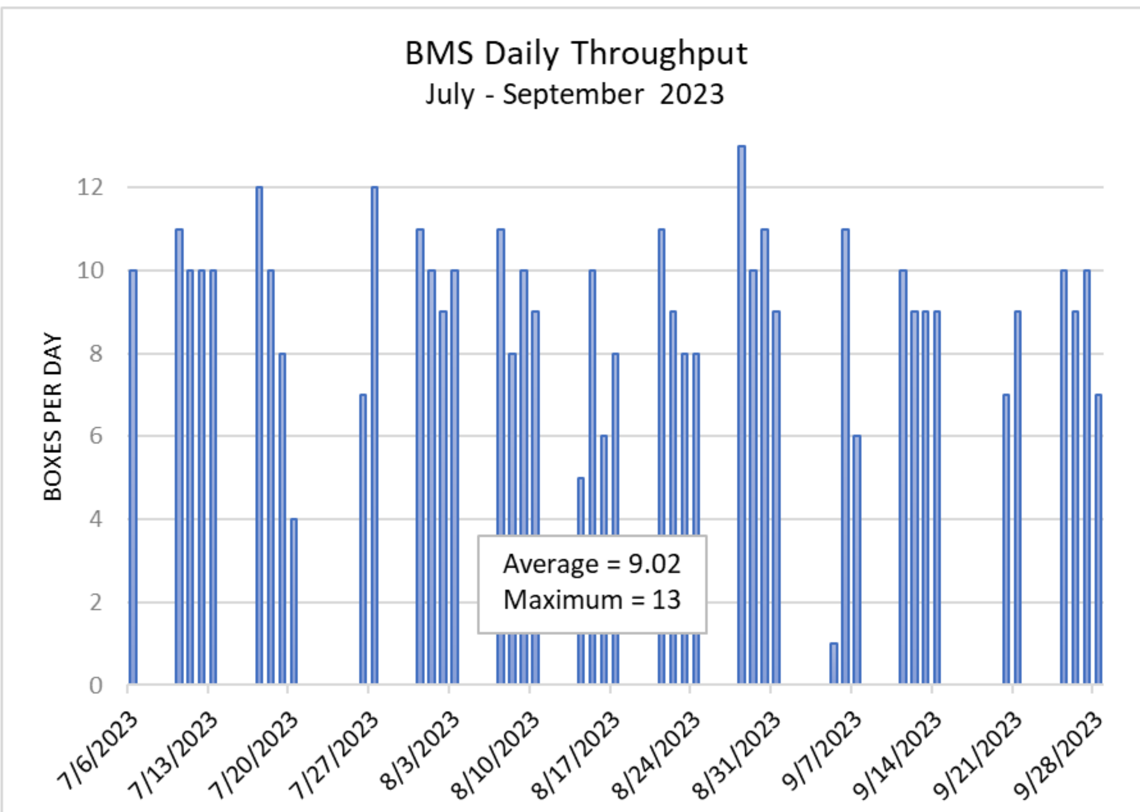

Figure 3 BMS Daily Production for July - September 2023.

CONCLUSIONS

Mirion Technologies performed a major modernization campaign on the Box Measurement System/Transmission Measurement System BMS/TMS at the Y-12 National Security Complex in Oak Ridge, TN. The separate BMS and TMS stations were combined into a single station now simply referred to as the BMS. The hardware upgrades included installation of four very large high resolution HPGe detectors with cryoelectric cooling, digital MCA's, and shielded Eu-152 transmission sources with electronically controlled shutters.

Software upgrades included integration of all box movements, data acquisition, and shutter controls using the PLC and NDA2000. One-pass and two-pass box counts were configured in NDA2000. Empty-box gamma efficiency calibration are performed for every measurement using ISOCS-on-the-fly. Differential Self Absorption Correction (DSAC) has been implemented to correct for gamma attenuation in small lumps of U_3O_8. A custom Data Management System was implemented to integrate BMS results with U-235 measurements obtained from the active neutron Crated Waste Assay Monitor (CWAM) system.

Testing of the upgraded BMS included efficiency calibration verifications, precision measurements, comparison of BMS results with prior BMS/TMS results, measurements of metals, baled waste, and concrete test boxes with average matrix densities up to 1.33 g/cm^3, and MDA measurements. All test measurements were acceptable. Daily QC measurements of a control box were defined with 18 QC parameters monitored and reported. BMS went into production mode in July 2023. For the first three months of production, the system averaged 9.03 boxes per day, an increase of 226% over the production target of the original BMS/TMS system.

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