Implementation and Performance Testing of a Sensitive Bulk Laundry Monitor for Use in Nuclear Power Stations -14004

Erik Lindberg*, Richard DelPizzo*, Tom Donohoue*, Ryan Lee**, Marc R. Looman*, E. Ray Martin* and John A. Mason*

* ANTECH Corporation, 9050 Marshall Court, Westminster, CO, 80031, USA

**Darlington Nuclear, Ontario Power Generation Inc., P. O. Box 4000, Bowmanville, Ontario, L1C 3Z8, Canada

ABSTRACT

This paper describes the implementation and performance of an upgraded Bulk Laundry Monitor (BLM) for detecting radioactive contamination in containers of laundry at Nuclear Generation Facilities operated by Ontario Power Generation (OPG). The unit is designed to detect radioactivity that may be present in the laundry and prevent radioactive contamination from leaving the facility. Laundry is measured in bins, which are loaded into a cart. A cart loaded with bins of laundry is positioned in the monitor for measurement. Relatively short measurements are made while the cart is in the measurement position, as the device has a high sensitivity based on the use of eight large area (and volume) plastic scintillator detectors. The BLM consists of a rectangular frame structure, which supports the eight plastic scintillator detectors each with an imbedded photomultiplier. The detectors are arranged four to each side. Lead shielding of 1.27 cm (0.5 in.) is provided to reduce the counting background. Fitted below the floor of the device is a load cell to measure the weight of the contents of the loaded cart. The output of each detector and photomultiplier is amplified by an amplifier with both upper and lower discriminators and is counted in a separate counting channel. BLM operation is controlled by a microprocessor, which collects counting data from the counting chains and weight data from the load cell. Total activity and specific activity for Cs-137 are determined using a calibration coefficient. Alarm limits are set based on the calibrated activity for the instrument. Over most of the measurement region of the BLM the spatial variation of the response using a calibrated Cs-137 source was measured and found to be less than 15%. Verification measurements of the calibration have been performed during the factory testing of the BLM. The empty measurement chamber minimum detectable activity (MDA) was measured as less than 7.4 kBq (200 nCi) based on the background measurements. The calibration employed Cs-137 sources, which are traceable to the National Institute for Standards and Technology (NIST) in the United States and the National Research Council (NRC) in Canada.

INTRODUCTION

This project arose as a result of the need to replace or upgrade legacy Bulk Laundry Monitors (BLM) operated by Ontario Power Generation (OPG) at both the Pickering and Darlington Nuclear Generation Facilities. The BLM units are employed to measure the activity of work clothing packed into baskets that are transferred to laundry facilities off site. The role of the BLM units is to prevent work clothing with elevated activity from leaving the site.

The decision was taken to upgrade rather than to decommission the units. The upgrade involved replacing both the electronics and the software and introducing additional diagnostic features while retaining the original functionality. In order to improve reliability and facilitate future maintenance the decision was also taken to replace the original four (4) large plastic scintillator detectors with eight (8) smaller detectors of equal total surface area and volume. The original large detectors, each with two photomultipliers and integral signal amplifiers, were both difficult to handle and difficult to maintain. The replacement smaller detectors (with the same total number of photomultipliers) were much easier to access and with detachable electronic amplifiers and high voltage power supplies both diagnostic testing and maintenance were facilitated.

The BLM consists of a rectangular frame structure with outer dimensions 1.12 m (44 in.) x 2.31 m (91 in.) x 1.42 m (56 in.) (W x H x D). This steel structure supports the 8 plastic scintillator detectors each with an imbedded photomultiplier. Lead shielding of 1.27 cm (0.5 in.) is provided on the outside surface of the detectors to reduce the counting background. The plastic scintillation “slab” detectors are arranged four to each side and they are used to measure the total gamma ray activity in a standard laundry cart or “silo”. Each BLM scintillation detector is 81.3 cm (32 in.) × 38.1 cm (15 in.) × 5.1 cm (2 in.) (l × w × d) and each scintillator detector is constructed of a solid polymer base material in which the primary fluorescent emitter, called a fluor, is suspended. The main component of the scintillator is polyvinyl toluene ($C_{27}H_{30}$), with a density of 1.032 $g.cm^{-3}$.

When a gamma ray interacts with the scintillator a photon of light is emitted. This light photon passes through the detector matrix and is received on the photocathode of the photomultiplier tube. The photocathode then converts the photon of light into low energy electrons that pass along an amplifying dynode chain. Each dynode serves to multiply the initial electrons produced by the photocathode until a cascade of electrons, related to the original scintillation event, are collected as a charge signal at the anode/output of the photomultiplier tube. The Laundry Monitor plastic scintillation detectors are specifically engineered to produce high light output when gamma rays, arising from radioactive sources in the bulk laundry, interact with the scintillation detectors. The detectors also exhibit a relatively rapid signal quiescence (short dead time) of approximately 2–4 nanoseconds.

New electronics have been implemented based on technology developed by ANTECH and employed in both portal monitors and Waste Segregation Monitors [1]. The output of each detector and photomultiplier is amplified by an amplifier with both upper and lower discriminators and is counted in a separate counting channel. Having separate counting channels for each detector facilitates the gathering of diagnostic information on the detector performance. BLM operation is controlled by a microprocessor, which collects counting data from the counting chains and weight data from the load cell, which is located beneath the floor where the cart or silo is positioned during measurement. Using the weight of the cart or silo, the net weight of the laundry is determined so that the specific activity for each measurement is provided.

The process of upgrading the BLM has provided a cost effective solution to both the obsolescence and measurement reliability problems faced by OPG. It has also reduced the radioactive waste that would result from decommissioning the BLM and, by maintaining as far as possible the original functionality, reduced the requirements for both operator and maintenance training.

LAUNDRY MONITOR SOFTWARE AND FUNCTIONALITY

New software has been designed and implemented as part of the BLM upgrading process. The software is based on a requirements specification and a design document that were approved by OPG. It is designed to maintain the functionality of the original systems and, at the same time, introduce new diagnostic functions and make the system more user friendly.

ANTECH *LaundryMonitor* software code provides the main software interface to the BLM. Software functions include sample measurements, functional checks of hardware and detector response, automated check source limit initialization, calibration verification, diagnostics, measurement or shipping log, and alarm notification.

The main sample measurement is initiated by clicking the Start Measurement button in the lower right corner of the Measurement tab (Fig. 1). User measurement interaction can be customized and can range from requiring entry confirmation for every input parameter to a single barcode scan to initiate a sample measurement. The buttons in the centre of the Measurement tab (Fig. 1) are used to setup the desired interaction.

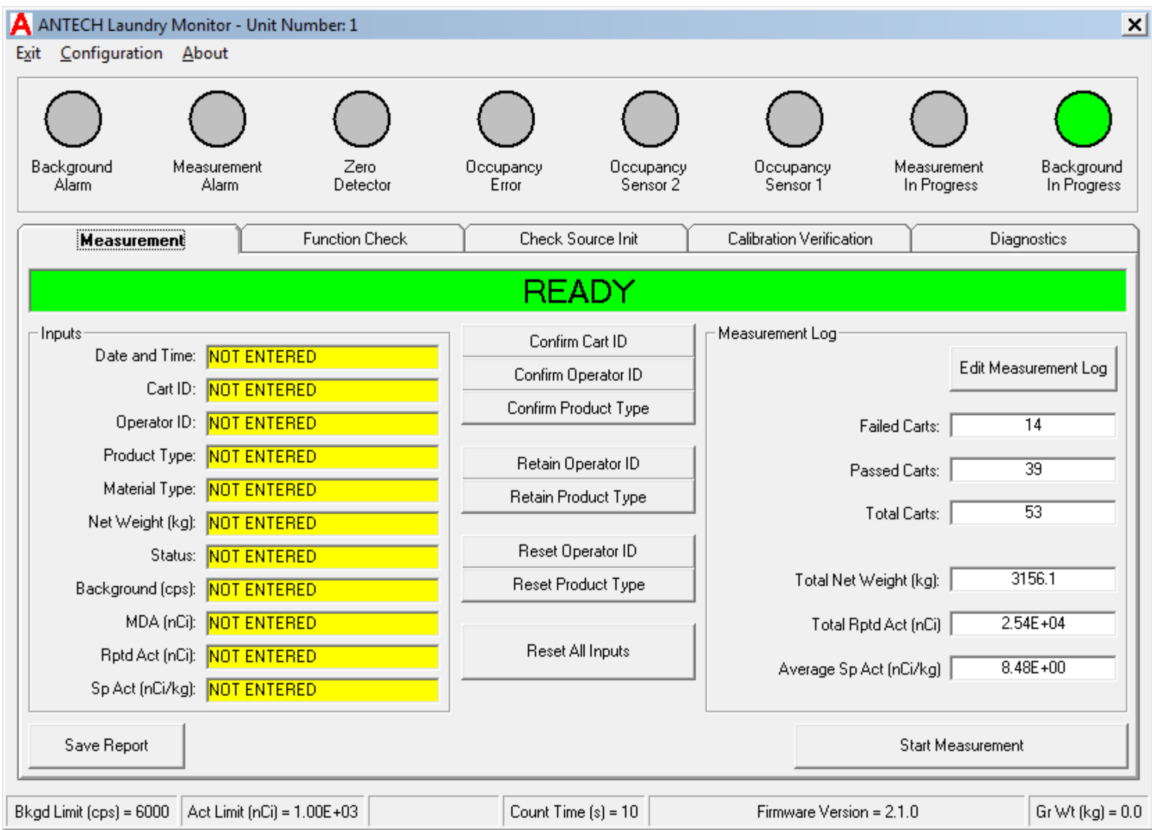
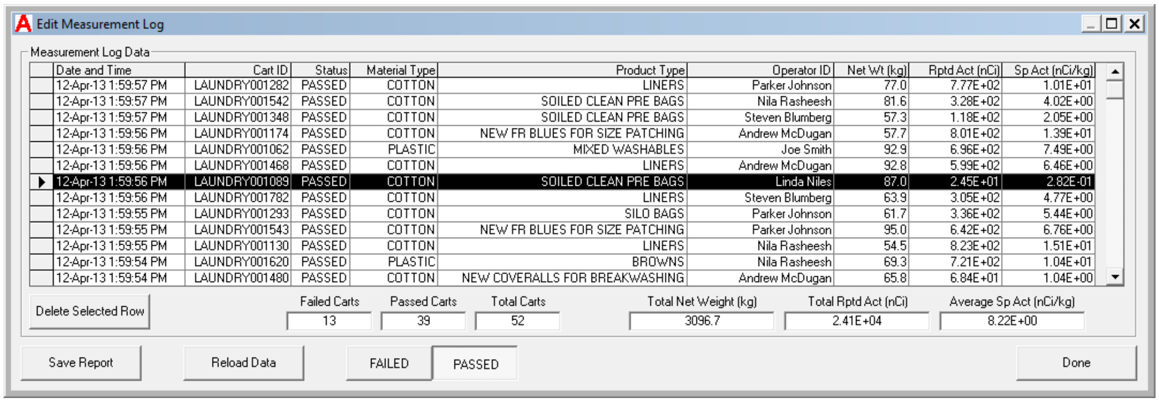


Fig. 1. Measurement Tab

The Cart ID, Operator ID, and Product Type can all be confirmed or automatically accepted upon scanning a barcode. The Operator ID and Product Type can be reset after each measurement or retained for the next measurement. With all three confirmation options set to skip confirmation and the two retention options set to retain the previous value, the system will initially require an Operator ID and Product Type to be scanned after which only a Cart ID will be required to initiate the next measurement. Retained values can be reset individually or all at once when moving to the next Product Type or during shift changes.

Activity reporting units can be Bq, Ci, µCi, or nCi; selected from a configuration screen. Other configurable options include check source setup, count time, product type, material type, and percentage error. Security can be enabled to lock the administrative screens in order to provide a single accessible tab for measurement operations.

The Measurement Log (Fig. 2) is a batch log or shipping log used for truck loading and shipment of laundry to laundering facilities. The accumulated activity, average specific activity, and total net weight for a shipment are automatically summed and displayed on the Measurement tab (Fig. 1) after each measurement is performed.



Date and Time	Cart ID	Status	Material Type	Product Type	Operator ID	Net Wt (kg)	Rptd Act (nCi)	Sp Act (nCi/kg)
12-Apr-13 1:59:57 PM	LAUNDRY001282	PASSED	COTTON	LINERS	Parker Johnson	77.0	7.77E+02	1.01E+01
12-Apr-13 1:59:57 PM	LAUNDRY001542	PASSED	COTTON	SOILED CLEAN PRE BAGS	Nila Rasheesh	81.6	3.28E+02	4.02E+00
12-Apr-13 1:59:57 PM	LAUNDRY001348	PASSED	COTTON	SOILED CLEAN PRE BAGS	Steven Blumberg	57.3	1.18E+02	2.05E+00
12-Apr-13 1:59:56 PM	LAUNDRY001174	PASSED	COTTON	NEW FR BLUES FOR SIZE PATCHING	Andrew McDugan	57.7	8.01E+02	1.39E+01
12-Apr-13 1:59:56 PM	LAUNDRY001062	PASSED	PLASTIC	MIXED WASHABLES	Joe Smith	92.9	6.96E+02	7.49E+00
12-Apr-13 1:59:56 PM	LAUNDRY001468	PASSED	COTTON	LINERS	Andrew McDugan	92.8	5.99E+02	6.46E+00
12-Apr-13 1:59:56 PM	LAUNDRY001089	PASSED	COTTON	SOILED CLEAN PRE BAGS	Linda Niles	87.0	2.45E+01	2.82E-01
12-Apr-13 1:59:56 PM	LAUNDRY001782	PASSED	COTTON	LINERS	Steven Blumberg	63.9	3.05E+02	4.77E+00
12-Apr-13 1:59:55 PM	LAUNDRY001293	PASSED	COTTON	SILO BAGS	Parker Johnson	61.7	3.36E+02	5.44E+00
12-Apr-13 1:59:55 PM	LAUNDRY001543	PASSED	COTTON	NEW FR BLUES FOR SIZE PATCHING	Parker Johnson	95.0	6.42E+02	6.76E+00
12-Apr-13 1:59:55 PM	LAUNDRY001130	PASSED	COTTON	LINERS	Nila Rasheesh	54.5	8.23E+02	1.51E+01
12-Apr-13 1:59:54 PM	LAUNDRY001620	PASSED	PLASTIC	BROWNS	Nila Rasheesh	69.3	7.21E+02	1.04E+01
12-Apr-13 1:59:54 PM	LAUNDRY001480	PASSED	COTTON	NEW COVERALLS FOR BREAKWASHING	Andrew McDugan	65.8	6.84E+01	1.04E+00

Fig. 2. Measurement Log Screen

The Measurement Log (Fig. 2) can be reloaded, viewed, and edited through a separate screen accessible from the Measurement tab (Fig. 1) on the main software screen. Individual measurements can be deleted and the totals are updated to reflect any changes. Measurements that are below the measurement limit are flagged as “PASSED” and are displayed separate from the “FAILED” measurements. This allows for two different types of laundry shipments; a normal shipment and an exception shipment where measurements are above the established limit and must be handled separately.

Once a complete Measurement Log has been reviewed the user can generate the Measurement Log Report (Fig. 3) by clicking the Report button in the lower left corner of the Measurement Log screen (Fig. 2). The information for the Measurement Log Report is grouped by Product Type with sub totals and grand totals at the bottom of the report as shown below. This report can then be used for shipment purposes.

Functional checks are performed at configurable intervals, or they can be performed as necessary. The Function Check (Fig. 4) will step the user through a series of checks to confirm operational status of the system. These checks include barcode scanner operation, micro-controller communications, occupancy sensor operation, load cell readings, and a sensitivity check to confirm detector response and the calibration correction factor setting. A valid Function Check is required before any sample measurements can be performed.

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Unitech Shipment 22-Apr-13 7:18:47 PM

Product Type: CLEAN ORANGE GLOVES                    Material Type: PLASTIC
Date        Time      Cart ID          Net Wt       Net Act      Net Sp Act       Status
Apr 22 2013 13:10:59 001993            7.64E+01 kg 1.00E+00 Bq  1.31E-02 Bq/kg   PASSED
Apr 22 2013 15:15:04 001466            7.92E+01 kg 1.09E+00 Bq  1.38E-02 Bq/kg   PASSED
Sub Totals     Carts: 2                155.6 kg    2.1 Bq       0.0 Bq/kg

Product Type: PLASTIC SUITS                          Material Type: PLASTIC
Date        Time      Cart ID          Net Wt       Net Act      Net Sp Act       Status
Apr 22 2013 12:21:58 001114            8.66E+01 kg 1.01E+00 Bq  1.16E-02 Bq/kg   PASSED
Apr 22 2013 15:10:32 001641            7.57E+01 kg 1.13E+00 Bq  1.49E-02 Bq/kg   PASSED
Sub Totals     Carts: 2                162.2 kg    2.1 Bq       0.0 Bq/kg

Product Type: YELLOWS                                Material Type: COTTON
Date        Time      Cart ID          Net Wt       Net Act      Net Sp Act       Status
Apr 22 2013 14:13:23 001959            8.04E+01 kg 1.12E+00 Bq  1.40E-02 Bq/kg   PASSED
Apr 22 2013 14:24:05 001071            7.24E+01 kg 1.09E+00 Bq  1.51E-02 Bq/kg   PASSED
Sub Totals     Carts: 2                152.8 kg    2.2 Bq       0.0 Bq/kg

Grand Totals   Carts: 6                470.5 kg    6.4 Bq       0.1 Bq/kg
Average                                                         0.0 Bq/kg
Total Gross Weight 1052.5 kg
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Fig. 3. Measurement Log Report

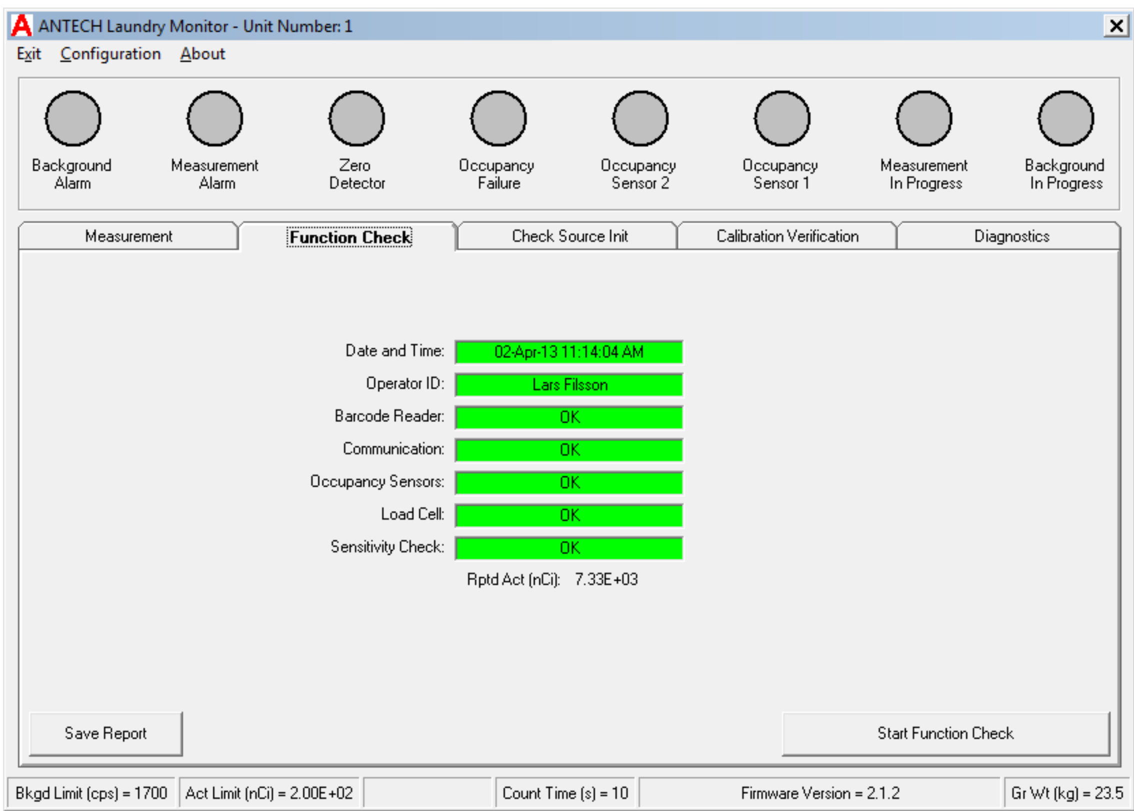

Fig. 4. Function Check tab

During a sample measurement a net count rate is acquired after which attenuation and calibration factors are applied to arrive at a final activity. The final activity and specific activity are checked against configurable limits and alarms are set as appropriate. The user must acknowledge all alarms and a system reset performed prior to continuing with the next measurement. Alarms are indicated in the top part of the main software screen (Fig. 5) and the various alarm indicators will turn red. The different alarms include the following:

- Background – Background count rate above an established and configurable limit
- Measurement – Measured activity or specific activity above limit
- Zero Detector – One of the detector channels is not registering any counts
- Occupancy Error – The sample was moved during the measurement

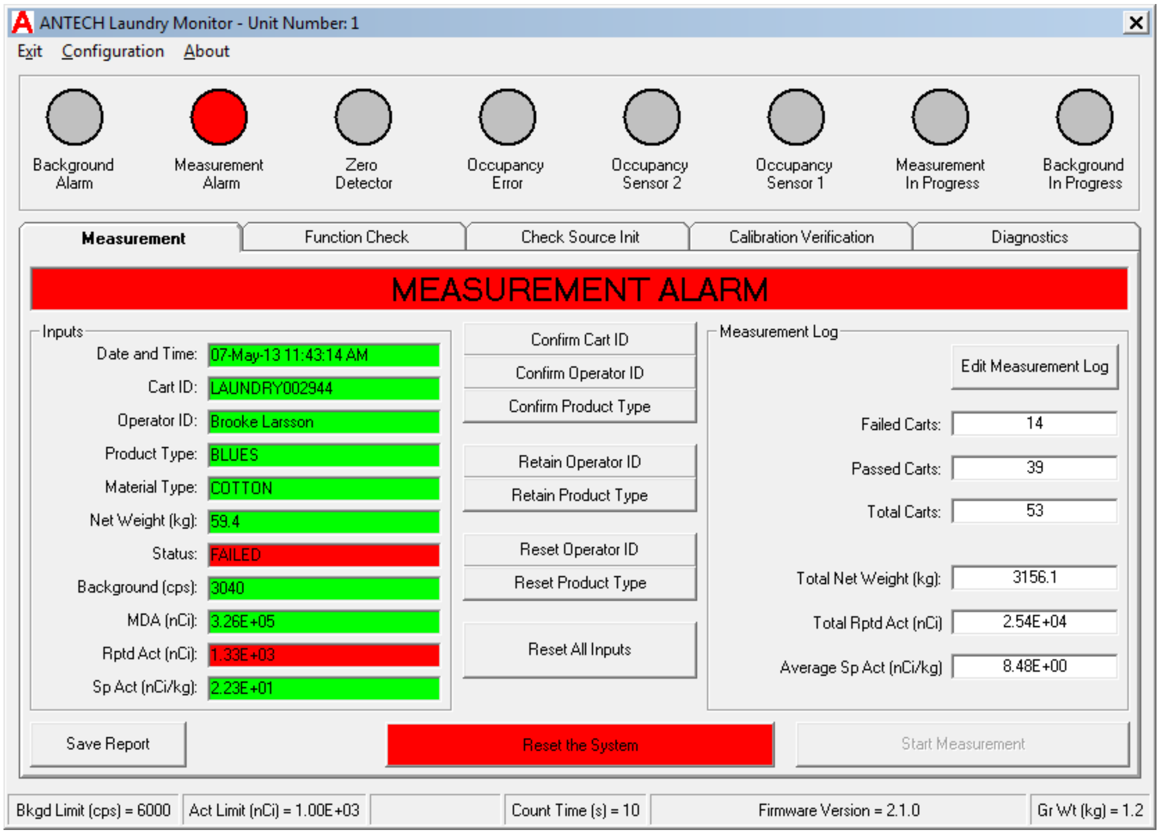

Fig. 5 – Alarm Notification

DETECTOR CHARACTERISATION AND CALIBRATION

Detector Characterisation

A comprehensive characterisation and calibration of the BLM was undertaken as part of the factory testing of the unit. The process involved using a Cs-137 NIST traceable point source positioned at various locations in a test structure simulating the mechanical configuration of the BLM in which the eight scintillation detectors were positioned. The characteristics of the test source are listed in TABLE I.

TABLE I. Characteristics of the Cs-137 point source used for measuring detection efficiency and the spatial variation of the detector response of the BLM.

Reference Activity (µCi)	10
Reference Date	5/1/01
Measurement Date	12/17/12
Activity on Measurement date in kBq (µCi)	283.05 (7.65)
Gamma Intensity (s^{-1})	2.39E+05

As part of the BLM characterisation and before calibration, the individual scintillation detectors were tested and evaluated. Each detector was balanced with respect to the other detectors of the measurement system. Initially, each individual detector was evaluated for light collection uniformity using a simple test of allowing a narrowly collimated gamma ray beam to strike selected portions of a scintillation detector to determine the homogeneity of the detector response. Each Laundry Monitor detector was individually tested, using the Cs-137 test source. The central area of each detector displays a relatively homogeneous response while the upper and lower corners of the slab return a response that deviates from the mean by < 10%.

An advantage of the electronics of the upgraded BLM is that the amplifier associated with each detector panel and photomultiplier is readily accessible and the amplifier gains and thresholds can be easily adjusted. In order to ensure a consistent and uniform detector response, relative to the measured Cs-137 source, the individual detector gains must be adjusted or balanced. During the evaluation of each detector panel, a position on the front surface common to each detector panel was selected that provided the best signal response, with low ambient noise and high count rate. Each detector panel was measured with the Cs-137 source positioned on this location for the purpose of detector panel intercomparison. Replicated measurements were performed to evaluate the response for each detector so that their responses could be compared and balanced. Fine amplifier gain adjustments are performed in order to balance the response for all detector panels.

Detector Response Measurement and Calibration of the Bulk Laundry Monitor

A test rig made of wood was constructed to support the eight (8) plastic scintillator panels for testing, calibration and response detector measurement. Each scintillation detector panel was placed into a configured array that is representative of the operational configuration of the BLM. The volume envelope that lies within the physical dimensions of the BLM frame, consisting of the overlapping regions that are viewed by the multi-detector (8) panel array, is defined as the Laundry Monitor measurement chamber. The test rig structure closely simulates the measurement chamber of the BLM.

The simulated measurement chamber includes the central volume that is occupied by the laundry cart or laundry silo. The internal physical dimensions of the silo are 190.5 cm (75 in.) × 68.5 cm (27 in.) × 99.1 cm (39 in.) (h × w × d) and it occupies a subset of the total volume envelope of the measurement chamber of the Laundry Monitor. For all practical purposes the calibration is a simple representation of detector response to a gamma ray signal emitted from a location within the simulated measurement chamber.

In performing the calibration the simulated measurement chamber was divided into eighteen volume elements consisting of three horizontal planes (top, centre, and bottom) subdividing the vertical or height component, two vertical planes (right and left) subdividing the width component and three vertical planes (front, centre, and back) subdividing the depth component. The Cs-137 calibration source was sequentially placed in each specified source location, within each of the eighteen calibration volumes of the measurement chamber and in each case the total count was recorded. Three measurements were made at each position and the average and standard deviation of each result was obtained. The total measured counts (summed counts from each of the eight plastic scintillator detectors) were recorded for each of the 18-calibration measurement locations. The measured count rate for each calibration location, corrected for background and normalized for count time, was used to construct a response profile for the measurement chamber. The data is displayed in TABLE II.

TABLE II. Background Corrected count rates from counting the Cs-137 point source at the various counting positions in the simulated measurement chamber. The Mean and Standard Deviation (SD) are based on three measurement repetitions for each position.

Source Position			**Count Rate (s^{-1})**	
Height (cm)	**Width (cm)**	**Depth (cm)**	**Mean**	**SD**
58.42	0	0	7336	6
58.42	-25.4	-50.8	7029	43
58.42	25.4	-50.8	7105	10
58.42	-25.4	50.8	7021	16
58.42	25.4	50.8	7194	10
124.46	-25.4	-50.8	8681	24
124.46	0	-50.8	7578	27
124.46	25.4	-50.8	8569	13
124.46	-25.4	0	10364	42
124.46	0	0	9183	16
124.46	25.4	0	10588	16
124.46	-25.4	50.8	8722	11
124.46	0	50.8	7544	10
124.46	25.4	50.8	8611	5
193.04	0	0	7100	36
193.04	-25.4	-50.8	6735	15
193.04	25.4	-50.8	6682	54
193.04	-25.4	50.8	6971	8
193.04	25.4	50.8	6821	39

For the chamber the average detection efficiency or detector response is determined based on the use of the calibrated Cs-137 point source measured at different positions within the chamber. Separately, based on background measurements, the minimum detectable activity (MDA) is calculated for the simulated measurement chamber. This should be higher than the value for the actual instrument when installed and in service. The actual instrument has 1.27 cm (0.5 in.) of lead shielding to reduce the counting background and despite a higher background in a nuclear power plant (NPP); the testing of the simulated measurement chamber was conducted in Denver Colorado, where the cosmic ray background is higher.

The calculated BLM detection efficiency 3.183% or 0.03183, which is based on the average of a selected number of Cs-137 point source measurements using the data in TABLE II. Using the background data obtained during these measurements, the estimated MDA [3,4] for the BLM is less than 7.4 kBq (200 nCi).

DETECTOR RESPONSE MODELLING

The Monte Carlo code MCNP [2] has been used to model the response of the plastic scintillator detectors to a Cs-137 point source equivalent to the source used for the response and calibration measurements (see TABLE II). The MCNP simulation (without modelling light transport within each plastic scintillator) has the advantage that many more source positions can be simulated than were measured so that more detailed response profiles can be generated. It also permits the simulation of the laundry cart or silo positioned in the measurement chamber and filled with representative bulk laundry containing a low level of radioactivity.

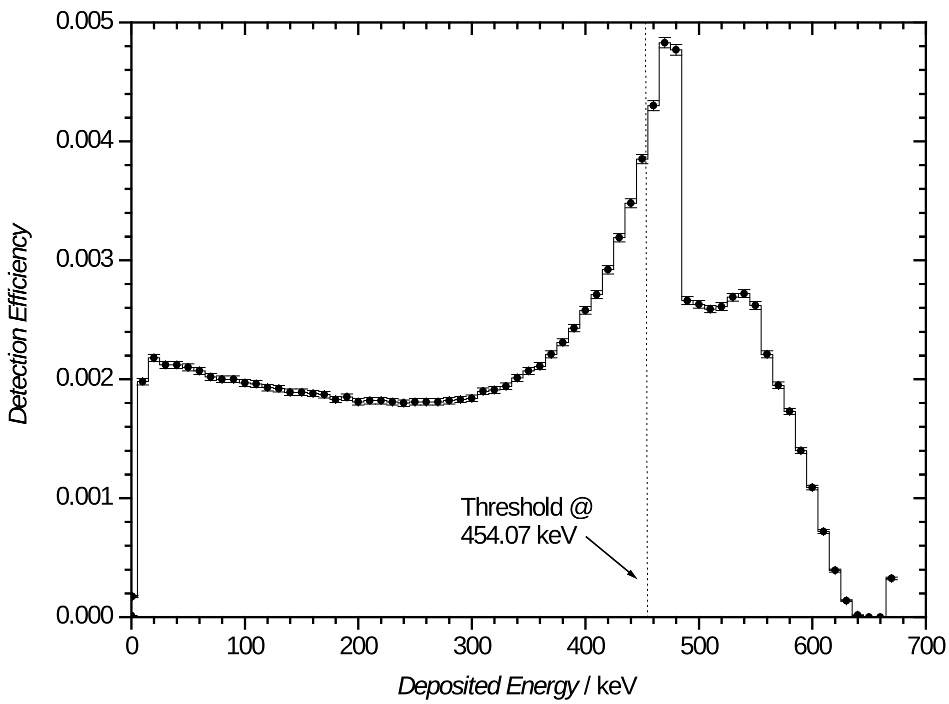

Fig. 6. Compton down scatter spectrum arising from MCNP simulation of the detection and scattering of 662 keV Cs-137 photons in the plastic scintillator panels

A typical Compton down-scatter spectrum arising from simulating the detection and scattering of 662 keV photons from a Cs-137 source in the plastic scintillator panels is shown in Fig. 6. In the simulation, the energy threshold of 454 keV was chosen as this produced detector count rates equivalent to those measured and tabulated in Table II. The measured and simulated data, presented in terms of detection efficiency for both experimental and MCNP simulated data is presented in Table III. The process of setting the energy threshold to obtain agreement between the measured and simulated data is part of the process of benchmarking of the MCNP calculation.

TABLE III. Experimental and simulation results for the BLM detection efficiency. Note that (where available) experimental results of TABLE 1 from symmetrical positions have been combined (with average and Standard deviation, SD, calculated).

Source Position			Count Rate (s^{-1})		Detection Efficiency					
					Experiment		Simulation		Sim/Exp	
Height (cm)	Width (cm)	Depth (cm)	Mean	SD	Value	Error	Value	Error	Value	Error
58.4	0.0	0.0	7336	6	0.0306	0.0001	0.027	0.0003	0.883	0.012
58.4	25.4	50.8	7087	70	0.0296	0.0006	0.0323	0.0004	1.090	0.023
124.5	0.0	0.0	9183	16	0.0383	0.0001	0.0347	0.0004	0.906	0.010
124.5	0.0	50.8	7561	17	0.0316	0.0001	0.0347	0.0004	1.098	0.012
124.5	25.4	0.0	10476	112	0.0433	0.0009	0.0407	0.0004	0.941	0.023
124.5	25.4	50.8	8645	59	0.0362	0.0005	0.0407	0.0004	1.123	0.018
193.0	0.0	0.0	7100	36	0.0296	0.0003	0.0258	0.0003	0.871	0.015
193.0	25.4	50.8	6802	18	0.0284	0.0002	0.0308	0.0003	1.084	0.013
								Average	**0.999**	

Figs. 7, 8 and 9 display detection efficiency contour plots or profiles for three levels (heights) in the measurement chamber of the BLM. They are based on benchmarked MCNP calculations with a grid size of 2.54 cm (1 inch). They show that over most of the central region where the baskets of bulk laundry are located, that the detection efficiency is relatively uniform.

MCNP has been used to perform a simulation with the laundry cart or silo, containing laundry, positioned in the BLM. The results for different configurations are tabulated in TABLE IV. The calculation has been performed with and without the aluminium sidewalls of the cart included and with the cart empty and with two different loadings of laundry.

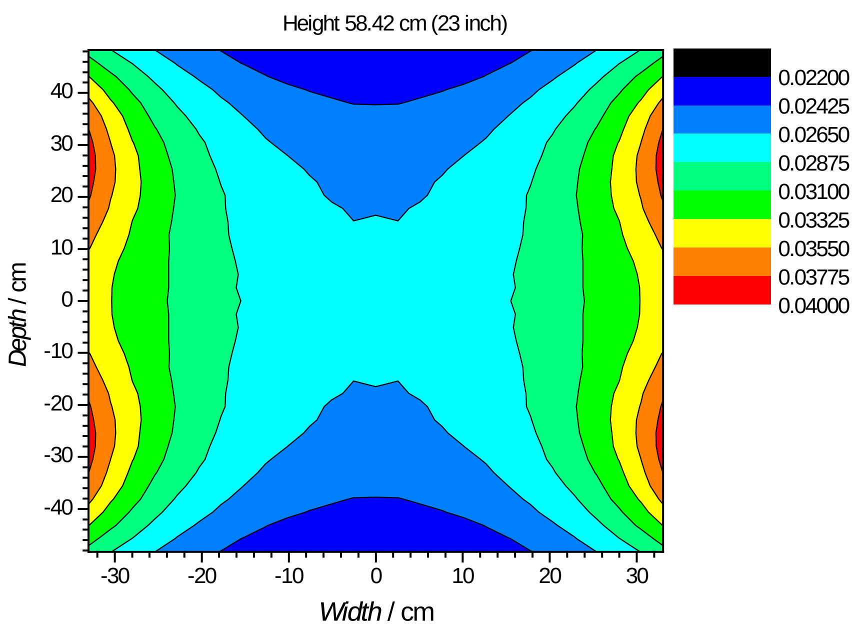

Fig. 7. BLM detection efficiency profile – lower plane at a height of 58.42 cm.

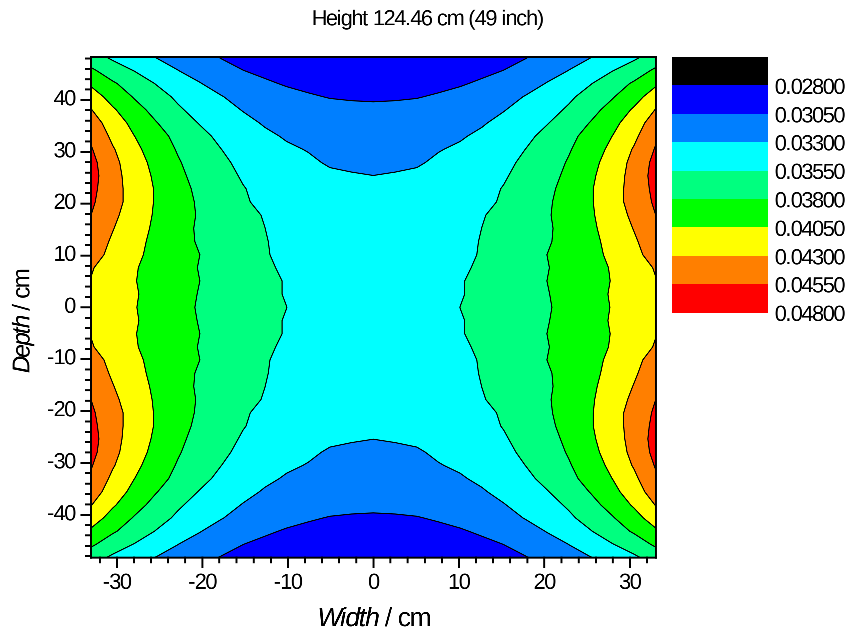

Fig. 8. BLM detection efficiency profile – central plane at a height of 124.46 cm.

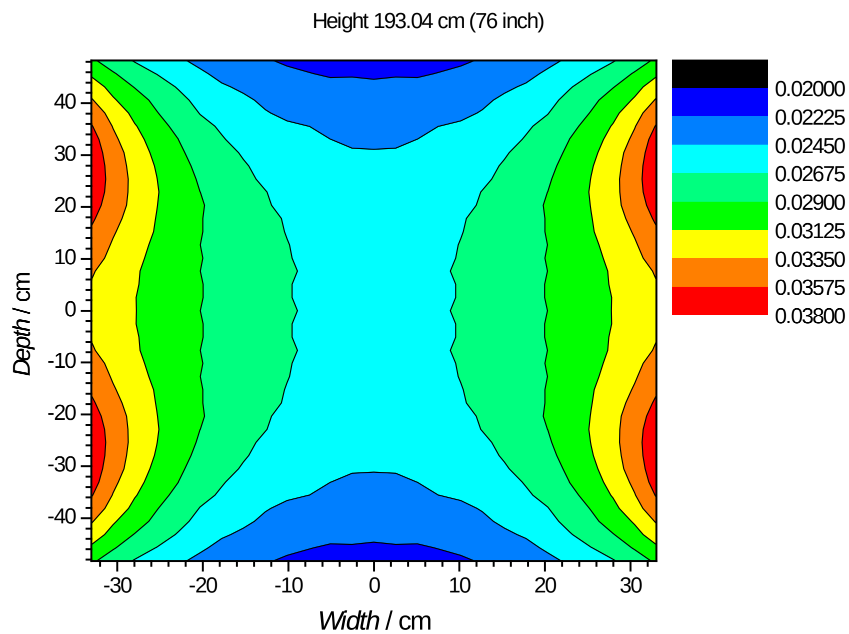

Fig. 9. BLM detection efficiency profile – upper plane at a height of 193.04 cm.

TABLE IV. MCNP simulation results for a Cs-137 volume source (entire volume of cart). Results are given for simulations with and without the 4 mm thick aluminium walls of the cart.

Matrix of Laundry cart or silo	Net Mass (kg)	Density ($g.cm^{-3}$)	Detection Efficiency				Transmission Ratio Through Cart Wall
			Aluminium Walls		No Walls		
			Value	Error	Value	Error	
Void (empty cart)	0	0.0000	0.02890	0.00003	0.03204	0.00003	0.902
Laundry (light load)	98	0.0856	0.02330	0.00003	0.02588	0.00003	0.900
Laundry (heavy load)	111	0.0969	0.02268	0.00003	0.02520	0.00003	0.900

The column “Transmission Through Cart Wall” shows the transmission ratio with and without the cart walls present. It is interesting to note that experimental determination of detection efficiency has provided a better than expected value of 0.03183, even though is based on relatively few measurement points. The value compares favourably with the more comprehensive MCNP simulation result in TABLE IV of 0.03204.

CONCLUSIONS

In this paper the characterisation and calibration of an upgraded BLM is described. The BLM units are employed to measure the activity of work clothing at nuclear power stations that is transferred to laundry facilities off site. The units are used as a screening measure to ensure that contaminated work clothing with elevated levels of radioactivity do not leave the nuclear power station site. Fig. 10 shows the mechanical configuration of one of the BLM units before the upgrade.

Fig.10. Bulk Laundry Monitor

Measurement results are presented for the calibration of the BLM using a calibrated Cs-137 point source and the average detection efficiency of the measurement chamber is determined, as is the MDA for the instrument of less than 7.4 kBq (200 nCi). The results are confirmed and detection efficiency profiles (contour plots) are generated using a benchmarked MCNP simulation of the measurement system. The simulation is also used to estimate the detection efficiency with contaminated laundry present in the measurement chamber. Overall, good agreement is obtained between measurement and simulation. Differences can be attributed in part to the lack of modelling of the light transport in the plastic scintillator detectors, however, averaged over all of the detectors, the resulting error is small.

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