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Field Trial of the Enhanced Data Authentication System (EDAS)

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1. Introduction

EDAS is a means to branch information from an existing measurement system (sensor⇔primary observer) to a secondary observer. EDAS creates a separate digital signal "branch" to the secondary observer from a tap-off point close to the measurement sensor, as illustrated in Figure 1. EDAS has no a priori understanding of, or expectation for, the meaning of the data it branches. In a nuclear safeguards deployment, the primary observer represents the facility operator system while the secondary observer is the safeguards inspectorate system.

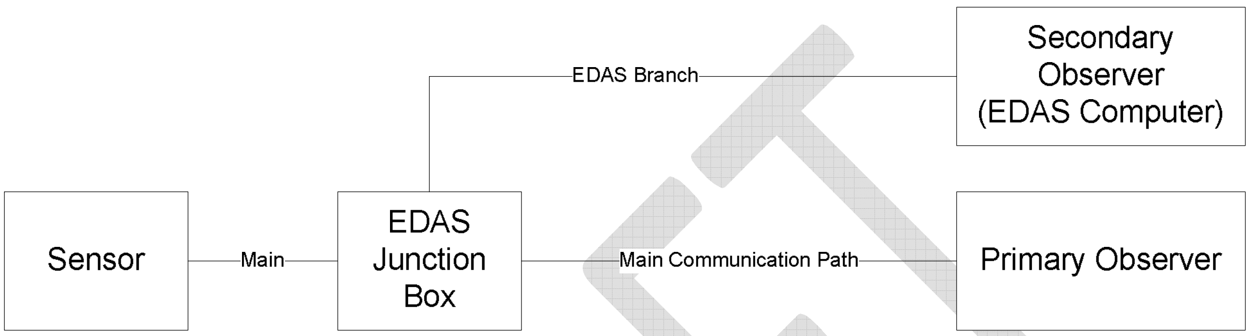

Figure 1: EDAS Branching Diagram

The EDAS development project is a collaborative effort between the U.S. DOE Sandia National Laboratories in the United States, the European Commission Directorate General for Energy (DG-ENER) in Luxembourg, and the European Commission Joint Research Centre (JRC) in Italy. The original project began in May 2008 under the auspices of a DOE-Euratom agreement[1] as Action Sheet (AS) 32, "Enhanced data authenticity via an electronics platform for the secure transmission and recording of sensors." That work focused on the inspector requirements for secure branching. The project team designed, built and demonstrated an initial prototype of EDAS to key stakeholders [1]. The project continued under AS 41, "Application of the Enhanced Data Authentication System to Operator Instrumentation." In this second phase, we adapted the concept to meet operator requirements as well; that is, to ensure that EDAS is non-interfering to facility operations, fail-safe, and conforms to instrumentation interface standards [2, 3]. Sandia incorporated the combined inspector and operator requirements into redesigned hardware and software for EDAS [4]. The new prototypes have been tested extensively, culminating in an extended field trial at an operational nuclear facility subject to Euratom safeguards [5].

The goal of the field trial of EDAS was to demonstrate the utility of secure branching of operator instrumentation for nuclear safeguards, identify any unforeseen implementation and application issues

[1] "Agreement between the European Atomic Energy Community represented by the Commission of the European Communities and the United States Department of Energy in the field of Nuclear Material Safeguards Research and Development," 6 Jan 1995. That agreement was superseded in November 2010 with one of expanded scope, "Agreement between the European Atomic Energy Community represented by the European Commission and the United States Department of Energy in the field of Nuclear Material Safeguards and Security Research and Development."

with EDAS, and confirm whether the approach is compatible with operator concerns and constraints. DG-ENER arranged to conduct the field trial at the Westinghouse Springfields Fuel Fabrication Facility in Lancashire, United Kingdom. We inserted EDAS junction boxes in two operator instrumentation lines for the field trial, a barcode scanner and a weight scale, both at a UF_6 cylinder transfer station. Data collection occurred for approximately nine months, from March through November 2015. The branched data transmitted continuously to an inspector computer and collected by the Euratom Remote Acquisition of Data and Review (RADAR) [6] data acquisition software for subsequent analysis by inspectors.

2. EDAS Prototypes

Sandia designed, developed, and manufactured prototype EDAS software and hardware to meet both operator and inspector requirements, incorporating commercial off-the-shelf (COTS) and custom hardware, as well as open source and custom software. EDAS features a modular design, which separates its general branching functionality from that which is specific to a particular instrumentation interface. The interface-specific part of EDAS is standard 9-pin RS232 serial, which matches the field trial barcode scanner and weight scale interfaces. Figure 2 is a picture of the EDAS junction box, which is approximately 9.5x6.3x4.0 cm. Power is supplied either directly or via USB; power-over-Ethernet is not supported by the processor.

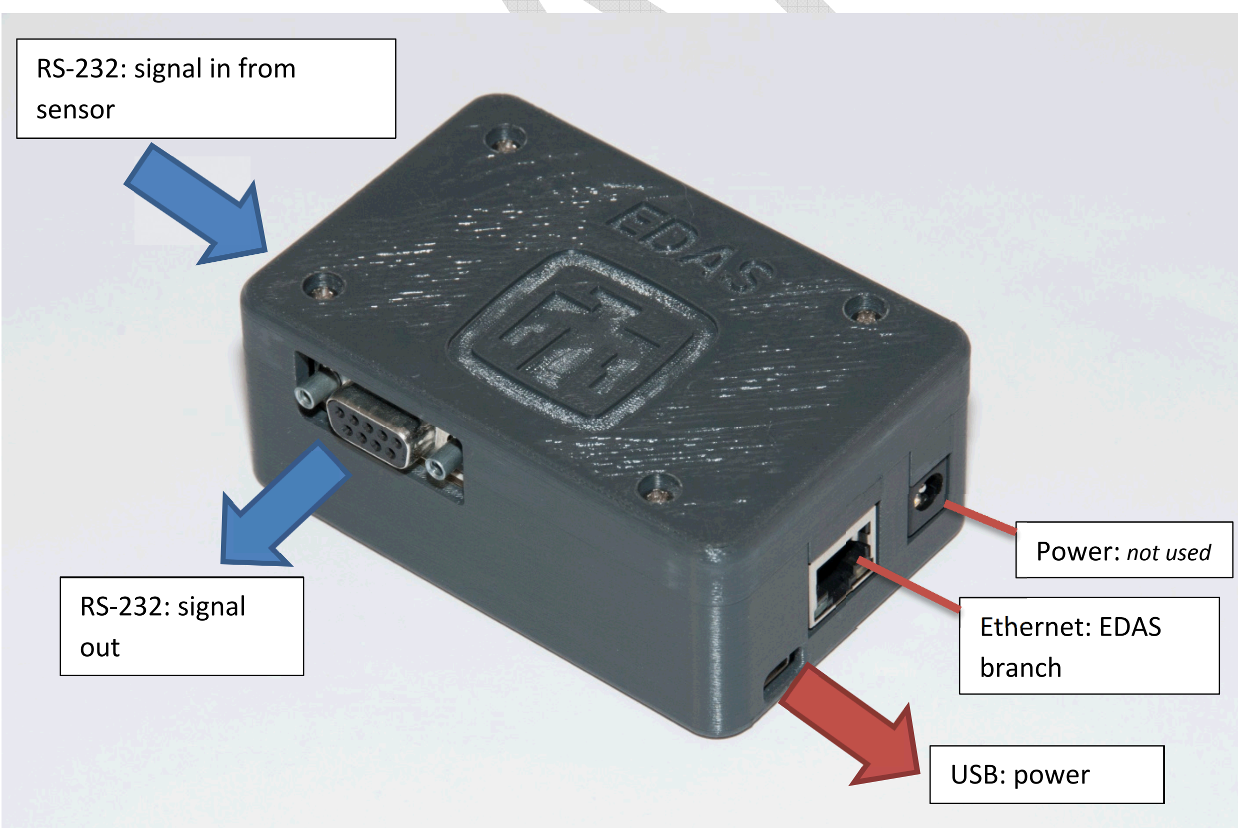

Figure 2: The EDAS Junction Box

EDAS employs a low-cost commercial BeagleBone Black embedded processor and a custom accessory board, called a "cape," that is attached to the BeagleBone Black board. The cape is interface-specific; it performs the branching function for both the "transmit" and "receive" signals in the RS-232 serial specification. Figure 3 is a picture of the EDAS cape inside the case. It links the primary instrumentation signal path between the in and out serial connectors, and includes sensing electronics to generate an isolated copy of the signal. DB-9 serial connectors on the cape use different genders, so that the primary instrumentation cables could be disconnected from the EDAS junction box and mated directly to each other, should the operator have reason to bypass the EDAS entirely.

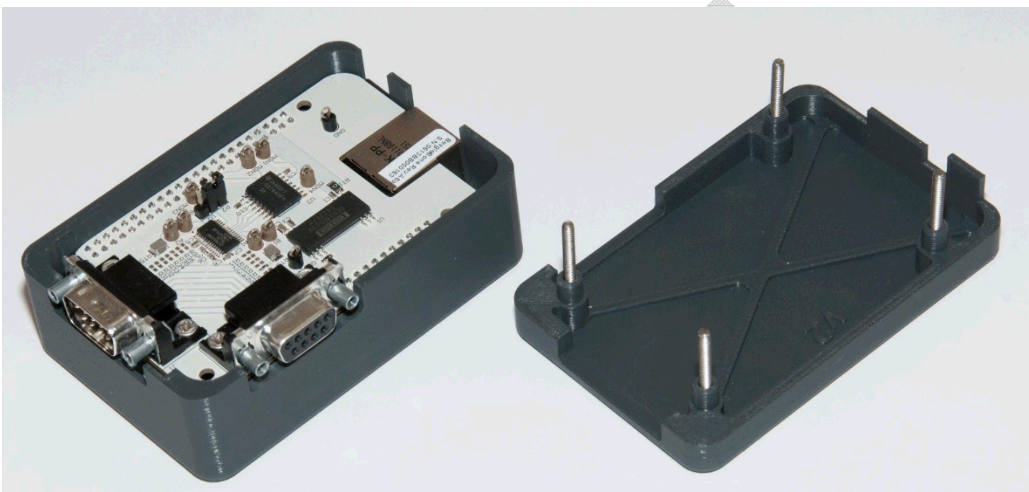

Figure 3: EDAS Cape

The BeagleBone Black comes preinstalled with the Debian Linux operating system. However, we replaced it with a slimmer distribution of Linux created for embedded systems, called Yocto, and further streamlined it to EDAS needs. We eliminated all extra functionality from the operating system to make it lightweight by removing software functions that may consume processor and memory resources. We also made the EDAS more secure by disabling access to ports not used for normal operation (e.g., FTP).

The custom firmware directs the embedded processor to collect and buffer all branched data from the main instrumentation signal path. The data are then compiled into discrete packets; digitally signed using a public key cryptographic algorithm; encrypted; and finally pushed over an Ethernet connection to the inspector computer. The firmware also periodically creates and sends state of health "heartbeat" messages to confirm that EDAS is operating normally. The inspector computer runs custom software that receives and decrypts the EDAS packets, verifies their authenticity, and writes the data to an output file for post-processing and analysis.

3. RADAR Integration

The EDAS junction box does not interpret the meaning of the data it branches, but forms data into packets and sends each via TCP/IP over Ethernet to the inspector computer. The EDAS software receives all EDAS packets from the network and writes these to a log file. The inspector computer runs EDAS RADAR software modules, which constantly scan the EDAS log files for new records.

DG-ENER created two EDAS RADAR software modules for the field trial to derive meaning from the EDAS branched bytes so that they are interpretable in the same way for the inspector and the facility operator. The modules convert the branched signals into event records containing a date and time stamp with the scanned barcode ID or weight measurement in kilograms. RADAR writes these records to specially created output files that are used for later analysis.

The development of the RADAR EDAS modules represents an important phase of the collaboration between DG-ENER and Sandia. Sandia shipped several EDAS junction boxes and software to Euratom headquarters in Luxembourg where EDAS RADAR software modules were developed and tested in a test bed using representative field trial equipment and simulators. EDAS integration with RADAR greatly facilitates our ability to analyze data from the field trial. This is because much of the analysis involves the comparison of operator records to the interpreted barcode and weight scale records in the RADAR files.

A further benefit is that RADAR is the standard data acquisition tool used by the Euratom inspectorate. RADAR converts EDAS data to a standard format that can be analyzed by other Euratom analysis tools, such as Central RADAR Inspection Support Package (CRISP). With the development of the field trial RADAR EDAS modules complete, it will be simple to develop new modules to RADAR in the future to support the branching of other instrumentation types.

4. Field Trial Setup

The field trial took place at a UF_6 cylinder transfer station at the Springfields fuel fabrication facility. During operations, cylinders enter the portal staging area one at a time and are placed on a scale. Per the facility procedure, an operator must scan the cylinder identification number with a barcode scanner and measure its weight. These two operations can happen in either order. To measure a weight, an operator must enter a command into the operator system, which triggers three consecutive weight commands. The operator weight scale control unit sends three successive weight measurements, in kilograms, to the operator system. The operator system then averages these three weights, which becomes the final weight measurement record. Both barcode scan and weight measurement records are written to an operator log file. Once the cylinder has been processed, it will reenter the portal transfer station and its identification number and weight measurement will be taken once again. The empty cylinder then leaves the facility. For the field trial, EDAS junction boxes were inserted at branch points in the barcode scanner and weight scale communication lines.

In early March 2015, the Sandia EDAS developers, Euratom inspectors, and operator representatives met at the Springfields facility to install EDAS and commence the field trial. The Sandia team provided several EDAS prototypes and cabling while Euratom provided the inspector computer running a version of the RADAR software to acquire the EDAS signals. The Springfields operator decided for its own reasons to acquire and install a lockable custom cabinet, pictured in Figure 4 below, to house both the

EDAS junction boxes and Euratom computer. The cabinet was fitted with feedthrough connectors for both RS-232 and power. Thus the operator instrumentation lines were interrupted not only by an EDAS junction box, but also two extra connectors (one “in” and another “out” of the cabinet).

Figure 4: EDAS Cabinet provided by Operator

We originally understood that the operator used a standard 9-pin RS-232 interface for the barcode scanner, but discovered only during the installation visit that the actual device was instead using a pen interface. The operator promptly replaced that barcode scanner with a new one that uses a 25-pin interface. To obtain the correct signal on the EDAS, the operator installed a Datalogic CBX800 adapter, shown in Figure 5, in the signal line between the barcode scanner and operator system. It is important to note that the Datalogic adapter splits the barcode signal, with one portion going to the operator system and the other to the barcode EDAS.

The operator classified the continuous and direct output from the scale as part of the facility safety system; branching here would have required a prohibitively long and uncertain approval process. Therefore, the EDAS branch point for the weight scale was at the output of the control unit for the scale, not at the scale itself. The control unit was a Mettler Toledo model IND690 weighing terminal. EDAS therefore did not sense weight continuously. Instead, it received weight data only when the facility instrumentation system triggered the IND690 to send a reading.

Figure 6 below shows the installed EDAS junction boxes and the Euratom inspector computer. The inspector computer was a ruggedized Windows computer with several redundant components for increased reliability. A switch handled EDAS network traffic between the EDAS prototypes and inspector computer. The team verified the successful branching of several facility barcode and weight events over several days before leaving the system to run unattended for the duration of the field trial.

Figure 5: Datalogic adapter that tees the barcode scanner data

Figure 6: EDAS System installed in operator cabinet, showing the Euratom computer (left), network switch (middle), and two EDAS branching units (right)

5. Field Trial Analysis

The field trial collected data for nine months, between March 5, 2015 and November 26, 2015. EDAS data were collected by RADAR on the installed inspector computer, and retrieved by DG-ENER during occasional Euratom inspection visits to the facility. Euratom inspectors retrieved the complete datasets on November 26 when the system was shut down, disconnected, and removed. DG-ENER obtained a separate transcript from the Springfields operator of timestamped system logs of barcode and weight scale data over the same time period. DG-ENER subsequently shared both EDAS and operator data with Sandia for the field trial analysis. Sandia analyzed these data using custom analysis software to compare and correlate the data.

In order to gauge the success of the EDAS field trial, we posed the following questions:

- Did each EDAS operate continuously for the field trial duration?
- Do the EDAS and operator barcode scanner datasets match? Each dataset must have the same total number of records, each matched record must occur at the same time (within a tolerance window), and the matched values of each record must be identical.
- Do the EDAS and operator weight scale datasets match? Each dataset must have the same total number of records, each matched record must occur at the same time (within a tolerance window), and the matched values of each record must be the same (within a weight tolerance).
- For every barcode scan is there a corresponding weight measurement, and does every weight measurement have an associated barcode scan?
- Are all weight scale data preceded by associated "send weight" commands? Conversely, is any command missing a weight scale response?
- Were other anomalies discovered?

The field trial analysis specifically addresses these questions, and the following sections report the results of the analysis. Additional interpretation is deferred to the Discussion later in the report.

5.1. Analysis Methodology

We wrote software to automate the analysis of the field trial data. The software applies several rules and assumptions that define the continuous operation of EDAS, correct format of a record, and tolerances that may arise from expected differences between the EDAS and operator system data. The following are the rules and assumptions we used for the field trial analysis:

- A barcode ID is an alphanumeric string.
- A weight is measured in kilograms.
- A weight scale command is considered valid if it matches the Mettler-Toledo IND690 control sequence: S<CR><LF><ACK>. Note that any variations are flagged as an anomaly.
- Packets sent from the EDAS junction box to the inspector computer are digitally signed and encrypted. For a received packet to be marked as authentic, the packet must correctly decrypt and authenticate.
- To prove that the junction boxes were continuously operating, EDAS junction boxes were configured to send heartbeat messages at a rate of once per minute. Therefore, heartbeat messages must occur at a rate of at least once every two minutes (to account for timing variations).

- For comparing the EDAS and operator barcode data, a match is recorded when the values are identical AND are within four minutes of each other. We selected four minutes to account for observed clock drift between the EDAS and operator systems over the course of the field trial.
- For comparing the EDAS and operator weight scale data, a match is recorded if the values vary by less than 0.1 kg AND are within four minutes of each other. Note that slight precision differences in measurement values is expected since three weight values are averaged independently by the operator and EDAS systems. We selected four minutes to account for observed clock drift between the EDAS and operator systems over the course of the field trial.
- Per the operator's procedure, both barcode and weight scale measurements are taken in close time proximity. We selected a time threshold of one minute based on our observations of this activity within the data.
- We expect an operator weight command to the IND690 (weight scale terminal) to be immediately followed by a weight scale measurement. We create an association if a weight command precedes a weight measurement AND the timestamps are within two seconds of each other. Note that this analysis is only possible with EDAS data because the operator does not keep a record of commands in the operator system logs.

5.2. Test for Continuous EDAS Operation

Both the barcode and weight scale EDAS units operated continuously for the nine month duration of the field trial. To check for continuous operation, we first checked that there were no interruptions in heartbeat messages from either junction box. There was no time during the field trial where more than two minutes passed between these messages.

We also searched the inspector computer log files for evidence of a network disconnect between an EDAS junction box and the inspector computer. Upon reestablishing a network connection, an EDAS junction box will create a new encryption channel and pass the public authentication keys to the inspector computer. The only recorded instance of establishing a network connection was the initial connection at the beginning of the field trial.

5.3. Test for EDAS and Operator Dataset Equality

Our analysis software compares the EDAS measurements collected by RADAR with the operator system data files to check whether either EDAS missed any records captured by the operator system. One test notes a match between the EDAS and operator barcode data if the records fall within a four-minute time threshold and the measurement values are identical. A subsequent test records a match between EDAS and operator weight data if the measurements fall within a four-minute time threshold and the measurement values are within 0.1kg of each other. A discrepancy, or difference, is any deviation from the above conditions, or any missing or additional EDAS data with respect to the operator system.

Table 1 illustrates the total number of barcode and weight data points analyzed for the field trial. Note that we are not analyzing measurements captured by EDAS from June 27 – 30 and September 2 since the operator did not include those log files. For the June measurements, our analysis excludes nine barcode/weight measurements captured by EDAS, while the missing September 2nd measurements exclude 11 barcode records.

Table 1: Total Barcode and Weight Events

Measurement Type	Operator	EDAS
Barcode Scanner	696	689
Weight Scale	655	654

The barcode EDAS did not branch seven events found in the operator log files over the course of the field trial. These events happened on four different occasions spread over the field trial duration. As stated above, there is no indication the EDAS malfunctioned during these periods. The operator also states that the Barcode EDAS was not bypassed at any time.

We identified one additional empty weight measurement of 0.0 kg in the operator log file that does not show up in the EDAS RADAR files. Upon closer examination of the EDAS inspector computer records, we found evidence of a malformed weight command sent at the same time as this extra operator weight record. We believe that this incomplete command was enough to register the empty weight event in the operator logs even though the operator weight scale did not send any actual data over the instrumentation signal line.

We also compared the EDAS measurements collected by RADAR with the operator system data files to check whether either EDAS observed any measurements not recorded by the operator system. Our analysis found that of the 689 and 654 events recorded by each EDAS, there was a 100% match with the operator files, indicating that each EDAS did not branch any extra events not reported by the operator.

5.4. Test for Barcode / Weight Correlation

Since each cylinder must have its barcode scanned and weight measured when entering or exiting, we looked for correlation between these events as captured by each EDAS junction box. Of 689 barcode and 654 weight events, 645 of them correlated. Forty-four bar code scans did not have associated weight data. Further analysis discovered several reasons for these discrepancies: (1) operator scanning a test pattern rather than a cylinder bar code, (2) inadvertently scanning the same barcode ID multiple times in rapid succession, or (3) accidentally scanning a barcode intended for autoclave processing. Note that for this last case, a second barcode scanner, attached to a different system, scans the cylinder identification number for subsequent processing in the autoclave. There were nine instances of weight data without corresponding barcode scans. Many of these are attributable to the seven events missed by the barcode EDAS that are discussed in the section above. The remainder consists of weights that are outside the range expected for a UF_6 cylinder in that they are less than the tare weight. The operator confirmed that these extra weight events were for scale testing purposes.

We also analyzed the operator record for correlation between barcode and weight data events. In this case, we count 696 barcode and 655 weight events from the operator record, of which 651 events correlate. Forty-five bar code scans did not have associated weight data; 4 weight events did not have associated bar code scans. Reasons for these non-correlated data are the same as for the EDAS, including barcode and weight scale testing and operator error.

We would ideally expect to see exactly the same discrepancies, whether from the operator record or the EDAS record. This is not possible since the barcode EDAS missed seven events captured by the operator system while the operator system recorded an empty weight. Note that when accounting for these differences, the barcode and weight discrepancies between the EDAS and operator are the same.

5.5. Test for Weight Command / Data Correlation

Of the 654 weight readings branched by the EDAS, 100% were correlated to a weight command that immediately preceded the event. We did not perform this test on the operator data since commands are not included in their log files. Also, note that this analysis does not apply to the barcode scanner data, since a human operator must squeeze the barcode scanner trigger to command the device and EDAS does not have access to this command signal.

5.6. Test for Other Anomalies

During field trial setup it became clear that the EDAS junction box electronics do not keep time well. The BeagleBone Black has an inaccurate system clock. For this reason, we relied instead on the inspector computer time: the inspector computer affixes its own timestamp to each EDAS message it receives. However, even using this timestamp in lieu of the EDAS timestamp was not without issues. We observed a dozen occasions when the inspector computer timestamps on successive EDAS heartbeat messages were only a few seconds apart, rather than the expected one-minute separation. We suspect that these heartbeat messages, sent by the EDAS junction box, were queued while the inspector computer was otherwise busy and unable to process them, causing a backlog of messages. At a later point, the inspector computer processed them in rapid succession, resulting in a cluster of closely spaced timestamps for these messages. Analyzing the EDAS timestamps, even though incorrect in an absolute sense, were sufficiently accurate on smaller timescales to confirm that the heartbeat messages were generated at the expected frequency of once per minute.

Another issue was the assignment of the local time zone to the timestamped EDAS data packets. Two daylight savings events occurred during the course of the field trial, causing timestamps to suddenly skip or move backwards an hour. An appropriate time correction factor was applied to rectify this issue.

6. Discussion

The field trial analysis has shown that EDAS and the inspector computer operated continuously and correctly over the nine month duration of the field trial, showing that EDAS can run unattended in an operation nuclear facility for long periods of time. There was never an interruption in heartbeat messages in both EDAS prototypes, and no network connectivity issues nor errors in the log files. In addition, the data were free of decryption and authentication errors, which satisfy the inspector requirements for data being both confidential and trustworthy, respectively, from the branch point forward.

EDAS correctly branched both barcode and weight data without interfering with the operator system. No unexpected data appeared in the operator system logs originating from EDAS. No unexplained EDAS weight scale events were missed as compared to the operator, indicating that EDAS correctly branched all 654 events during the field trial. The Barcode EDAS did miss seven events out of 696 total events, and there is no evidence that suggests a malfunction of the Barcode EDAS or a disconnection of the operator barcode signal cable from the EDAS. One possible explanation for intermittently missing events is that Datalogic adapter split the signal outside of EDAS, which may have electrically weakened the signal traveling to the EDAS. While causation cannot be proven, it is interesting that the Weight EDAS, which did perform branching during the field trial, captured all weight data. Nevertheless, this issue highlights why the EDAS junction box must be the actual branch point rather than using a separate, external signal splitting device. Also notable is that neither EDAS recorded events that were absent from the operator system.

With multiple EDASs installed in a facility, there are other first-order analyses that can correlate data to look for consistency. When a UF6 cylinder enters or exits the facility, one would expect the cylinder to be both barcode scanned and weighed at approximately the same time. Yet comparing barcode scans to weights between the EDAS prototypes showed over 40 discrepancies. As discussed earlier, these differences can all be explained from operator tests and errors. The operator barcode and weight data from its log files were also compared, and the discrepancies largely matched those of the analysis between the EDASs. Another analysis performed found 100% correlation of EDAS weight commands and data, which proves that in every case a command immediately preceded a weight. More generally, the installation of multiple EDASs independently observing various aspects of a process can increase confidence for the safeguards inspector since they can correlate data from each to check for consistency in data. The ability to check data consistency across multiple EDASs makes cheating on a representative process in the nuclear fuel cycle more complex and difficult.

The decision to build a lockable custom cabinet to house the field trial equipment affected setup and installation. While such a cabinet is advantageous for an inspectorate to house the inspector computer, there are downsides to placing the EDAS junction boxes inside. For one, it makes it difficult for the small form-factor EDAS junction box to be installed as close to an instrumentation sensor as possible. In addition, the pass through connectors, built into the cabinet, add more capacitance to the instrumentation signal path, which will affect data transmission and integrity for both the operator and inspectorate. A further point is that the operator foregoes the "bypass" option designed into the EDAS junction box and would instead have to create a bypass external to the cabinet.

The field trial exposed several issues with timing. The EDAS built-in clock, included with the BeagleBone processor, is not very accurate and resets to a default value if it loses power. A low-cost, high-accuracy real time clock with battery backup can be added to future versions of EDAS to fix the problem. It is also essential to standardize the time zone used by the EDAS and inspector computer, irrespective of installation location. A universal time zone such as UTC (Coordinated Universal Time) should be set, which does not observe daylight savings transitions. Clock drift between EDAS and operator system is another important concern for the future since the inspector does not have the ability to regulate time on the operator system. The time drift between these systems is an issue that could impact event correlation and should be given further consideration.

More sophisticated field trial analysis could yield patterns of facility operations for the branched instrumentation by correlating multiple measurements over time. For this field trial, it may be possible to calculate the net weight difference of cylinders, get a sense of the residence time of each cylinder within the facility, and the direction of cylinder movement. From such data can be extracted a fairly good measure of uranium hexafluoride mass processed at the facility per unit time as well as how many and which cylinders are currently inside the facility. The types of patterns extracted by an EDAS installation can be extrapolated to other areas of the nuclear fuel cycle.

7. Conclusions

The field trial of EDAS was successful in that it operated continuously and correctly in a safeguarded operational nuclear facility over a nine-month period. There are several field trial takeaways that can be incorporated into a future version EDAS. These include issues such as the incorporation of better time keeping with a battery backup and the use of a universal time zone. We recommend that future EDAS hardware be compatible with 25-pin RS-232 (e.g., a standard 25- to 9-pin adapter). Future versions of EDAS may need to incorporate different instrumentation interfaces, such as USB or Ethernet. In addition, a tamper indicating enclosure is a recommended addition to protect the EDAS cryptographic keys.

The EDAS benefits both the facility operator and safeguards inspectorate. The Springfields facility operator is pleased that the EDAS prototypes did not interfere with their operational UF_6 portal in any way. The Euratom inspectorate views the field trial as a full success and is pleased with the continuous, correct, and secure branching of safeguards relevant data.

A successful field test of EDAS is a critical step in addressing the IAEA Long Term R&D plan item 7.1, "Develop minimally intrusive techniques that are both secure and authenticated to enable the use of operator's systems, instruments and process monitoring for cost effective safeguards implementation." EDAS connects to facility instrumentation, and therefore reduces the need for duplicate equipment that would slow down throughput and cost money. EDAS is a useful tool for the nuclear safeguards inspection community to securely monitor existing operator instrumentation without undue burden on the facility operator. Indeed EDAS could be a useful tool in other areas where a secondary observer has a need to remotely monitor a sensor.

8. References

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