

A Mock UF₆ Feed and Withdrawal System for Testing Safeguards Monitoring Systems and Strategies Intended for Nuclear Fuel Enrichment and Processing Plants

December 2009

Prepared by
Alan M. Krichinsky
Bruce M. Bates
Joel B. Chesser
Sinsze Koo
J. Michael Whitaker

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Global Nuclear Security Technology Division

**A Mock UF₆ Feed and Withdrawal System for Testing Safeguards
Monitoring Systems and Strategies Intended for Nuclear Fuel
Enrichment and Processing Plants**

Alan M. Krichinsky
Bruce M. Bates^{*}
Joel B. Chesser^{*}
Sinsze Koo[†]
J. Michael Whitaker

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^{*}Nuclear Science and Technology Division

[†]University of South Carolina, Columbia

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
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DEDICATION

This report is dedicated to the memory of Joel Chesser, who passed away before it was published. Joel was instrumental in helping lead the assembly of the system described herein, and his coauthors wish to recognize his achievements with this small gesture. He is missed very much by his friends and colleagues at Oak Ridge National Laboratory.

CONTENTS

LIST OF FIGURES	vii
EXECUTIVE SUMMARY	ix
1. INTRODUCTION.....	1
2. MOCK F&W SYSTEM DESCRIPTION	2
2.1 SYSTEM COMPONENTS	2
2.2 SYSTEM LAYOUT.....	4
3. MONITORING SYSTEMS	6
3.1 DATA COLLECTION SYSTEM ARCHITECTURE.....	6
3.2 LOAD CELL MONITORING	7
3.3 OTHER MONITORING COMPONENTS.....	8
4. BASIC MOCK F&W SYSTEM OPERATION.....	9
4.1 RUN DESCRIPTIONS	9
5. FUTURE PLANS FOR THE MOCK F&W SYSTEM.....	10
6. CONCLUSIONS.....	11
7. REFERENCES.....	11

LIST OF FIGURES

Figure	Page
1 Mock F&W system showing feed tanks (right, rear), product tanks (left), tails tanks (front, center-right), and process tank (top, center).....	3
2 Color-coded diagram of mock F&W system—with green feed tanks, yellow product tanks, blue tails (or waste) tanks and a red process tank.....	5
3 Plan view of mock F&W system diagram.....	5
4 Elevation view of mock F&W system diagram.....	6
5 Data collection system architecture.....	7
6 Centering pan for 250-kg capacity scales.....	8
7 Process schematic for mock F&W system.....	10

EXECUTIVE SUMMARY

This report describes an engineering-scale, mock UF₆ feed and withdrawal (F&W) system, its operation, and its intended uses. This system has been assembled to provide a test bed for evaluating and demonstrating new methodologies that can be used in remote, unattended, continuous monitoring of nuclear material process operations. These measures are being investigated to provide independent inspectors improved assurance that operations are being conducted within declared parameters, and to increase the overall effectiveness of safeguarding nuclear material. Testing applicable technologies on a mock F&W system, which uses water as a surrogate for UF₆, enables thorough and cost-effective investigation of hardware, software, and operational strategies before their direct installation in an industrial nuclear material processing environment.

Electronic scales used for continuous load-cell monitoring also are described as part of the basic mock F&W system description. Continuous monitoring components on the mock F&W system are linked to a data aggregation computer by a local network, which also is depicted. Data collection and storage systems are described only briefly in this report.

The mock UF₆ F&W system is economical to operate. It uses a simple process involving only a surge tank between feed tanks and product and withdrawal (or waste) tanks. The system uses water as the transfer fluid, thereby avoiding the use of hazardous UF₆. The system is not tethered to an operating industrial process involving nuclear materials, thereby allowing scenarios (e.g., material diversion) that cannot be conducted otherwise. These features facilitate conducting experiments that yield meaningful results with a minimum of expenditure and quick turnaround time.

Technologies demonstrated on the engineering-scale system lead to field trials (described briefly in this report) for determining implementation issues and performance of the monitoring technologies under plant operating conditions. The ultimate use of technologies tested on the engineering-scale test bed is to work with safeguards agencies to install them in operating plants (e.g., enrichment and fuel processing plants), thereby promoting new safeguards measures with minimal impact to operating plants. In addition, this system is useful in identifying features for new plants that can be incorporated as part of "safeguards by design," in which load cells and other monitoring technologies are specified to provide outputs for automated monitoring and inspector evaluation.

1. INTRODUCTION

A major aspect of international safeguards is the verification of declared nuclear material transactions by independent inspectors—such as personnel from the International Atomic Energy Agency (IAEA). Traditional methods typically rely upon static batch tracking of material flows and periodic surveillance of operations through inspector visits. With the planned construction of uranium enrichment plants of significantly larger capacities than existing facilities, new safeguards measures such as continuous, multi-layered operations monitoring will be necessary to maintain effective and efficient safeguards without increasing inspector personnel requirements.

Therefore, new safeguards measures are being tested, and evaluated at Oak Ridge National Laboratory (ORNL) to dynamically monitor material flows, allowing quicker and easier verification of operator declarations and automatic indication and recording of off-normal events. To facilitate technology implementation, a mock UF₆ feed and withdrawal (F&W) system has been assembled at ORNL. This system allows testing the performance characteristics of new monitoring components—individually and as a complement to other technologies—to screen their usefulness in industrial applications and to identify issues surrounding industrial implementation. In addition, the system accommodates the evaluation and demonstration of methodologies for integrating multifaceted monitoring technologies into an integrated safeguards operations monitoring system amenable for direct installation in an industrial nuclear material processing environment.

One basic technology for monitoring material flows involves collecting process load-cell data from feed and withdrawal stations. This technology provides a continuous stream of data—collected during periods between inspections—that is valuable for verifying operator declarations of uranium hexafluoride (UF₆) inputs and outputs. The mock F&W system was assembled to demonstrate the effectiveness of load cells and, eventually, other technologies for continuously monitoring inputs and outputs from F&W stations.

The test bed described in this report is considered to be an engineering-scale system—that is, larger than a bench-top (or laboratory) system but smaller than pilot scale. The classic application of UF₆ F&W is the uranium enrichment plant. Although enrichment technologies may differ from plant to plant, each enrichment facility has feed stations, product stations, and tails stations. The mock F&W system resembles an enrichment plant mainly with respect to its having multiple stations for feeds, products, and tails, and providing a configuration for conducting batch or semi-continuous operations involving a process fluid. The system uses water as a surrogate for UF₆, to allow cost-effective testing of instruments intended to monitor non-nuclear aspects of material flow (e.g., mass changes, cylinder ID tag tracking, pump power consumption, flow rates, etc.).

The mock UF₆ F&W system is not considered to be prototypical of an enrichment plant in any way; however, *monitoring systems* tested and demonstrated on the mock F&W system *are* considered to be prototypical of those intended for field application. Technologies demonstrated on the engineering-scale system lead to field trials [which already show promising results from ongoing studies conducted in the X-344 Transfer Facility at the Portsmouth Gaseous Diffusion Plant (PORTS) in Piketon, Ohio, and in the fuel manufacturing operations at the Global Nuclear Fuel (GNF) Fabrication Facility in Wilmington, North Carolina] for determining monitoring technology implementation issues and performance under plant operating conditions. The ultimate use of technologies tested on the engineering-scale test bed is to work with safeguards agencies to install them in operating plants (e.g., enrichment and fuel processing plants), thereby promoting new measures for enhanced safeguards, with minimal impact to operating plants. In addition, the mock F&W system is useful in identifying features for new plants that can be incorporated as part of "safeguards by design," in which load cells and other monitoring technologies are specified to provide outputs for automated monitoring and inspector evaluation.

2. MOCK F&W SYSTEM DESCRIPTION

The mock UF₆ F&W system is a group of feed, product, and tails (or waste) tanks serving the simplest of processes—a surge tank. A surge tank is a holding point typical of industrial processes for accumulating solution from one chemical process unit before it proceeds to the next chemical process unit. The mock system's surge tank represents an entire process with an in-process inventory. In the mock UF₆ F&W system, no actual chemical or physical change is imparted on the feed material such that the feed, “product,” and “tails” (or “waste”) materials are identical, differing only in quantity—which is analogous to a uranium enrichment process in which only the isotopic mix changes. The process itself can be thought of as a black box within which any real chemical or physical process—large or small—can be substituted. In this test bed, UF₆ is replaced by water as the transfer fluid.

The system consists of three feed stations (connected in parallel), two tail stations, and three products stations allowing continuous operations. The capacity of the tanks used at the feed and tails stations is 100 L. The volume of product tanks is 10 L. Tanks are scaled roughly to 1/100th (mass basis) of what would be expected in operating enrichment F&W facilities. This scale allows manipulating tanks in a large laboratory setting and completing feed batches easily within a few hours. Each station is monitored by electronic scales to continuously collect weights at a data concentrator. These station scales are comparable to the plant's process scales used by operators to monitor the F&W processes. Two other electronic scales serve as accountancy scales which, currently, are *not* connected to the local network for automatic data collection. The system currently is located in a laboratory room at ORNL (see Fig. 1; accountancy scales are not shown).

2.1 SYSTEM COMPONENTS

The mock UF₆ F&W system is composed of plastic tanks, pumps, piping, valves and support structures. Each of these is described as follows in more detail. Dimensions and weights are approximate.

Feed and tails tanks—which are interchangeable in the mock F&W system—are nominal 25-gal (100-L), horizontally oriented, cylindrical polyethylene tanks. These tanks measure 16³/₈ in. outside diameter (OD) by 33³/₄ in. long and are fitted with molded “feet” protruding at the bottom near each dished end, and a sump measuring 4¹/₄ in. × 4 in. × ³/₄ in. deep at the middle. Each tank weighs 13 lb (5.9 kg) when empty. A threaded aluminum, hexagonal insert is embedded in the bottom of each foot to accommodate 5/16–18 UNC bolts for securing the tank to a platform or, as shown in Fig. 1, to a lift cradle.

Each feed and tails tank has a 6-in.-OD top opening fitted with a vented screw cap. To retard water evaporation (important where mass balances are involved), the cap remains installed on the opening but has a 1¹/₂-in.-diameter hole drilled into it (off-center to avoid the vent) for accommodating the feed uptake or the tails fill line. The feed uptake and tails fill lines have stopper-like fittings to further close off the opening when the line is in place. Although there is contact between the feed uptake and tails fill lines, the influence on weight measurements is small compared to tank mass and is analogous to plant situations in which cylinders are connected to the process by quick-disconnect fittings at the end of flexible lines.

Lift cradles for the feed and tails tanks are constructed of welded stainless steel. Nominal 2 in. × 4 in. rectangular tubing is used as receivers for lift truck tines to facilitate tank movement. The lift cradles weigh 65 lb (29 kg) each; therefore, when a tank is fitted to a cradle, it yields a package with a tare (empty) weight of about 77 lb (35 kg). When filled, tanks with lift cradles can weigh up to 160 kg (which includes water filled almost to overflowing).



Fig. 1. Mock F&W system showing feed tanks (right, rear), product tanks (left), tails tanks (front, center-right), and process tank (top, center).

Product tanks are 2.5-gal (10-L), 9 $\frac{3}{4}$ -in.-OD, polypropylene carboys with a 3 $\frac{3}{8}$ -in., screw-capped opening at the top. Each product tank, with lid, weighs 2 $\frac{1}{2}$ lb (1.14 kg) when empty. Due to their light weight and to avoid introducing additional measurement errors, it was decided that the product fill lines would not be fitted with stopper-like fittings to retard evaporation since they would alter readings substantially. As a matter of practice, water typically is not stored in product tanks, so evaporation is not a problem. A full product tank can weigh up to approximately 12.5 kg.

The **process (surge) tank** is a nominal 85-gal (322-L) polyethylene, flat-bottom, open-top, cylindrical tank. Its nominal dimensions are 28 in. in diameter and 32 in. high. The tank comes with a flat polyethylene lid (which has a hinged flap) that rests on a ledge, inside a lip at the top of the tank's sidewall. A threaded bulkhead fitting is installed on the sidewall, near the bottom of the tank. The process tank was procured with a steel stand elevating it 36 in. off the floor. Product and tails are withdrawn by gravity flow from the elevated process tank. Currently, the level in the process tank is manually controlled by throttling valves (needle valves) on the product and tails headers, although automatic control is planned.

Diaphragm pumps transfer water from the feed tanks to the process tank in the current configuration. These positive-displacement pumps, one per feed station, have rated discharges at pressures up to 20 psig (1.3 bar), and pumping capacity of 21 gal (80 L) per hour through 3/8-in.-ID tube fittings—although they have demonstrated flow capacities about 20% higher than rated. To facilitate varying run flow rates, the pumps have an overall turndown ratio of 100:1 when both stroke frequency and length are reduced. Wetted surfaces (diaphragms, check valves, etc.) are made of polyvinyl chloride.

Tubing and fittings connect system tanks (and pumps) and form headers, or manifolds, for collecting and distributing flow from/to the parallel-connected tanks. Tubing segments are clear, flexible, ½-in.-ID × ¾-in.-OD tubing connected with a combination of bronze and plastic, 3/8-in. ID, barbed elbows and tees. Thick-walled (1/8 in.) plastic tubing is used to avoid tubes' collapsing on pump suction lines or kinking at any tube bends (although plastic elbows are used in places where sharp bends occur). Tube segments on the discharge side of feed pumps are secured with hose clamps. This tubing configuration facilitates installation of additional future process features and in-line monitoring technologies. A drip flow controller (the type used in intravenous drug delivery) provides flow-rate control for the sample/leak/diversion path on the product header.

Ball valves control flow from and to parallel feed, product, and tails tanks. **Needle valves** (one on each header) control the distribution and flow rate of process withdrawal between product and tails headers.

Framed structures support tubing, valves, pumps, and connections in three segments—one each for feed, product, and tails. The framing is made of T-Slotted Aluminum Extrusions—a modular system of structural members, joining components and fasteners. The feed and product structures are freestanding and are anchored to the concrete floor.

The structure at the feed stations also is anchored to the wall and is designed to support a 300-lb load on the elevated shelf (for planned gravity feed operation) above the feed stations. Heavier loads are allowed for each station when fewer than three elevated feed stations are used. (Only two elevated stations are planned since a fire suppression sprinkler head is near one of the elevated positions and would be imperiled unnecessarily.)

The tails support structure is designed so it can be pivoted readily out of the way (to free floor space when needed). As such, it is supported at one end by the process vessel stand—where it is hinged—and, at the other (outboard) end, by guy wires anchored to the pillar located along the wall, behind the process tank.

2.2 SYSTEM LAYOUT

The mock F&W system occupies much of one wall in the lab, as shown in Fig. 2. The three feed stations (green) and three product stations (yellow) are positioned on either side of a support pillar, while the process tank (red) stands out from the pillar with the two tails stations (blue) extending from the process tank stand, farther into the room. A lift truck, used to manipulate feed and tails tanks, also is depicted (in blue).

Feed and withdrawal have multiple stations to allow continuous operation, as is typical of many process plants. Positive-displacement diaphragm pumps (two of which are depicted in gray above the green feed tanks in Fig. 2; the third pump is mostly hidden behind the red process tank) provide the motive force for transferring fluid from each of the feed tanks into the elevated process tank; gravity is used for withdrawing fluid from the process tank, although its flow is controlled by needle valves, one each for the product and tails headers. A sample/leak/diversion path line also is installed on the product withdrawal header (not evident in the diagram) to test the capabilities of monitoring components for detecting “undeclared” activities or potential process upsets.

Overall system dimensions are given in Fig. 3 and Fig. 4 for plan and elevation views, respectively.

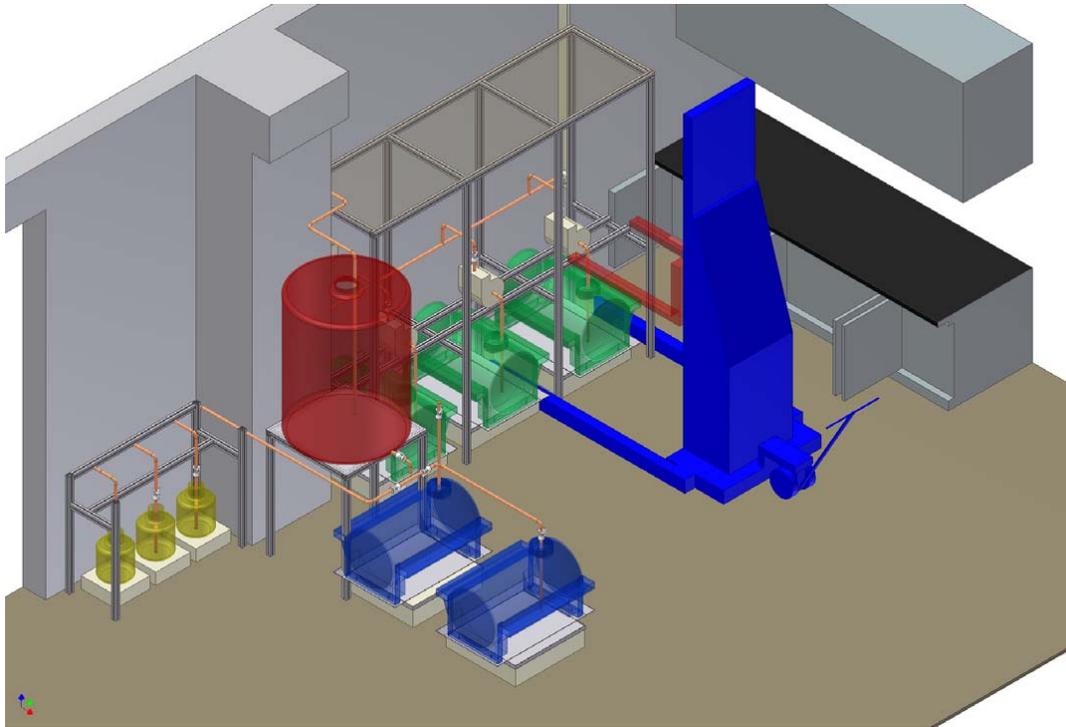


Fig. 2. Color-coded diagram of mock F&W system—with green feed tanks, yellow product tanks, blue tails (or waste) tanks, and a red process tank.

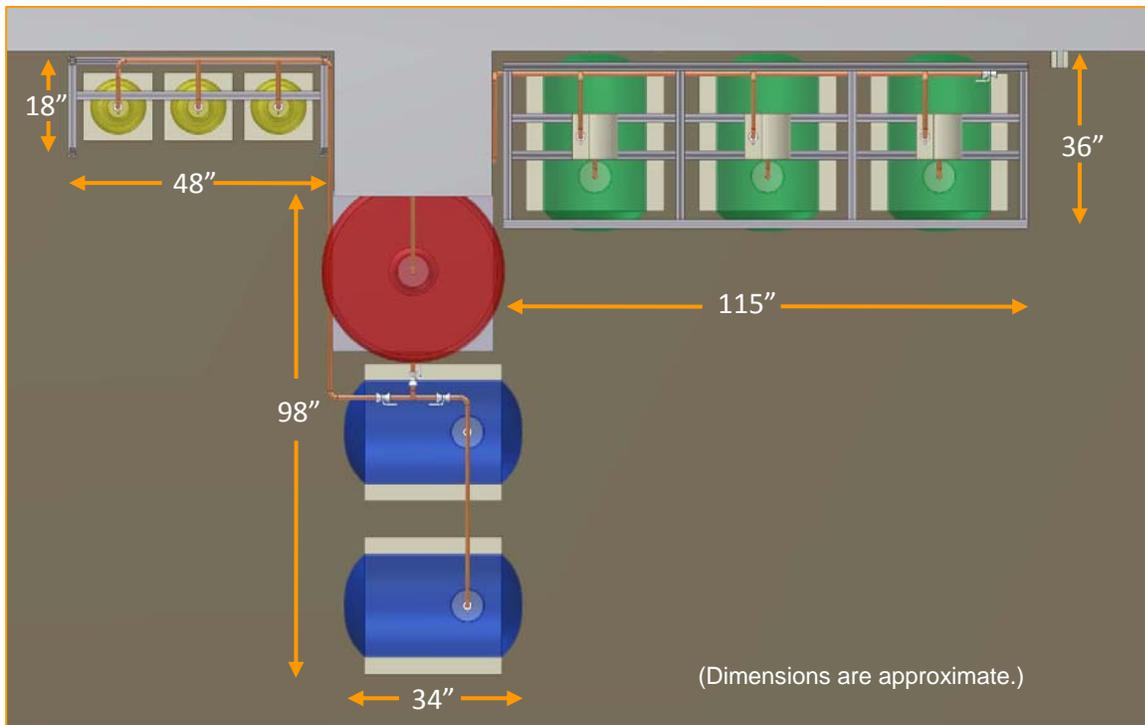


Fig. 3. Plan view of mock F&W system diagram.

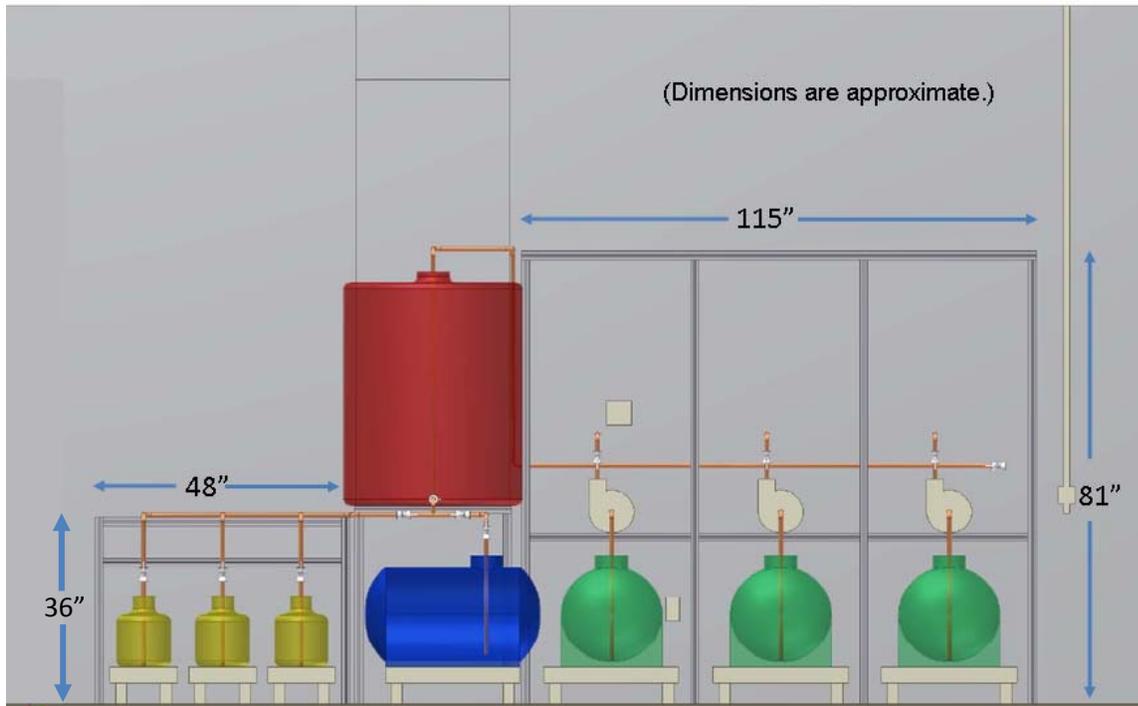


Fig. 4. Elevation view of mock F&W system diagram.

3. MONITORING SYSTEMS

The main focus of this paper is a description of the mock UF₆ F&W system. However, monitoring strategies will be described briefly here since load cells are an integral part of this installation, and the ability to accommodate and test load cells and other monitoring strategies forms the core purpose of the mockup.

For reliability of operation, monitoring software is deployed as a Windows service. Services are designed to run continuously, for long periods—while performing specific functions—without user intervention. Such services can be configured to start when the operating system is booted and run in the background as long as Windows is running, as is done for safeguards monitoring systems.

3.1 DATA COLLECTION SYSTEM ARCHITECTURE

Network architecture has been adopted to connect modular equipment as shown in Fig. 5. This configuration promotes accessibility for diverse sensor and equipment types spread over an industrial site. A network-centric approach allows reliable access to a wide range of useful information—from network cameras and radio frequency (RF) readers to individual sensors—that provides a comprehensive approach to safeguards monitoring.

The long-term plan calls for supporting public key authentication (at the data sources) protocols endorsed by IAEA. Encryption can be added in the future when the system requires remote, unattended monitoring.

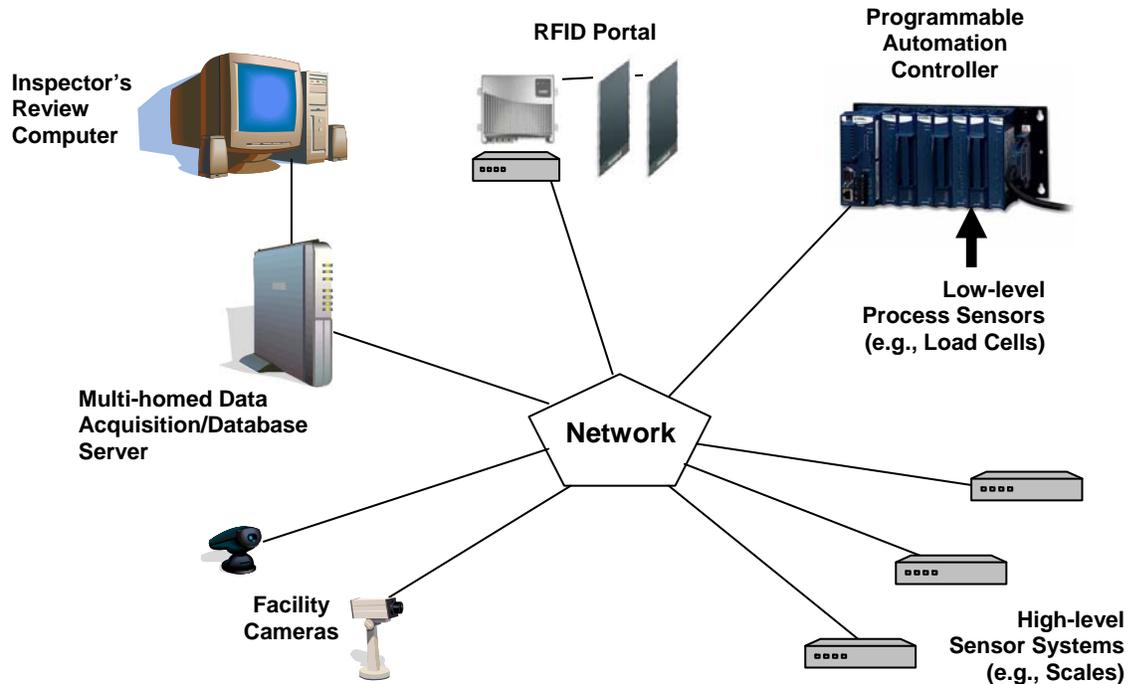


Fig. 5. Data collection system architecture.

3.2 LOAD CELL MONITORING

Process load cells (or digital scales) could provide the basic technology for verifying operator declarations of UF₆ inputs and outputs at enrichment plants since they provide a direct indication of feeds into and withdrawals from the process. Signal authenticity can be inferred by comparing weights from process load cells before and after emptying or filling with values obtained from accountancy scales during pre- and post-process weighing.

The terms load cells and scales are used interchangeably in this report. However, it is recognized that they are different. The most marked difference between the two—from a signal standpoint—is that scales have built-in electronics to provide a digital output directly in weight or mass units, while load cells provide a voltage signal that must be converted by a programmable controller which retains the calibration to the weight or mass range for its intended use.

Digital scales are the mass measurement components for the continuous load cell monitoring (CLCM) system installed on the mock F&W system. Two sizes are used:

- Feed and tails stations (five scales): 250-kg capacity with readability to 0.01kg and
- Product stations (three scales): 25-kg capacity with readability to 0.001kg.

The large (250-kg capacity) scales have platform dimensions (24 in. × 24 in.) that are slightly smaller than the 25-in. span between the “feet” of the feed and tails tanks lifting cradles. Therefore, to accommodate feed and tails tanks—and to promote centered loading of tanks on the scales—the large scales were fitted with a fabricated, stainless steel, centering pan (Fig. 6).

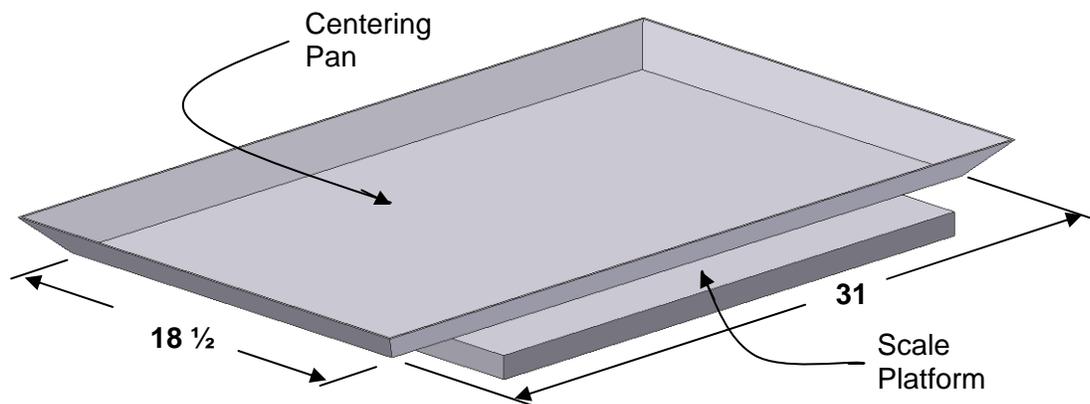


Fig. 6. Centering pan for 250-kg capacity scales.

Two additional scales (one each of the large and small capacities) serve as accountability scales which currently are not networked to the data acquisition computer. Like the feed- and tails-station scales, the large accountability scale also is fitted with a centering pan.

The accountability scales were calibrated to ascertain their accuracy. For both the small-capacity and large-capacity units, the scales were found to be accurate within 0.01% of full scale over the bottom half of their calibration range and within 0.03% of full scale over the top half of their calibration range as delivered from the factory.

The feed-, product- and tails-station scales were not calibrated, but tank measurements on these scales were compared with relevant accountability-scale measurements. Large-scale values taken from monitored feed and tails stations agree with the large-accountability-scale values within 0.15% of full scale, while small-scale values taken from product stations agree with the small accountability scale within 0.1%. The difference in readings between accountability scales and station scales may be attributed to environmental factors (air currents, building vibrations, etc.) in the lab, and due to fluid movements within the tanks (e.g., lack of fluid quiescence after moving a tank, before recording accountability values).

3.3 OTHER MONITORING COMPONENTS

Load cells (or scales) provide the basic technology to continuously verify simulated operations for integrated operations monitoring. Load cells are integrated and tested with additional automated monitoring techniques that, together, provide enhanced assurance that operations remain within declared parameters. Current plans for integrated safeguards operations monitoring include video monitoring, RF-based item tracking, and flow monitoring. Most of these technologies can be added externally to process equipment. These include video cameras, RF tags and antennas, pump power consumption, and laser-based position monitoring. However, flow monitoring must be installed in tubing sections. Other technologies that could be accommodated include fluid density and x-ray fluorescence for concentration monitoring.

A completed assembly of an integrated safeguards operations monitoring system—including instrument interfaces, data concentrators, database software, GUI, and external-to-process data collection equipment—represents a functional industrial prototype that can be, and is being, tested in field trials at an operating plant.

4. BASIC MOCK F&W SYSTEM OPERATION

The basic flow pattern for mock F&W runs is shown in Fig. 7. For simplicity, only one pump is shown as if it serves all three feed stations (whereas each station actually has a dedicated pump for transferring feed).

4.1 RUN DESCRIPTIONS

A typical run proceeds as follows:

1. Operator weighs feed, product, and tails tanks individually on the appropriate accountancy scales and then places on scales at their respective stations.
2. Operator sets valves to allow flow from the designated feed tank to the process tank and, finally, to the designated product and tails tanks.
3. Operator turns on feed pump at the designated station and sets the flow rate as prescribed for the scenario.
4. Operator observes process tank to ensure that the level remains essentially constant—representing a constant holdup. Operator adjusts throttle valves at product and tails headers as needed to maintain holdup constant.
5. When the feed tank is empty, the operator
 - turns off feed (for a single batch run) or
 - switches feed to a different feed tank—including appropriate valve adjustments and pump settings—for an extended, semi-continuous run.
6. Operator switches appropriate valves from full product and/or tails tank to an empty product and/or tails tank as these tanks fill.
7. Operator weighs empty feed tanks and full product and tails tanks individually on their respective accountancy scales.
8. After accountancy weighing, operator switches roles of empty feed tanks so they serve as tails collection tanks; complementarily, full tails collection tanks become feed tanks. Full product tanks are used to make up feed quantities for less-than-full feed tanks, as needed. In such cases, additional accountancy weights are acquired for the manually emptied product tanks and manually replenished feed tanks.
9. Operator turns off pumps, closes valves, and puts lids in place to retard evaporation when the run is completed.

Most of the above steps also include entries into a narrative log, including times, run conditions, accountancy measurements, etc. These steps parallel similar steps that would be conducted in an operating plant procedure to feed or withdraw UF₆ to or from an enrichment process.

Feed flow in the mock F&W system currently is provided by pumps (which are shown above the green feed tanks in Figs. 2, 3, and 4) for the three feed tanks to provide nearly constant flow typical for pumped (or otherwise pressurized) fluid transfer in other processes. (There is a subtle reduction in flow rate—as the contents of feed tanks are pumped—due to increasing pump-suction lift with diminishing tank liquid levels.) Gravity feed, when implemented, will provide a more pronounced diminishing-flow profile that may occur as UF₆ gas cylinders empty. Fluid from the elevated process tank is transferred by gravity to withdrawal lines.

Process withdrawal is split into product and tails headers by a tee at the process outlet. Each header has a needle valve (located immediately after the tee) to control the relative flow rate of the two streams. Typically, withdrawals are controlled to yield 90% or more of tails and 10% or less of product material, by mass. The product header also has a side stream made with small-diameter, thin-walled tubing and a

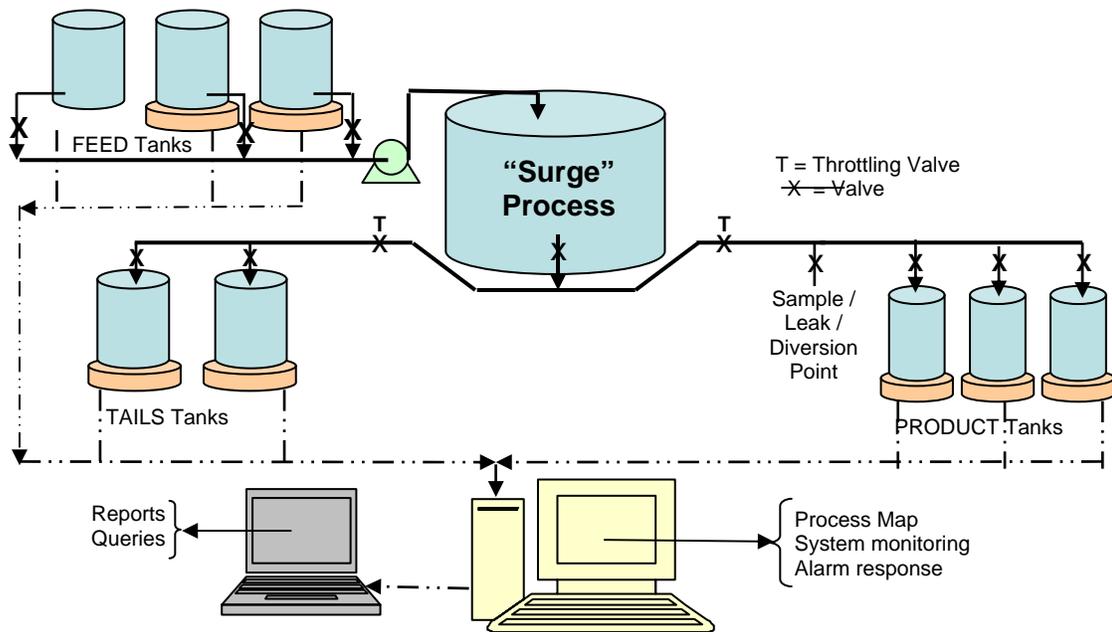


Fig. 7. Process schematic for mock F&W system. [Each tank is shown resting on a dedicated scale (depicted in tan).]

drip flow controller (the kind used for intravenous delivery of medicines) for simulating sampling, a system leak, or a diversion of material.

Although there is no chemical or physical change to the process fluid (water) in our system, the mock F&W system is capable of providing numerous different scenarios depicting real UF₆ F&W operations. In general terms, these scenarios include the following.

- Batch or semi-continuous operations
- Feeds and withdrawals at constant flow rates
- Feeds and withdrawals at varying flow profiles
- Feeds and withdrawals with diversion

5. FUTURE PLANS FOR THE MOCK F&W SYSTEM

In addition to continued operations, plans include some enhancements to the mock F&W system. Several improvements involve installing other safeguards monitoring technologies to work in parallel with CLCM. The following is a list of likely upgrades.

- Automated flow control for process withdrawal to facilitate maintaining constant in-process inventory
- Gravity feed capability
- Pump electric power monitoring
- Radio frequency identification tag monitoring of tanks at individual stations
- In-line flow monitoring

Rules-based event monitoring also is planned for implementation on the mock F&W system. Event monitoring compares monitored sensor indications with defined thresholds to generate events. Generated events represent significant changes to monitored process sensors. Generated events are then compared with other events based on predefined rules that are related by process definitions. This second rules-based comparison filters the significant changes to a subset that should be of greater interest to the independent inspector reviewing the data. Event generation (directly from testing sensor indications) was demonstrated conceptually as part of the bench-scale load-cell monitoring system that preceded the current mock F&W system. Plans also include reinstating event-triggered video camera image capture, which also was demonstrated conceptually as part of event monitoring tests on the bench-top system.¹

6. CONCLUSIONS

The mock F&W system provides a test bed for evaluating and demonstrating the performance of advanced safeguards monitoring components. Because this system uses a simple process, involves no hazardous materials, and is not tethered to an operating industrial process, experiments can be conducted safely, economically, and quickly, thereby yielding meaningful results with a minimum of expenditure and turnaround time.

The system allows screening component usefulness in industrial applications and helps identify issues surrounding industrial implementation. The mock F&W system also facilitates testing methodologies, hardware, and software for integrating multifaceted monitoring technologies into an integrated safeguards operations monitoring system amenable for direct installation in an industrial nuclear material processing facility.

One basic technology, continuous load-cell monitoring, is integral to the mock F&W system and provides a continuous stream of data that has demonstrated its value in verifying operator declarations of inputs and outputs. Network architecture connecting modular equipment and collecting monitoring data has proven to promote accessibility for diverse sensor and equipment types spread over an industrial site.

The ultimate use of technologies successfully tested on the mock F&W system is to install them in operating plants (i.e., uranium enrichment and fuel processing plants) for use by an independent inspectorate such as the IAEA, thereby enabling new safeguards measures with minimal impact on facility operations. Currently (at publication time), continuous load-cell monitoring is undergoing a proof-of-principle field trial at the Portsmouth Gaseous Diffusion Plant (PORTS) X-344 Transfer Facility. This facility is used for transferring UF₆ from one cylinder in an autoclave to another cylinder resting on a roughing scale (monitored by CLCM) for the purpose of consolidating heels or removing trace contaminants (such as ⁹⁹Tc by way of a cold trap, in-line between the two cylinders). Two of the four transfer stations are being monitored at the facility. Another field trial is being conducted using radio-frequency (RF) tracking of cylinders fitted with RF identification tags at the GNF Fuel Fabrication Facility. Software and connective hardware components tested in the lab are being used directly in the field trial at PORTS and GNF. Data collected thus far has already demonstrated a capability to identify operational events and process anomalies.

7. REFERENCES

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