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OPERATING EXPERIENCE WITH A NEAR-REAL-TIME INVENTORY BALANCE IN A NUCLEAR FUEL CYCLE PLANT

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OPERATING EXPERIENCE WITH A NEAR-REAL-TIME LIQUID-VOLUME BALANCE IN A NUCLEAR FUEL CYCLE PLANT

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ABSTRACT

The principal objective of the ORNL Integrated Safeguards Program (ISP) is to provide enhanced material accountability, improved process control, and greater security for nuclear fuel cycle facilities.

With the improved instrumentation and computer interfacing currently installed, the ORNL ^{233}U Pilot Plant has demonstrated capability of a near-real-time liquid-volume balance in both the solvent-extraction and ion-exchange systems.

Future developments should include the near-real-time mass balancing of special nuclear materials as both a static, in-tank summation and a dynamic, in-line determination. In addition, the aspects of site security and physical protection can be incorporated into the computer monitoring.

INTRODUCTION

Safeguards is the system that ensures the protection of a nuclear facility and the materials therein, particularly the special nuclear materials (SNM). The Oak Ridge National Laboratory (ORNL) ^{233}U Pilot Plant safeguards system incorporates three functions: physical security, internal control, and accountability.

As defined within the Pilot Plant, physical security is protection of the site, its boundary, and the facility. Internal control is subdivided into materials control and personnel control. Materials control includes all required direction, regulation, and verification for proper materials storage, movement, and location. Personnel control consists of appropriate authorizations and restraints to permit necessary access and movement of personnel within the site and, as a separate entity, the facility. Accountability applies to all material inventory activities.

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OPERATIONAL HISTORY

Twice during the last twelve years, the ORNL Building 3019 ^{233}U (Radiochemical Processing) Pilot Plant prepared large kilogram quantities of $^{233}UO_x$ for tests in reactors. The operations performed within the Pilot Plant were dissolution, solvent extraction, ion exchange, oxide conversion, and blending. The first time, the customer pelletized our powder and fabricated fuel rods, which provided the entire fissile core for the Shippingport, PA light water breeder reactor. The second time, the Pilot Plant loaded and sealed the powder in special fuel packets for the ANL Zero Power Reactor Experiment.

Over these two operational periods, the inventory difference (ID) and the limit of error on ID (LEID) were both consistently below 0.5%.* This is an unprecedented achievement for a fuel reprocessing facility and was made possible by (1) consistent quality of process materials; (2) limited variations in process conditions; (3) time-shared computer assistance for inventories; (4) nondestructive analysis (NDA) of waste materials (continual gamma spectroscopy over 90 d); (5) accountability by routine shutdown-cleanout inventory; (6) the ability to cease operations when closing the material balance; and (7) the large number of samples taken, larger than normal for a production facility.

CURRENT PROGRAM

The ORNL ^{233}U Pilot Plant Section has developed an R&D program in safeguards because of the national urgency for reduction of the ID/LEID of all facilities that handle SNM. The principal objective of this Integrated Safeguards Program (ISP) is to provide enhanced material accountability, improved process control, and greater security for nuclear fuel cycle facilities by totally integrating all aspects of internal control and physical security into the monitoring and accountability system. Subsidiary objectives include minimizing the ID/LEID, quickly detecting

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*The ID/LEID performance was described in ref. 1.

material diversions, and providing capability for ample warning to the appropriate authorities if process anomalies occur. Capability for limited use denial under abnormal circumstances may also be warranted. All normal operational aspects of ISP must be designed to prevent interference with the management and operators of the facility.

Improved instrumentation, with recently installed computer hardware and software interfaces, currently allows operations performed in the ^{233}U Pilot Plant* to be monitored as an accurate, near-real-time† liquid volume balance in the solvent extraction (SX)‡ and ion exchange (IX) systems. The computer system is dedicated to the task of monitoring both the process and safeguards activities and has the potential to provide for onsite and offsite process and operations monitoring and control by any combination of plant operators, plant management, and inspectors. This type of system would then provide an onsite and/or offsite link to nuclear fuel operations and can be the link between having a full-time resident inspector and enforcing national safeguards.

OPERATIONS

The ^{233}U Pilot Plant computer has been fully operational since February 1980. The system is capable of producing a static, or dynamic, liquid-volume balance in any group of vessels by calculating a net summation of system volumes before, during, and after transfers.

An active, near-real-time, total-liquid volume balance has been maintained by the computer during two SX runs of ~4d each. The computer and associated instrumentation monitor all transfers, and the computer provides alarms when the system volume appears to deviate from expected normal operation. The static and dynamic bulk quantity balancing, including both liquid volumes and solid masses, is calculated for all operational systems and transfers. For accountability purposes, this composite, when complemented by analytical results, is the basis for the ^{233}U Pilot Plant materials inventory.

RESULTS

More than 160 volume balances have been performed in the ^{233}U Pilot Plant process systems between March 1980 and January 1981. Two SX runs lasting a week each were completed, one in July 1980 and one in January 1981.

The volume balance data is summarized and printed out by the ^{233}U Pilot Plant computer. A

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*The Facility-Integrated Computer System (FICS) has been described in refs. 2 and 3.

†Near-real-time is the equivalent of a maximum 15 s to 30 min delay in determining the in-process material inventory and the associated ID and LEID in our facility.

‡The SX system has been described in ref. 1.

dynamic volume balance is a comparison of liquid volume before and during system operations (i.e., while the system is dynamic). A dynamic balance is conducted for all active system vessels within near-real-time. A static volume balance is a comparison of liquid volume before and after single transfers. Both types of printout, from dynamic and static volume balances, contain data in the same format. Table 1 shows the variables calculated by the computer.

Table 2 lists the data obtained from examination of the computer printouts from 166 volume balances. In order to improve the quality of the physical data from the computer, a qualitative (and subjective) analysis of the volume balance results was conducted.

The mean of the 42 in-limit, static, non-jet volume transfers is -0.18σ.* The mean of the 31 in-limit, static, jet transfers is $+0.69\sigma$. It was assumed that the two means and groups of data are from different populations and that their difference of $+0.87\sigma$ is significant. If this is a significant difference between the means, too much volume, on the average, appears in the jet transfer balances; the source of this excess volume is the mathematical addition of 5% dilution to the quantity $v_1 - v_1'$. By mathematically reducing the in-limit, jet-transfer volumes for which at least 25% of the volume-transfer uncertainty can be attributed to dilution† and then equating the jet-transfer mean to that for the nonjet, static-transfer mean, the most probable dilution factor has been calculated to be ~1% with a maximum upper limit of 2%. If this nominal 1% dilution factor is adopted, the following data replace those in Table 2:

Static, with jet transfer

ΔV positive	20 (In)	11 (Out)	31 (Total)
ΔV negative	8	8	16
Totals	28	19	47

These new data more accurately reflect the results from the nonjet, static transfers.

In addition, the true uncertainty on the volume-balance difference $(V - V')$ correlates more closely to 1σ or 68% confidence and not the 2σ or

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*The mean, μ, is calculated from:

$$\mu = \frac{1}{m} \sum_{k=1}^{m} \left[\frac{(V-V')_k \cdot 2}{2\sigma_k} \right]$$

where V, V', and 2σ on $V - V'$ (all in L) are defined in Table 2. In limit means no error message occurred and $2\sigma > V-V'$.

†If the transfer-volume uncertainty is much larger than the estimated volume of dilution, no significant volume difference is noted between 0 and 5% dilution. Thus, enough dilution volume is required for it to be significant when compared with the total volume change.

95% confidence as originally thought. The propagation of error (POE) should give 2σ or a 95% confidence level; however, when the data from all 150 valid volume balances are evaluated, as shown in Table 3, the results show closer correlation with the 1σ/68%-confidence level. (See Fig. 1.)

CONCLUSIONS

Volume uncertainties and differences can be caused by many physical and environmental factors, such as nonlinear changes with differing salt and acid concentration, layering (nonmixing), nonuniformity of ring and other packing in tanks, calibration errors, temperature, and evaporation. Larger volumes tend to have greater uncertainties; and, therefore, these uncertainties tend to dominate the total volume balance uncertainty. Often, these volumes contain very dilute or no SNM (e.g., the liquid waste). Thus, a near-real-time SNM mass inventory must include both flow and concentration (direct elemental and isotopic) measurements. Thus, true SNM quantity, and not volume, is what must be measured and provide for either self-correction or warning of differences caused by physical and environmental factors.

A methodology for dynamic, near-real-time volume balancing has been demonstrated. The volume balance technique requires only information already available for process control.

FUTURE PROGRAM

To obtain a near-real-time SNM-mass-balance materials-inventory capability for the ^{233}U Pilot Plant, more effective analytical instrumentation will have to be installed. For a static system in which no operations are being conducted (except possible single-tank operations, such as mixing), the mass balance could be determined by in-tank analytical instrumentation without extensive analytical sampling. When the system becomes dynamic during material transfers and operations, in-line analytical instrumentation will permit a dynamic, near-real-time mass balance for the entire ^{233}U Pilot Plant.

The basic structure of an integrated safeguards system is envisioned as follows. A network of dedicated microprocessors, each located at a separate instrument measurement or detection point, collects and analyzes all data locally. Individual microprocessors can provide an alarm (signal to some higher level in the monitoring system and/or to personnel) if a process anomaly is detected. Ideally, minicomputers, each of which redundantly monitors all of the microprocessors associated with a specific and preferably independent portion of the process or security, provide the final operational data needed to safeguard materials and the facility. The central computer(s) contain(s) the overall facility information that can provide the management or the enforcement inspectorate with material and facility status, while at the same time provide the facility operators with data for both safe, efficient operation and assurance of high-quality product.

Process monitoring can be accomplished in two modes. First, in the inventory mode, the computational network should provide a total, near-real-time process (SNM) mass balance by adding all the individually measured increments. Thus the inventory, I, is the sum of the various measured masses of material, M_i, with appropriate error limits:

$$I = \sum_{i=1}^{n} M_i \ ,$$

and

$$\sigma^2_I = \sum_{i=1}^{n} \sigma^2_{M_i} \ .$$

Second, in the differential mode the computational network, by concentration on the unit process logic for each part of the process, can provide a much smaller differential uncertainty through redundant and replicate measurements and by more frequent measurements. For example, if a pump is running at rated capacity, flow meters on the inlet and outlet should agree with each other and with the pump capacity. Thus, for a single inventory entry with multiple measurement,

$$\sigma'_{M_i} \text{ (the new uncertainty) } < \sigma_{M_i} \ ,$$

and

$$M_i' = \int_{t_1}^{t_2} \frac{dM_i}{dt} \ ,$$

where

$$dM_i/dt = M_i; \text{ thus}$$

$$\sigma_{M_i}' < \sigma_{M_i}'$$

SUMMARY

The ISP has been developed because of the national urgency for reduction of the ID/LEIDs of all facilities that handle SNM. The results of this program will provide, to both management and inspectors, process material inventories and long-term accountability records. The major design features of ISP are (1) integration of all safeguards aspects into a single monitoring and information system; (2) near-real-time inventory determination; and (3) continual independent monitoring of all the separate smaller and often less diversion-resistant portions of the process and security systems, as well as of the total facility.

We have demonstrated the capability for near-real-time volume balancing in an operational nuclear fuel cycle facility. Since large volume uncertainties exist, conversion of the volume-balance information into an SNM mass balance will be necessary.

ACKNOWLEDGMENTS

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REFERENCES

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Table 1. Volume balance data (as it appears on computer printouts)

Vessel identification	Pretransfer volume	Posttransfer volume	Net transfer out	Transfer method
#1	v_1	v_1'	$v_1 - v_1' \pm 2\sigma$	a
.	.	.	.	
.	.	.	.	
.	.	.	.	
#n	v_n	v_n'	$v_n - v_n' \pm 2\sigma$	
Balance Totals	$\sum_{i=1}^{n} v_i \ (= V)$	$\sum_{i=1}^{n} v_i' \ (= V')$	$V - V' \pm 2\sigma$	b

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[a] Method listed; for steam jet transfer, an asterisk appears and the quantity ($v_i - v_i'$) has 5% added to it as a dilution quantity.

[b] Each volume, as calculated, has an uncertainty (1 σ) attached to it. The 2σ or 95% confidence levels are printed out in the column entitled "net transfer out." If the absolute value of ($V - V'$) is greater than the 95% confidence level (2σ), an error message appears under the quantity totals.

Table 2. Results from volume balance computer printouts

Group	Number (% of total)
Dynamic volume balance[a]	
In-limits, ΔV positive	11 (6.6)
ΔV negative	17 (10.2)
Out-of-limits, ΔV positive	0 (0.0)
ΔV negative	6 (3.6)
Static volume balance, jet transfers	
In-limits, ΔV positive	24 (14.5)
ΔV negative	7 (4.2)
Out-of-limits, ΔV positive	12 (7.2)
ΔV negative	4 (2.4)
Static volume balance, other (than jet) transfers	
In-limits, ΔV positive	21 (12.7)
ΔV negative	21 (12.7)
Out-of-limits, ΔV positive	16 (9.6)
ΔV negative	11 (6.6)
Unusable (singularities[b])	16[c] (9.6)
Total	166 (100.)

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[a] All dynamic volume balances have at least one jet transfer. All dynamic balances contain at least one resolvable singularity.

[b] Singularities include: numbers larger than allowed for the printer field (asterisks appear instead of a number); no net volume transfer (all ΔVs = 0; usually resolved); tank heel value undefined (v_i and/or v_i' exactly 0.00; usually resolved); etc. Unusable results contain one or more unresolvable singularities.

[c] The 16 unusable printouts include 6 'no-transfer' balances not included in the statistical analyses.

Table 3. Volume-balance distributions

In-limit range selected (in σ)[a]	Fraction of volume balances within range[b]				Calculated value[b]	Expected values[c]	
	D	S	J	T	T	1σ	2σ
−0.25 to +0.25	6/34	26/69	2/47	34/150	0.227 ± 0.039	0.100	0.197
−0.50 to +0.50	11/34	28/69	4/47	43/150	0.287 ± 0.044	0.197	0.383
−1.0 to +1.0	16/34	35/69	12/47	63/150	0.420 ± 0.053	0.383	0.683
−1.5 to +1.5	27/34	39/69	26/47	92/150	0.613 ± 0.064	0.547	0.866
−2.0 to +2.0	28/34	42/69	31/47	101/150	0.673 ± 0.067	0.683	0.955

[a] The volume-balance results have been calculated by:

$$\text{Difference (in } \sigma \text{ units)} = \frac{V - V'(\Delta V, \text{in L})}{2\sigma \text{ value (in L)}} \times 2 .$$

[b] Fractions for grouped ranges are number within range as numerator and total number of that group as denominator. D is dynamic; S is no-jet, static; J is jet, static; and T is total, also expressed as decimal equivalent in calculated value. J is unadjusted for new dilution factor (results when adjusted are within error band). Error band is equivalent to $\pm\sqrt{n}$; i.e. T for −0.25 to +0.25 is $(34 \pm \sqrt{34})/150$.

[c] Expected values are for POE results for 2σ (95% confidence level) and 1σ (68% confidence level).

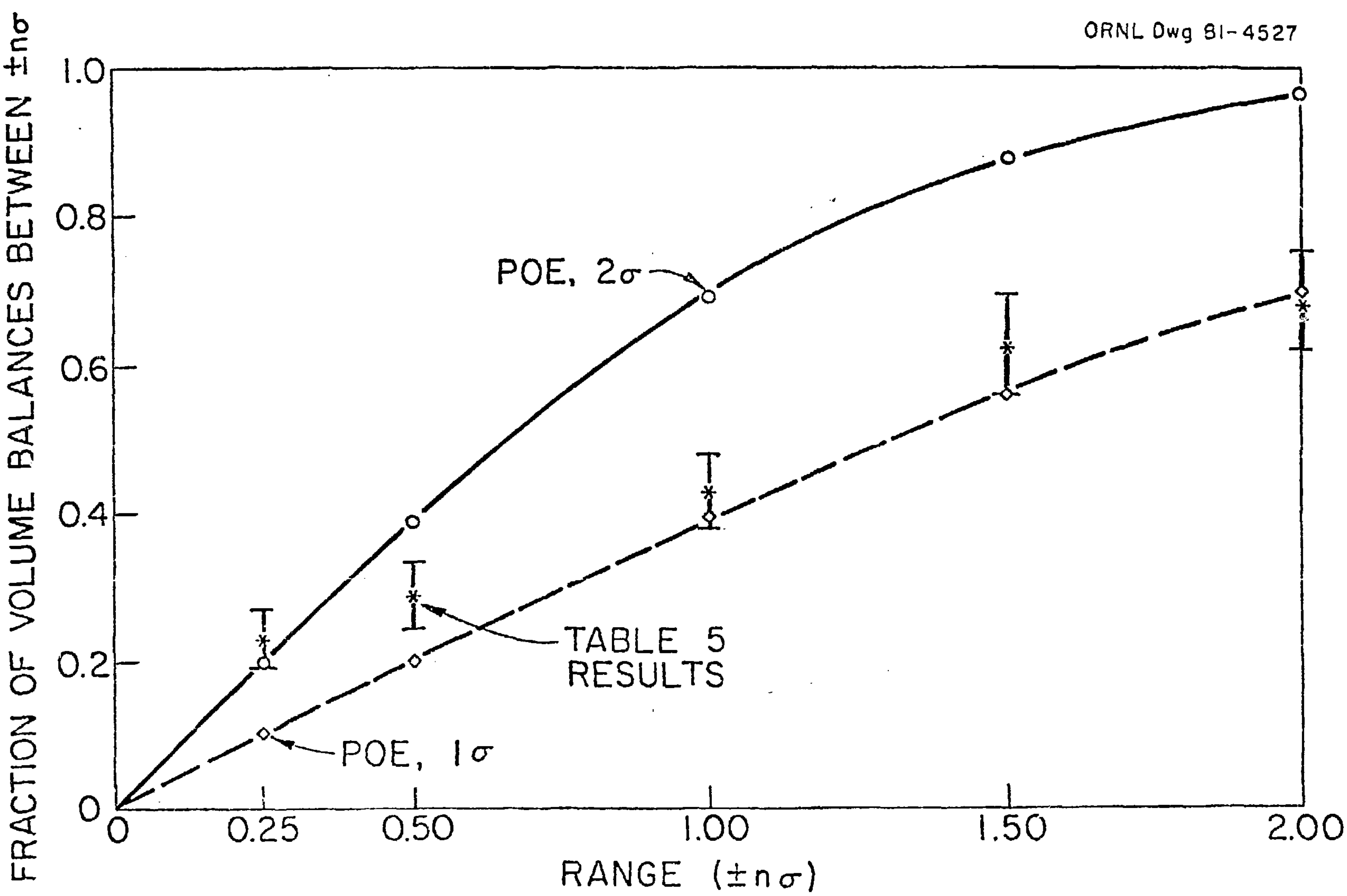

Fig. 1. Volume Balance Probabilities