Cost/Benefit Prioritization for Advanced Safeguards Research and Development

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Abstract – *A system level study utilizing commercially available Extend^{TM} software, has been initiated to perform cost/benefit analyses for advanced safeguards research and development. The methodology is focused on estimating standard error in the inventory difference (SEID) for reprocessing and fuel fabrication facilities, for various proposed advanced safeguards measurement technologies. The inventory duration, and consequent number of inventories per year, is dictated by the detection of a significant quantity of special nuclear material (SNM). Detection is limited by the cumulative measurement uncertainty for the entire system. The cost of inventories is then compared with the cost of advanced instrumentation and/or process design changes. Current progress includes development of the methodology, future efforts will be focused on ascertaining estimated costs and performance. Case studies will be provided as examples of the methodology.*

INTRODUCTION

The Global Nuclear Energy Partnership (GNEP) is a cooperation of those States that share the common vision of the necessity of the expansion of nuclear energy for peaceful purposes worldwide in a safe and secure manner. It aims to accelerate development and deployment of advanced fuel cycle technologies to encourage clean development and prosperity worldwide, improve the environment, and reduce the risk of nuclear proliferation.[1] The primary pillars of the GNEP program are shown in Figure 1 to be (1) proliferation resistant recycling that avoids pure plutonium product, (2) advanced burner reactors (ABRs) to efficiently transmutate long-lived waste, (3) reliable fuel services to reduce the expansion of uranium enrichment, and (4) advanced safeguards technologies to increase reliability of monitoring and verification.

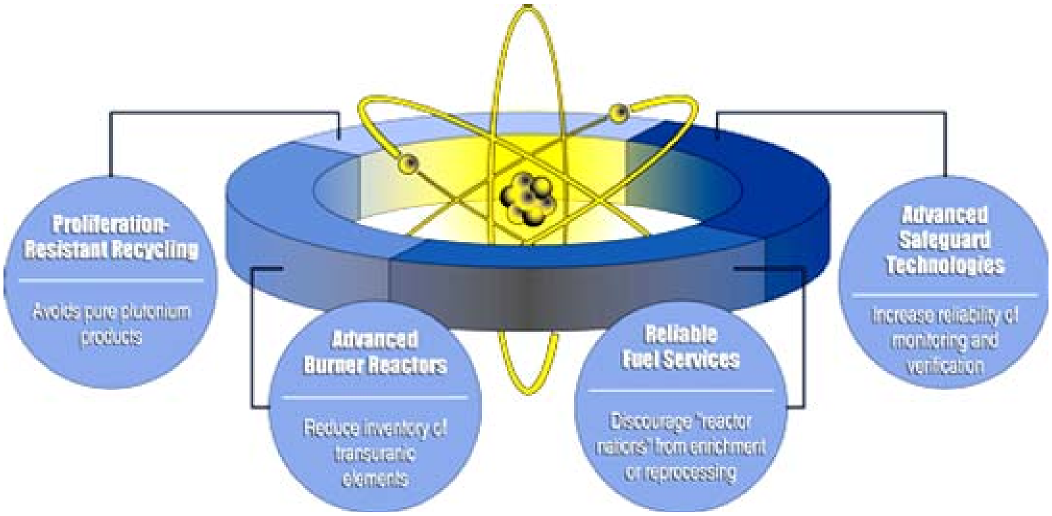

Fig. 1. Pillars of the Global Nuclear Energy Partnership (GNEP).[1]

As part of the Global Nuclear Energy Partnership (GNEP) the United States has begun to design a reprocessing and fuel fabrication research and development (R&D) facility to support spent fuel transmutation and power production by way of fast reactors. The reprocessing and fuel fabrication R&D facility is referred to as the Advanced Fuel Cycle Facility (AFCF) and the reactor is the Advanced Burner Reactor (ABR).

The closed fuel cycle supported by the AFCF and ABR will serve two primary purposes (1) reduce the underground waste repository (or repositories) size and engineered barrier requirements, and (2) recycle more proliferation resistant fuel than the existing plutonium mixed oxide (MOX) fuel cycle. Figure 2 represents the AFCF/ABR closed fuel cycle.

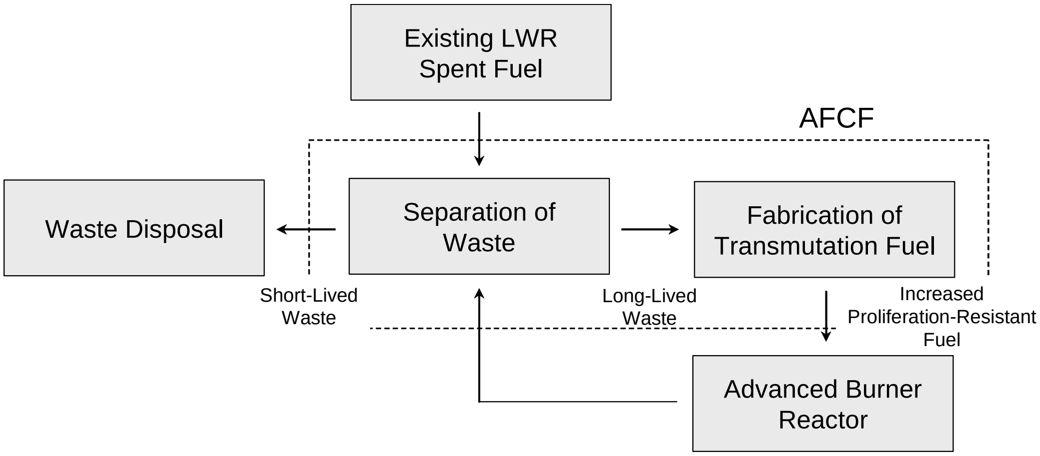

Figure 2. The AFCF and ABR closed fuel cycle.

In support of GNEP and a closed nuclear fuel cycle, advanced safeguards cost/benefit studies have begun to aid prioritization of research and development (R&D) activities. However, in order to identify these R&D activities, knowledge of the safeguards requirements is necessary. The governing agencies for which the requirements exist are both domestic and international. Figure 3 attempts to broadly summarize these requirements.[2] It is the Interim Accountancy requirement that is the focus of this cost/benefit study.

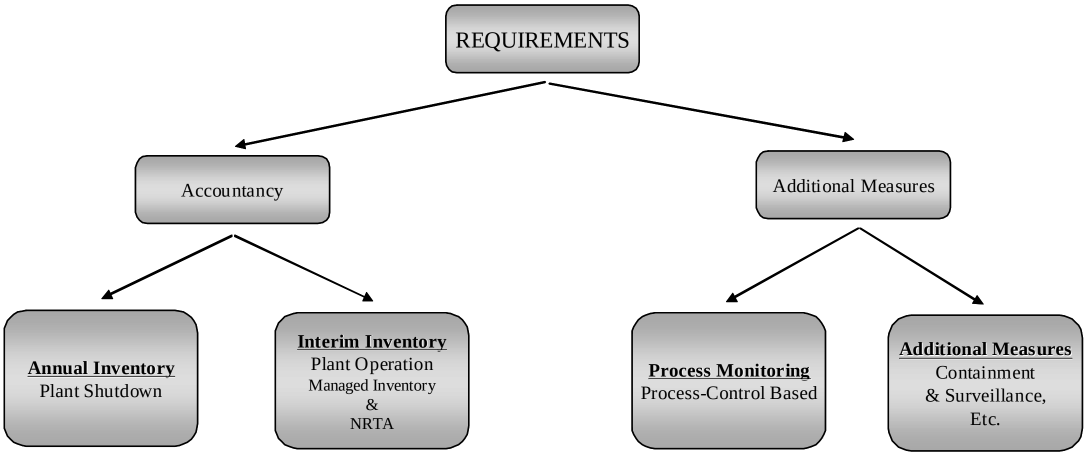

Figure 3. Safeguards requirements.

Accountancy requirements for nuclear facilities are usually related to diversion detection of a significant quantity of nuclear material. When the statistics of measurement uncertainty are considered, such as detection of a significant quantity of material at high confidence, accountancy goals for large throughput facilities become nearly impossible to achieve. For this reason a cost/benefit methodology for prioritizing advanced safeguards R&D, based on modelling of the Standard Error in the Inventory Difference (SEID) for Interim Inventory measurement, is proposed and discussed here. A cost/benefit analysis is particularly important for the case of Interim Inventory because unrestrained efforts to increase detectability could make instrument and operation costs impractical. The use of advanced safeguards will only be embraced if the additional expense can be justified in view of the overall cost of energy production.

METHODOLOGY

Extend^{TM} simulation software was used to model PUREX and UREX reprocessing for demonstration of the cost/benefit methodology.[3] An 800-MTHM/yr facility was used for the baseline simulation with measurement uncertainties based on nominal values for a PUREX type process as reported by ESARDA, see Table 1.[4]

Table 1. Assumed systematic and random measurement uncertainties for PUREX and UREX.

	% Error at 1-Standard Deviation				Inventory	Co-variance
	$\sigma_{s,c}$	$\sigma_{s,m}$	$\sigma_{r,c}$	$\sigma_{r,m}$		
Feed	0.20	0.20	0.30	0.30		Product
Product	0.20	0.05	0.20	0.05		Feed
Waste	0.20	0.05	0.40	0.10		
Process tanks	n/a	n/a	0.30	0.45	90%	
Process non-tanks	n/a	n/a	1.00	1.00	10%	

The basis for the cost/benefit study is the standard error in the difference (SEID) for the Interim Inventory measurement. The individual measurement uncertainty can be approximated as the square-root of the variance for systematic error, and the square-root of the variance divided by the number of measurements for the random error. Equation 1 represents an individual measurement uncertainty, based on systematic and random error, for concentration and mass. Measurement uncertainty for the entire process is then represented by the cumulative uncertainty, or more specifically the SEID, which was estimated as the sum-of-the-squares of all individual measurements for demonstration of the methodology.

$$\sigma^{2}{}_{\text{individual}} \approx \sigma^{2}_{\text{s,c}} + \sigma^{2}_{\text{s,m}} + \frac{\left(\sigma^{2}_{\text{r,c}} + \sigma^{2}_{\text{r,m}}\right)}{\text{n}} \qquad (1)$$

To date, this study has been focused only on demonstrating methodology, with specific cost/benefit values remaining for the future. Examples of effects on cost follow:

1) R&D activities
2) Operations
    a. Inventory management
    b. Sampling
    c. Laboratory analyses
3) Instruments/ equipment
4) Inspection labor

RESULTS

For the Interim Inventory plant shutdown is not practical; however, the process inventory is managed such that approximately 90% exists in only a few tanks where inventory is more easily measured. Only plutonium accountancy has been considered for this initial study; however, it is recognized that with the use of transmutation fuels minor actinides such as americium and neptunium may need to be included. Several scenarios have been considered for demonstration of the cost/benefit methodology:

1) PUREX versus UREX
2) Automation of DA for the feed and process inventory in the process cell
3) Replacement of DA for the product with NDA

PUREX versus UREX

Interim Inventory measurement for PUREX and UREX should not differ significantly for the feed since the material is similar (dissolved spent fuel). The product material will differ in that minor actinides such as Am, Cm and Np may be present; however, it is assumed DA is the baseline for both PUREX and UREX where Pu is separated in the laboratory prior to measurement. Consequently, for this study it is assumed product measurement uncertainty does not differ for PUREX and UREX. Accountancy of the minor actinides has not been considered for this evaluation. The cost of product measurement will differ due to more complex sample preparation. What will differ between PUREX and UREX is the process inventory. Since UREX has more separation steps, additional feed tanks and respective process hold-up will be required. For this study it has been assumed UREX requires 25% additional process inventory. Figure 5 shows estimated Interim Inventory measurement performance for PUREX and UREX. The y-axis represents 3.3 times the SEID, where the SEID is based on individual measurement uncertainties at one standard deviation, and then 3.3xSEID represents high confidence as defined by the International Atomic Energy Agency (IAEA).

As shown in Figure 4 for the PUREX process, if the period between Interim Inventory measurements is greater than approximately 17-days, the loss of a significant quantity of Pu (8-kg) can not be detected with high confidence. For UREX, if the period between Interim Inventory measurements is greater than approximately 7-days, the loss of a significant quantity of Pu can not be detected with high confidence.

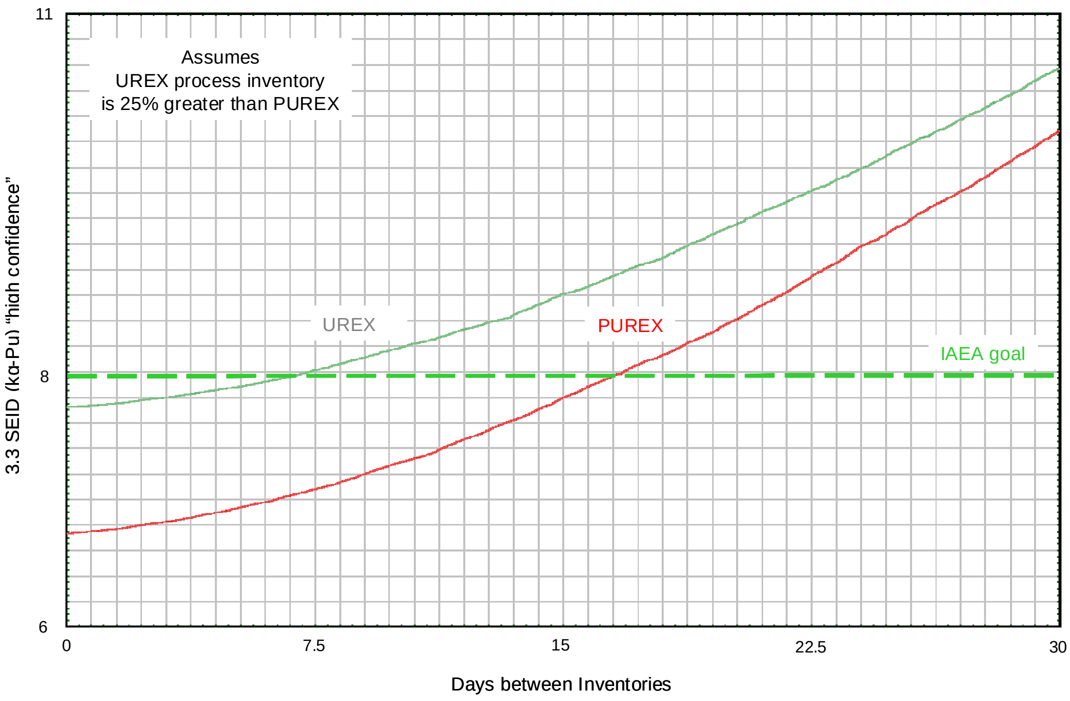

Figure 4. Interim SEID for 800-MTHM/yr PUREX and UREX.

Automation of Feed DA and NDA of Product for UREX

For this scenario laboratory DA of the feed inventory tank is replaced with automated DA in the process cell. For this case it is assumed mass measurement based on tank level does not differ; however, the concentration measurement does.

It is assumed that both the random and systematic errors are twice as great for the process cell automation. This is due to the requirement for more robust instrumentation and more difficult calibrations. NDA measurement uncertainty for the product rather than laboratory DA is assumed similar for mass, but five times greater for NDA. Current NDA techniques typically have a measurement uncertainty ten times greater than DA; therefore, it is assumed five times greater is advanced technology. Additionally, typical PUREX feed and product inventory DA measurements are done with similar instruments following product dissolution. This leads to a covariance and elimination of the systematic error. This will not be the case if NDA is used for the product. Table 2 summarizes these differences.

Table 2. Assumed UREX measurement uncertainties for Feed DA automation and Product NDA.

	$\sigma_{s,c}$ (%)	$\sigma_{s,m}$ (%)	$\sigma_{r,c}$ (%)	$\sigma_{r,m}$ (%)	Inventory	Co-variance
BASELINE						
Feed	0.20	0.20	0.30	0.30		Product
Product	0.20	0.05	0.20	0.05		Feed
Waste	0.20	0.05	0.40	0.10		
Process tanks	n/a	n/a	0.30	0.45	90% total	
Process non-tanks	n/a	n/a	1.00	1.00	10% total	
FEED DA AUTOMATION						
Feed	0.40	0.20	0.60	0.30		No
PRODUCT NDA						
Product	1.00	0.05	1.00	0.05		No

As shown in Figure 5 for the baseline UREX process, if the period between Interim Inventory measurements is greater than approximately 7-days, the loss of a significant quantity of Pu (8-kg) can not be detected with high confidence. If laboratory DA of the feed is replaced with automated DA in the process cell, a period between Interim Inventory measurements greater than approximately 3-days will not permit detection of the loss of a significant quantity of Pu with high confidence. If laboratory DA of the product is replaced with NDA, a period between Interim Inventory measurements greater than 1-2 days will not permit detection of the loss of a significant quantity of Pu with high confidence.

Replacement of Laboratory DA with Automated DA for Process Inventory

For this scenario laboratory DA of both the feed inventory tank and process inventory tanks is replaced with automated DA in the process cell. For this case it is assumed mass measurement based on tank level does not differ; however, the concentration measurement does. It is assumed the both the random and systematic errors are twice as great for the process cell automation. This is due to the requirement for more robust instrumentation and more difficult calibrations. However, when using automated DA for process inventory the hold-up is not dictated by laboratory turn-around time. Therefore, it is assumed the process inventory is 50% less with automated in-cell DA. Table 3 summarizes these differences.

As shown in Figure 6 for the baseline UREX process, if the period between Interim Inventory measurements is greater than approximately 7-days, the loss of a significant quantity of Pu (8-kg) can not be detected with high confidence. If laboratory DA of the feed is replaced with automated DA in the process cell, a period between Interim Inventory measurements greater than approximately 3-days will not permit detection of the loss of a significant quantity of Pu with high confidence. However, if laboratory DA of both the feed inventory and process inventory tanks is replaced with automated DA in the process cell, a period between Interim Inventory measurements up to approximately 17-days will permit detection of the loss of a significant quantity of Pu with high confidence.

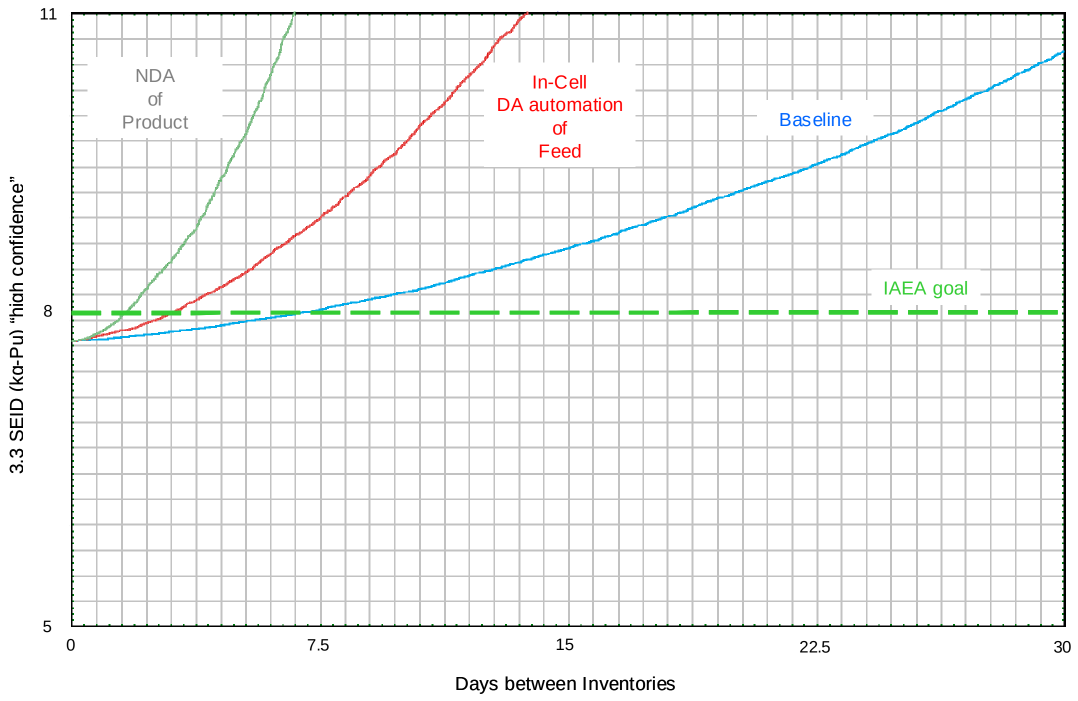

Figure 5. Interim UREX SEID for Feed DA automation and Product NDA.

Table 3. Assumed UREX measurement uncertainties for Feed DA automation with 50% process inventory reduction.

	$\sigma_{s,c}$ (%)	$\sigma_{s,m}$ (%)	$\sigma_{r,c}$ (%)	$\sigma_{\rho,m}$ (%)	Inventory (kg-Pu)	Co-variance
BASELINE						
Feed	0.20	0.20	0.30	0.30		Product
Product	0.20	0.05	0.20	0.05		Feed
Waste	0.20	0.05	0.40	0.10		
Process tanks	n/a	n/a	0.30	0.45	0.9(800)	
Process non-tanks	n/a	n/a	1.00	1.00	0.1(800)	
FEED DA AUTOMATION						
Feed	0.40	0.20	0.60	0.30		No
Process tanks	n/a	n/a	0.60	0.45	0.9(1000)	
Process non-tanks	n/a	n/a	1.00	1.00	0.1(1000)	

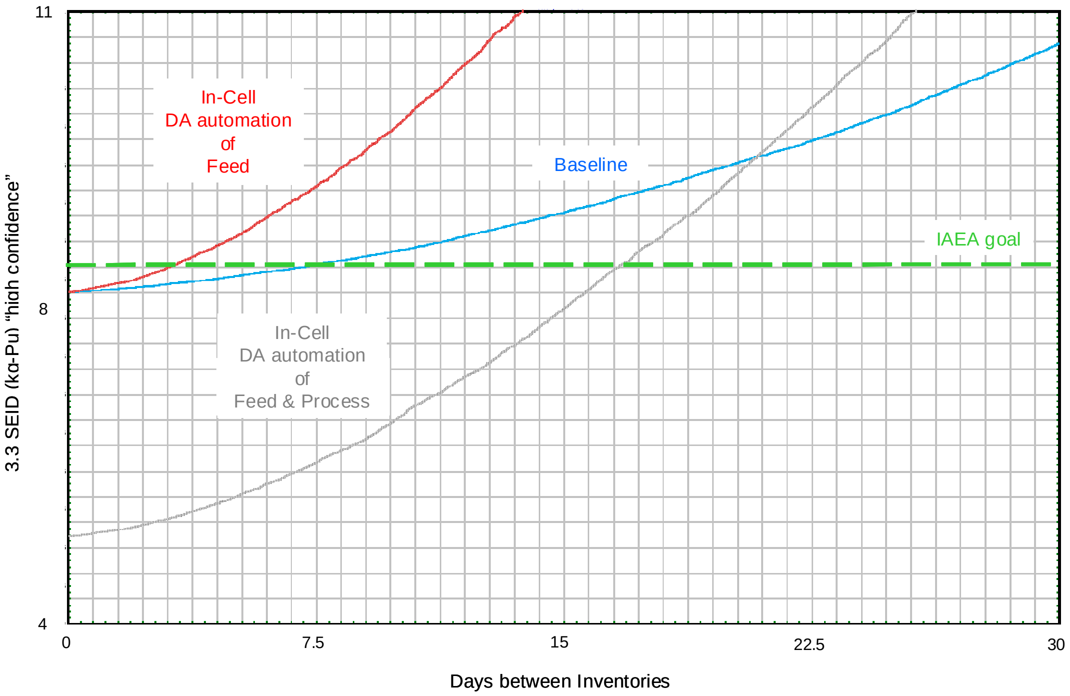

Figure 6. Interim UREX SEID for Feed DA automation and Process inventory.

CONCLUSIONS

PUREX versus UREX

As shown in Figure 4, due to the increased process inventory for UREX, meeting the IAEA goal for Interim Inventory measurement will be significantly more difficult than for PUREX. This increased difficulty may result in the requirement for more frequent inventory measurements or increased additional measures such as process monitoring and/or containment and surveillance, which will increase cost. Since the process inventory is dictated to a large degree by the measurement sampling and analysis turnaround time, it will be critical to reduce this time for advanced safeguards.

Automation of DA for the Feed and Process Inventory in the Process Cell

As shown in Figure 5 and 6, while the use of automated DA in the process cell for feed inventory measurement will significantly reduce laboratory DA cost, the negative impact on Interim Inventory period is significant.

However, if both feed and process inventory measurements are replaced with automated DA in the process cell so that process inventory can be reduced, the increase in Interim Inventory period is significant.

Replacement of DA for the Product with NDA

As shown by Figure 5, while the use of NDA in the process cell for product inventory measurement will significantly reduce laboratory DA cost, the reduced Interim Inventory period is dramatic. Although a full cost/benefit analysis has not yet been completed, it is likely that advanced NDA measurement uncertainty for the product will need to be less than assumed in this study (NDA=5xDA).

Future Work

This study was intended to demonstrate only the cost/benefit methodology; whereas, actual costs savings for specific instrumentation is left as a follow-on activity. Costs including both the monitoring agency and facility operations need to be included. Performance data for advanced instrumentation will need to be estimated based upon preliminary modelling and bench-scale testing. While collection of initial data will be difficult, experience will simplify the effort with time.

NOMENCLATURE

n = number of measurements during the inventory period
n/a = not applicable
SEID = cumulative measurement uncertainty for inventory difference at one standard deviation
$\sigma_{s,c}$ = systematic measurement uncertainty for the concentration at one standard deviation
$\sigma_{s,m}$ = systematic measurement uncertainty for the mass at one standard deviation
$\sigma_{r,c}$ = random measurement uncertainty for the concentration at one standard deviation
$\sigma_{r,m}$ = random measurement uncertainty for the mass at one standard deviation

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