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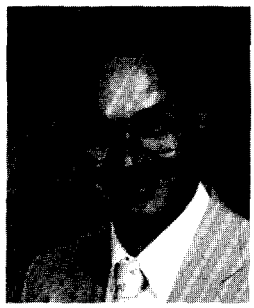

In an article that appeared about a year ago in the American Nuclear Society's *Nuclear News* (June 1991), James F. Malley pointed out that the development of national consensus standards is one of American National Standards Institute's (ANSI) best-kept secrets. As secretariat of Standards Committee N14 on Packaging and Transportation of Radioactive Materials and Standards Committee N15 on Methods of Nuclear Material Control, INMM also is a major developer of ANSI standards and guides — and we have been keeping the same secret. I would like to use this column to tell you all about the development of ANSI standards and the important — but largely unrecognized — work that more than 100 of our members and associates do in this area.

I use the term "ANSI standard," although, strictly speaking, there is no such thing as an ANSI standard, because ANSI neither develops nor sponsors any of the effort necessary to develop a standard. The organization establishes the procedures for developing standards, approves the topics for new standards and arranges for the approval and publication of the final standard.

An ANSI standard developed by the INMM generally establishes requirements for the construction, performance or use of instrumentation or approved practices and procedures in some area of interest to the members of the Institute. An old example that I participated in was ANSI N-15.20-1975, the American National Standard Guide to Calibrating Nondestructive Assay Systems. The requirements contained in the ANSI standard become "law" only when an organization chooses to invoke them, or when a regulating agency formally endorses the standard. For example, several of our standards have been endorsed by the U.S. Department of Energy in its orders.

Standards are usually developed by a small working group of experts in the subject, reviewed by a larger subcommittee for technical accuracy and eventually approved, by formal ballot, by a consensus committee comprising representatives from all elements of the interested/affected community — technology developers, users, regulators and the regulated. The process takes a long time, usually years. Throughout, it is overseen by ANSI and results in a standard practice that is truly a consensus.

John Arendt is chair of N14, and Sharon Jacobsen is chair of N15. I urge you to seek them out, find out what standards are being developed in your area of interest and become involved. Or at least, contact them and thank them. And thanks also to all of you who already are involved for your many, many hours of quiet, professional effort on behalf of INMM and ANSI.

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Complying with international standards

The article on Swedish experience in implementing national and international safeguards was presented at the INMM Annual Meeting in New Orleans last year, but was inadvertently omitted from the Proceedings. This article should be of considerable interest to those who define and those who must comply with national and international safeguards requirements. The paper describes the Swedish system for control of and accounting for nuclear materials and the Swedish program to provide assistance to the International Atomic Energy Agency (IAEA).

The European Safeguards Research and Development Association has published its information on how accurate nuclear material measurements should be, data which the IAEA uses as a guide to the accuracy that should be expected at nuclear processing facilities. Wanda Mitchell, of the U.S. Department of Energy's analytical standards laboratory, describes the measurement goals which the Department of Energy has tentatively adopted and the actual accuracies attained at the major government-owned nuclear facilities. Since many of these facilities have been involved in developing and improving the measurements for nearly 50 years, high-quality results are to be expected. On the other hand, because of the wide variety of the nuclear materials involved, the accuracies achieved are impressive.

The Los Alamos safeguards group has long been involved in the development and application of neutron nondestructive measurement instruments, as well as other NDA instruments and safeguards systems. In this issue, Howard Menlove describes an impressive instrument to measure very small quantities of plutonium in 200-liter drums. The instrument and its performance are clearly described as well as the use of an added source to characterize the other materials which may be in the drum and measures to reduce the background due to cosmic rays. Whether or not others may wish to duplicate the instrument, many of the techniques employed should be useful for different applications.

Finally, Jonathan Sanborn presents an analysis of randomized and periodic inspection approaches regarding timeliness and probability of detection, with reference to other papers which have recently been published in this general area. Since I lost a bet with him not long ago, I have decided to let others comment on this if they should disagree with his conclusions or consider that they have a better analysis to propose.

With your help, we can continue to increase the quality and the scope of the technical articles in your *Journal.*

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Adventures of three mathematicians

Adventures of a Mathematician
S. M. Ulam
University of California Press:
Berkeley, California, 1991.

Prisoner's Dilemma
William Poundstone
Doubleday: New York, New York, 1992.

The Road from Los Alamos
Hans A. Bethe
American Institute of Physics:
New York, New York, 1991.

It is now almost half a century since the first members of what was to be the most distinguished team of scientists ever to work together toward one common goal began to arrive at a former boys school on a remote mesa top overlooking the Rio Grande Valley in New Mexico. Their design and development of three successful nuclear devices in the short span of three years will long be regarded as an astonishing achievement. This accomplishment, together with the development of the fundamental principles of thermonuclear weapons at Los Alamos by 1951 and the building of intercontinental ballistic missiles, have forever shaped the strategic balance among the nations of the world. In a real sense, everything that has taken place in the development of strategic weapons during the last four decades may be regarded as a sequel to those early events.

As yet, only a few memoirs or biographical accounts have been written by or about the members of the remarkable scientific team that worked at Los Alamos during the war years. In this regard, one must cite Laura Fermi's book *Atoms in the Family* and the closely related work by Emilio Segre, *Enrico Fermi, Physicist*. Recently, three books have appeared in this area which are well worth the reader's time. These are *Adventures of a Mathematician* by Stanislaw Ulam (a new edition of a book first published in 1976 and revised in 1983), *Prisoner's Dilemma* by William Poundstone and *The Road from Los Alamos* by Hans Bethe.

The first of these, *Adventures of a Mathematician*, is the personal odyssey of the gifted mathematician Stanislaw Ulam, who had a long and close association with Los Alamos. As is the case with many people, his life was segmented into a number of well-defined chapters. Born in 1909 into a prominent and well-to-do Jewish family in Lwow, Poland, his interest in, and talent for, mathematics was evident at an early age. Like many other individuals who later excelled in pure science, he was first persuaded by his family, who foresaw few opportunities in academic life, to take a more practical course and apply for admission as an electrical engineering student at the Lwow Polytechnic Institute. Since the quota for electrical engineering students was already full, he actually enrolled in the Department of General Studies. He immediately became totally absorbed in mathematics and never returned to electrical engineering. In his book, he describes this as, "not so much that I was doing mathematics but that mathematics had taken possession of me." At that time, the cities of Lwow, Cracow and Warsaw were each home to a distinguished and lively school of mathematicians, part of a rich cultural and intellectual tradition in Poland that is little known or appreciated in the English-speaking countries, with roots stretching back to the Renaissance. The Lwow school was noted for its informality, with many of its important results derived from discussions among its members, not carried out in offices or classrooms but in favorite cafes and coffee houses, especially the famous Scottish Cafe. In this milieu, Ulam soon established his reputation, becoming sufficiently well-known at the age of 23 to be invited to speak at a congress in Zurich. He won his doctorate at the age of 24, but there were no prospects of a university position in Poland.

After a brief stay at Cambridge University, in England, an event occurred which profoundly affected the course of his life, and in fact, may well have saved him and his younger brother, Adam, from extermination at the hands of the Nazis. In 1935, John von Neumann, who had met Ulam earlier in Europe and recognized his talents, arranged for an appointment for him at the Institute for Advanced Study at Princeton. Von Neumann was one of three friends and colleagues who had a profound influence on Ulam, the others being Stefan Banach, one of the most famous members of the Lwow school, and Enrico Fermi. His stay at Princeton (1935-36) was followed by two other academic appointments, in the Harvard University Society of Fellows (1936-41) and at the University of Wisconsin (1941-43).

The next chapter in his life began in 1943, when von Neumann, who was already working at Los Alamos, arranged for Ulam to join the effort there. There he was assigned to work with Edward Teller on theoretical calculations to determine the feasibility of the thermonuclear "super" which Teller was already vigorously promoting. These studies and other studies on neutron multiplication occupied his time until 1945.

After a brief sojourn in Southern California as a faculty member of the University of Southern California, a period that was marred by a particularly dangerous illness, probably encephalitis, he returned to Los Alamos in 1946, to remain there until his retirement in 1967. At Los Alamos he again returned

to work on the "super." With C.J. Everett, a colleague from earlier days at Madison, he carried out theoretical studies to determine the feasibility of the configuration for the "super" that had been proposed by Teller. By early 1951, they had demonstrated the impracticality of that approach. It was then, in February 1951, that he conceived, in a flash of insight, a configuration for a thermonuclear device based on a radically new principle. Teller, when Ulam approached him with this idea, proposed a related alternative which has become the standard approach for all subsequent designs for those devices. In less than two years, the practicality of this approach was demonstrated in the successful test of the "Mike" device at Eniwetok in November 1952. His discussion of these events is rather brief and reticent compared with other published accounts, possibly for classification or other reasons.

Ulam will also be remembered as one of the key figures, along with von Neumann, Fermi and Nick Metropolis, in the development of the powerful Monte Carlo method, that can be used to obtain solutions for many difficult calculational problems which are intractable to ordinary analytical methods. Although the idea of attacking calculational problems by means of statistical sampling was proposed early in this century, it was only with the development of fast digital computers that this approach become truly useful. Ulam and his collaborators were quick to recognize the power of the computers developed in post-war years in attacking these problems.

The reader will find Stanislaw Ulam's book interesting as the personal account of a gifted and very interesting individual, as a description of the atmosphere during the war years at Los

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International Safeguards & Non-proliferation Division

Following the November 1991 meeting of the International Safeguards & Non-proliferation Division at the IAEA in Vienna, Austria, proposed papers for the July 19-22,1992, INMM Annual Meeting in Orlando, Fla., were considered by the participants and their colleagues. As a result of this and several other efforts, there will be seven IS&NP Sessions at the Annual Meeting, as well as a panel discussion with recognized experts on International Safeguards and Non-proliferation.

There has been a very positive response to the establishment of the IS&NP Division, particularly in view of the numerous important issues which have occurred in the past 12 months to 18 months.

The next meeting of the IS&NP Division will be held on July 19, 1992, in Orlando. Current IS&NP topics will be discussed.

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Physical Protection Division

For the past year, the Physical Protection Division has been involved in several programs.

For the past eight years, there have been more than 40 papers presented on all aspects of Physical Protection at the Annual Meeting. This year is no exception. In fact, at the 1992 Annual Meeting, there are 76 papers in the Physical Protection/Safeguards and Security areas. These papers are organized into 10 sessions.

The organization of the Physical Protection Division is now in process. We will have a short Division Meeting at the close of Session B, "Physical Protection — Information Protection Systems," Wednesday morning, July 22, 1992.

The Division also plans to report pertinent activities of Physical Protection in the *Journal of Nuclear Materials Management*.

A workshop, "Safeguards and Security: Threat, Consequences and Performance," was held at Pleasanton, Calif., March 15-19, 1992. Nearly 70 participants attended. Rokaya Al-Ayat of the Lawrence Livermore National Laboratory was the workshop chair. The workshop was enthusiastically received with numerous suggestions that we repeat it in the future.

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Waste Management Division

The following summarizes the activities of the Waste Management Division (WMD) for the period of August 1991 through July 1992.

The INMM Spent Fuel Management Seminar IX was successfully organized and held at Loew's L'Enfant Plaza Hotel in Washington, D.C., Jan. 15-17, 1992. Approximately 170 persons attended (our largest turnout to date). Talks were given by David Leroy, the U.S. Nuclear Waste Negotiator and Dr. John Bartlett, director of the Department of Energy's Office of Civilian Radioactive Waste Management. Fred Peso, executive director of the Tribal Council of the Mescalero Apache Tribe, led the 31 speakers at the meeting. One session was afforded television coverage by the "Wall Street Journal" television program.

The WMD is in the process of developing an outline for a monograph on spent fuel storage for prospective publication by INMM.

Also, the WMD provided INMM co-sponsor representation on the Steering Committee for the 1992 International High Level Radioactive Waste Management Conference held in Las Vegas, in April 1992. The WMD will continue this support for the 1993 conference.

The WMD has organized and finalized the waste management sessions for the 1992 INMM Annual Meeting in Orlando, Fla., July 19-22, 1992. A total of 33 waste-related papers are scheduled for presentation.

The division also has organized a session on waste management for the 1992, AICHE Summer National Meeting to be held in Minneapolis, Aug. 9-12, 1992.

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Mathematicians *continued*

Alamos, and for his accounts of his interactions with others, colleagues in the world of academic mathematics, and especially Teller, Fermi and von Neumann. Another worthwhile and interesting source of material on Stanislaw Ulam is the special issue of "Los Alamos Science" (No. 15), published in 1987, which is a *festschrift* dedicated to him containing both personal reminiscences of a number of individuals and a number of mathematical contributions.

The book *Prisoner's Dilemma* by William Poundstone is a multifaceted work which is not only a biography of the brilliant, and in some respects enigmatic mathematician John von Neumann, but also an interesting introduction to the subject of game theory, a mathematical discipline which has had a considerable influence on strategic planning in our country the past several decades. The book also contains an interesting account of the early years of the RAND Corp. and the debate in the early years of the cold war on our national policy on the use of nuclear weapons.

In many respects, von Neumann's career closely paralleled that of Stanislaw Ulam's. He was born in Budapest in 1903 in a wealthy Jewish family, was recognized early as a child prodigy and persuaded by his family to pursue studies in chemistry. His studies took him from the University of Budapest to the University of Berlin, to Zurich, where he earned a degree in chemical engineering, and then back to Budapest, where he earned a Ph.D. in mathematics in 1926. He accomplished all of this in five years. After holding several academic positions in Germany, including one with the great mathematician David Hilbert, he moved to Princeton in 1929. When the Institute for Advanced Study was founded in 1933, he was named a professor there, the youngest of a very distinguished group. He remained there until 1943, when J. Robert Oppenheimer invited him to join the Los Alamos effort. During the war years at Los Alamos, he made contributions toward understanding the theory of the hydrodynamics of the implosion process.

In addition to his many important contributions in mathematics, John von

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Mathematicians *continued*

Neumann will be remembered for important contributions in three other areas — the development of digital computers, originating game theory and, as mentioned above, the development of the Monte Carlo method. Each of these accomplishments, taken by itself, has had a profound impact on our current world.

In addition to his life in academia, von Neumann moved very easily in the highest levels of our government, both civilian and military. This culminated in his appointment by President Eisenhower to the Atomic Energy Commission in 1954. He retained that post until his untimely death in 1957.

The author of *Prisoner's Dilemma* skillfully combines the biographical material on von Neumann with an introduction to game theory, its development by von Neumann and co-workers, and a discussion of game theory in the context of our competition with the Soviet Union, for example, during the Cuban Missile Crisis. The reader will be interested in his discussion of the campaign from some quarters within our government during the early 1950s for a pre-emptive nuclear strike against the Russians, especially of von Neumann's advocacy of this policy. It is an unanswered question to what extent this brilliant and humane individual was influenced by the experience of growing up in a small nation that had been ruled by the communist Bela Kun regime after World War I, and twice had popular revolutions crushed by troops sent in by its giant neighbor in 1848 and 1956.

The book *The Road from Los Alamos,* by Hans Bethe, is not biographical in nature, but rather a collection of articles written between 1947 and 1989. He was head of the theoretical physics division at Los Alamos during the war years, and was awarded a Nobel prize in 1967 for his fundamental contributions to theoretical astrophysics. Hans Bethe, now a professor emeritus at Cornell, is well-known for his many contributions to nuclear physics. Most of these deal with public policy in the areas of nuclear weapons, arms control and nuclear power. There are also five eulogies on various colleagues and two popular papers on energy production in stars and the physics of supernovae.

The articles on public policy are distinguished by their reasonableness, common sense and clarity of thought. Readers concerned with arms control questions should be particularly interested in the articles dealing with this subject, especially *Chop Down Nuclear Arsenals*, written in 1989, which recommended a policy which has since been adopted, a major reduction in the nuclear arsenals of both the United States and the former Soviet Union, and *Space-based Ballistic-missile Defense*, written with Richard Garwin, Kurt Gottfried and Henry Kendall in 1984, which deals with the Strategic Defense Initiative.

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An Examination Of Randomized Inspection Schedules With Respect To Two Detection Criteria

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ABSTRACT

Three broad classes of schemes for randomizing inspection schedules are examined in light of two inspection criteria: average or expected time to detection, and probability of timely detection. It is shown that among two classes of inspection schemes, for the criterion of average detection time, no scheme performs better than a simple periodic inspection schedule. A simple periodic inspection schedule is also optimal for the probability of timely detection criterion when adequate inspection resources are available; if this is not the case, the optimal strategy is shown to be one in which inspection opportunities at fixed intervals are "sampled" or chosen randomly with a fixed probability.

INTRODUCTION

This paper examines the question of whether schemes for randomizing inspection schedules have the potential to reduce inspection effort without reducing timeliness or detection probability goals. The situation considered corresponds in general terms with visits to a reactor to determine whether spent fuel is missing, and assumes that missing material will be detected with probability 1 upon the arrival of the inspector. Two types of detection objectives are considered: (a) average time-to-detection (time to the next visit of the inspector after the diversion) and (b) "timely detection": the probability that detection will occur within a specified length of time.

Three broad classes of randomized inspection strategies are considered; constraints on inspection effort are built into the definitions of these categories. The randomized schemes considered must be compared with a simple, periodic inspection schedule. The remainder of the paper defines these various inspection strategies more carefully, states three basic results, and provides concluding comments. The proofs of the results are given in the appendix.

This work performed under the auspices of the U.S. Department of Energy, under Contract DE-AC02-76CH00016.

CANDIDATE INSPECTION STRATEGIES

In the situation considered, a facility undergoes a *mandatory* inspection at the beginning of each year, with additional *interim* inspections scheduled on the basis of the various schemes to be evaluated. The year is divided evenly into N "inspection intervals," so that there are N - 1 possible interim inspection opportunities. The average number of interim inspections available to the inspector per year is called K. It is important to remember that interim inspections occur in the time period between subsequent mandatory inspections, which are not accounted for in the number K. The results below relate two rather simple specific inspector strategies and three broad classes of strategies.

- The periodic strategy. The inspector makes K interim inspections per year at equal intervals. For simplicity

$$N = (K+1)m \qquad [1]$$

where m is an integer; thus interim inspections occur at opportunities $m, 2m, \ldots Km$.

- The sampled periodic strategy. The year is divided into R periods (where R must be greater than or equal to K+1) and instead of inspecting with probability 1 at the end of each period, an inspection occurs with probability K/(R-1). The choice of whether of not to inspect at each of the R-1 opportunities is made independently. R is assumed to divide evenly into N. The periodic strategy is actually a special case of the sampled periodic strategy with K = R-1.

The three general classes of strategies are defined as follows.

- Strategy class A. The inspectorate chooses K out of the N - 1 opportunities by some (deterministic or random) scheme, and inspects on those dates. This class or set of strategies obviously encompasses many possible schemes. The periodic strategy is a class A strategy, but in general the sampled periodic strategy is not, because this strategy may give rise to more than K inspections in a given year, even though the average number of inspections per year

is K. The "lottery" strategy (in which the dates of the K opportunities are picked from the N-1 possibilities like balls from an urn) which has received attention in IAEA thinking, is a Class A strategy.

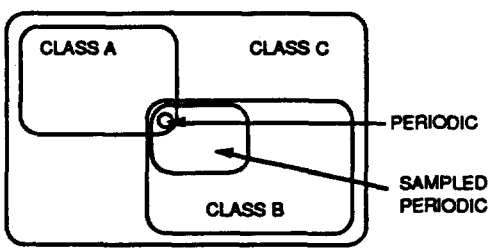
- Strategy class B. For each of the N - 1 opportunities, the inspectorate computes a probability of inspection p_i (i = 1,2, ... N - 1) and inspects at opportunity i with probability pi; the choices are statistically independent. In order to constrain the inspection effort involved, we assume the expected number of inspections per year is

$$\sum_{i=1}^{N-1} p_i = K \qquad [2]$$

strategy class B contains both the periodic strategy and the sampled periodic strategy.

- Strategy class C. Class C is defined as was B but without the restriction of independence. This is an extremely general class of strategies, since any randomized or non-randomized strategy will generate some set of probabilities $\{p_i\}$. Strategy class C contains classes B and A.

The relationships between the various strategy classes are shown below.



Relationships among the various classes of inspection strategies

INSPECTOR - ADVERSARY "GAME"

In the situation we are examining, both the inspector and the adversary choose strategies: the inspector chooses an inspection scheme, and the adversary chooses a scheme to determine when he will divert. The inspector's objective is to achieve the detection goals (whichever of the two is under consideration) and the adversary's objective is to divert without the detection goals being achieved. There are, however, asymmetries in the inspector-adversary relationship. Because the diverter can observe how safeguards inspections are implemented, it is realistic and prudent to assume that the adversary knows the strategy of the inspectorate[1], and will choose the best possible strategy he can to defeat it. On the other hand, the inspector does not know the diverter's strategy; the best he can do is choose a strategy for himself where the adversary can do him the least harm in terms of his objective. It is therefore that inspector strategy which provides the best results for the inspector in the face of the adversary's worst-case strategy that is sought in this paper. Avenhaus and Canty, in a recent report on this topic[2], call this the "inspector leadership" situation.

THE "EXPECTED TIME TO DETECTION" CASE.

In this situation the adversary tries to maximize, and the inspector tries to minimize, the expected or average time to detection. The periodic inspection strategy where the inspector comes every m inspection opportunities guarantees to the inspector a time to detection of no worse than m = N/(K+1). The mathematical results proved in the appendix are as follows.

Result 1. For any Class A inspection strategy, there is an adversary strategy whose expected time to detection is greater than or equal to m=N/(K+1).

Result 2. For any Class B inspection strategy, there is an adversary strategy whose expected time to detection is greater than or equal to m=N/(K+1).

This clearly implies that if the criterion is average time to detection, there is no better inspection scheme (at least among class A or B) than that of a simple periodic inspection schedule. The adversary strategies used to derive the two results are different. The strategy used in the first proof involves calculating the expected or average times between inspections (not inspection opportunities), picking that which is the longest (e.g., the average time between the second and third inspections is greater than any of the other average intervals) and diverting at the start of that interval (e.g., diverting immediately after the inspector leaves after his second inspection). The strategy used in the second proof involves waiting until a specific inspection opportunity, and diverting after that opportunity, whether the inspector had inspected at that opportunity or not.

It is of course still possible that there is some very complex inspection strategy, not in class A or B, which has an average worst-case time to detection shorter than that for the simple periodic schedule. Such a strategy might, for example, involve randomizing the number of inspections in a year (with mean value K) and then choosing some different strategy for each value.

THE "PROBABILITY OF TIMELY DETECTION" CASE.

In this case, the objective of the inspector is to maximize the probability of timely detection, where the definition of "timely" is a given specific length of time. The objective of the diverter is to minimize this probability. In this situation the inspector is given no credit for non-timely detection and no extra credit for detection prior to the timeliness goal. We will assume that this length of time divides evenly into a year,

$$N = RM \qquad [3]$$

where M is the timeliness goal in units of inspection intervals, and R is an integer. It is clear that if the available inspection effort K satisfies

$$K \geq R-1 \qquad [4]$$

then the goal of timely detection can be achieved with detection probability 1 using a periodic inspection schedule, and no randomized scheme can do any better this. If the inequality is not satisfied, it is equally clear that any fixed non-random scheme will have gaps greater in duration than the timeliness goal that will allow the adversary to be successful with probability 1, so any non-random scheme must be deemed ineffective with respect to this criterion. The question of inspection scheduling when [4] is satisfied is therefore rather easily answered. What remains is the problem of scheduling inspections when [4] cannot be satisfied.

An approximation to the periodic strategy which however need not satisfy [4] is the sampled periodic strategy. A sampled periodic strategy whose intervals between possible inspections equals the timeliness criterion clearly achieves timely detection with probability K/(R-1) or equivalently KM/(N- M).

Result 3. For any Class C inspection strategy such that KM/(N-M) < 1, there is an adversary strategy whose probability of timely detection is less than or equal to KM/(N- M).

The adversary strategy used in the proof is to divide the year into R periods, determine which such period is being inspected least intensively, and divert at the beginning of that period. This result indicates that there is no better inspector strategy for the timely detection criterion than the sampled periodic strategy.

CONCLUSION

The results above suggest that randomization in the timing of inspections *per se* provides no free lunch: no real improvement in detection capability over simple periodic inspection schedules can be attributed to randomization alone. A process of sampling periodic inspection opportunities appears useful in the case of attaining timely detection when resources are inadequate to attain detection with probability 1. This "sampled periodic" concept has been considered previously in the context of material accounting at enrichment plants[3] and recently extended by Lu and Teichmann[4] who showed how the numbers of inspections can be traded off against probability of detection at the inspection (in this paper this parameter was assumed to be 1, so this question does not arise). The only open question is whether some complex inspection strategy, not in class A or B, might improve on the expected detection time m = N/(K+1); the existence of such a strategy would be surprising and very interesting.

Recent articles by Canty and Avenhaus[5,6] however, appear to provide different conclusions than those quoted here. In particular, their paper suggests the possibility of improved average times to detection over periodic inspection schedules for inspector strategies that fall into what this article calls Class A, contradicting Result 1. The difference arises because the Avenhaus-Canty derivation disallows the adversary strategy which is the basis of result 1, a strategy in which the diverter uses information gathered during the period in question to make his decision on when to divert; in this paper it is also assumed that the diverter knows the nature of the inspector's inspection strategy. The problem is illustrated by the inspection strategy defined by the table below suggested by Canty and Avenhaus as a solution to the average time to detection problem with N=12 and K=2 (the first line in the table, for example, indicates that an inspection will occur at the end of month 1 and 5 with a probability of 0.035). The strategy is a Class A strategy, since there are always the same number of inspections each year. Result 1 above indicates that no inspection strategy can do better than 12/(2+1) = 4 months time to detection, whereas a 3-month limit is claimed by the authors under their somewhat different set of assumptions.

Months on which inspections occur	Probability
1,5	.035
1,6	.167
1,7	.005
2,7	.195
2,8	.004
3,8	.200
4,8	.046
4,9	.163
5,9	.170
5,10	.015

If the diverter must choose the date of diversion before the year starts, the 3-month limit is achieved. However, if the diverter waits until the first inspection (whose date is not known to him at the beginning of the year) is complete and then diverts, the expected time between the first and second interim inspections is about 4.76 months[7], a value that exceeds the 3-month criterion (the probability of timely detection for such a strategy is 0). In a more recent report[8], Canty and Avenhaus examine the possibility of using information gained during the inspection period to schedule subsequent inspections, although the situation examined differs slightly from that considered here (the assumptions of this paper for result 2, however, appear to be very similar to those of section 3.2 in the Canty-Avenhaus paper, and the result proved there is essentially the same as result 2).

A sampled periodic scheme for the situation above would have a timely detection probability of 0.67 and an average detection time of about 4.4 months. A periodic scheme would provide an average time to detection of 4 months and a timely detection probability of 0.

APPENDIX

Result 1. For any Class A inspection strategy, there is an adversary strategy such that the expected time to detection is greater than or equal to m.

Proof. Let X_i be the time between inspection i -1 and inspection i, for i = 1, 2, ... K + 1 (X_1 is the time between the mandatory inspection and the first interim inspection; X_{K+1} is the time between the last interim inspection and the next year's mandatory inspection). The X_i can be thought of as random variables. Clearly, with probability 1,

$$\sum_{i=1}^{K+1} X_i = N \qquad [5]$$

so that

$$\sum_{i=1}^{K+1} E[X_i] = N \qquad [6]$$

where E[ ] denotes expected value. Let i* be that i for which $E(X_i)$ is the maximum, and let the adversary employ the following strategy: wait until inspection i*-1 has occurred and divert immediately thereafter. Clearly the expected time to detection is $E(X_{i^*})$ but

$$E[X_{i^*}] \geq \frac{N}{K+1} = m \qquad [7]$$

which follows from [1] and [6].

Result 2. For any Class B inspection strategy, there is an adversary strategy whose expected time to detection is greater than or equal to m.

Proof. The expected time to detection if diversion occurs immediately after the ith inspection opportunity i is

$$e_i = p_{i+1} + 2q_{i+1}p_{i+2} + 3q_{i+1}q_{i+2}p_{i+3} + \cdots + (N-i)p_N \prod_{j=i+1}^{N} q_j \qquad [8]$$

where $q_i = (1-p_i)$, and p_o and p_N are taken to be 1. It is not hard to see that

$$e_i = 1 + q_{i+1}e_{i+1} \qquad i = 0,1,2,\cdots,N-1 \qquad [9]$$

Summing over i gives

$$\sum_{i=0}^{N-1} e_i - \sum_{i=0}^{N-1} q_{i+1}e_{i+1} = N \qquad [10]$$

But this may be written (using $p_o = p_N = 1$) as

$$\sum_{i=0}^{N-1} e_i p_i = N \qquad [11]$$

Let i* be that i for which e_i is the greatest. Then e_{i^*} must be greater than or equal to m, for if all the e_i were strictly less than m, then from [2] and the fact that $p_0 = 1$,

$$\sum_{i=0}^{N-1} e_i p_i < \sum_{i=0}^{N-1} m p_i = m(K+1) = N \qquad [12]$$

and this would contradict equation [11]. Thus if the adversary were to adopt the strategy of diverting immediately after inspection opportunity i*-1, his expected time to detection will be e_{i^*} which is greater than or equal to m.

Result 3. For any Class C inspection strategy such that

$$\frac{K}{R-1} \leq 1 \qquad [13]$$

there is an adversary strategy whose probability of timely detection is less than or equal to KM/(N - M).

Proof. Divide the set of integers 1....N into R subsets of M consecutive numbers, and label each of these subsets with the index r. Define

$$T_r = \sum_{j=(r-1)M+1}^{rM} p_j \qquad [14]$$

Let r* be the value of r for which T_r is a minimum. Since

$$\sum_{r=1}^{R-1} T_r = \sum_{i=1}^{(R-1)M} p_i \leq K \qquad [15]$$

therefore

$$T_{r^*} \leq \frac{K}{R-1} = \frac{MK}{N-M} \qquad [16]$$

Let the adversary divert immediately after inspection opportunity (r*-1)M; the probability of timely detection (during inspection opportunities (r*-1)M+1 to r*M) must be less than the sum of the probabilities of detection at each opportunity, but this sum, according to [14] is T_{r^*} which is less than or equal to MK/(N-M) by [16].

REFERENCES

1. The adversary is assumed to know the statistical parameters of the inspection strategy, but not the results of any randomized choice by the inspectorate. For example, if the inspector is selecting items at random from a stratum for verification, the adversary would be assumed to know the sample size, but not the particular items to be chosen.
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Passive Neutron Waste-Drum Assay With Improved Accuracy And Sensitivity For Plutonium Using The Add-A-Source Method

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ABSTRACT

Techniques have been developed to improve the accuracy and sensitivity for the nondestructive measurement of plutonium in scrap and waste containers. The 200-L-drum assay system is based on the classical nondestructive assay method of passive neutron coincidence counting to determine the plutonium, but has added the new feature of ^{252}Cf "add-a-source" to improve the accuracy of matrix corrections and has added statistical techniques to improve the low-level detectability limits. The errors introduced from matrix materials in 200-L drums have been reduced by one order of magnitude by using the add-a-source technique. The statistical filters to reduce the cosmic-ray spallation neutrons have decreased the coincidence neutron background by approximately a factor of 2.

INTRODUCTION

The measurement of plutonium scrap and waste in 200-L drums is important for accountability, safeguards, and waste disposal. Because of the heterogeneous waste materials, representative sampling is not possible and nondestructive assay (NDA) methods are preferred over destructive analysis.

During the past two decades, NDA systems employing both active and passive assay techniques have been used to measure the plutonium content of 200-L drums. The active assay systems are used primarily to measure ^{235}U and ^{239}Pu and include 14-MeV neutron (D,T) generators with delayed-neutron counting,[1] (D,T) generators with the differential die-away technique,[2] and ^{252}Cf neutron shufflers.[3]

Passive assay systems have used gamma-ray emissions (for example, segmented gamma-ray scanners)[4] or passive neutron signals (for example, passive drum counters).[5-7]

We have developed a new passive neutron measurement technique to improve the accuracy and sensitivity of the NDA of plutonium scrap and waste. The 200-L-drum assay system uses the classical NDA method of counting passive neutron coincidences from plutonium but has added the new features of "add-a-source" to improve the accuracy of matrix corrections and statistical techniques to improve the low-level detectability limits. The add-a-source technique introduces a small source of ^{252}Cf (10^{-8} g) near the external surface of the sample drum; the drum's perturbation of the ^{252}Cf coincidence counting rate provides the data to make a matrix correction for the plutonium inside the drum. The measurement errors introduced from matrix materials in 200-L drums have been reduced by one order of magnitude by use of this technique. In addition, this method can detect the presence of unexpected neutron shielding material inside the drum that might not allow the detection of nuclear materials.

ACTIVE VS. PASSIVE PLUTONIUM ASSAY METHODS

In general, passive assay methods are superior to active assay methods for measuring plutonium because the passive methods are less costly and often give more accurate results. Passive neutron assay has the following advantages over active neutron interrogation:

(a) Passive assay measures only the neutron emitted by the plutonium sample, whereas active assay measures both these neutrons and those induced by the external source. Thus the neutron self-shielding and matrix problems are much larger for active assay.

(b) Active signals vary by 2 orders of magnitude depending on the energy of the interrogation neutrons. Large uncertainties in the assay are caused by matrix materials moderating neutron energies.

(c) Thermal-neutron absorbers such as boron and chlorine cause a large error in active assays,[8] but the absorbers have almost no effect on the passive neutron coincidence assay because of the high neutron energy of the passive signal and the time gate (128 μ s) for coincidence counts.

(d) Scrap metals such as iron allow accurate passive assays with good sensitivity,[8] whereas the accuracy of active assays on iron-bearing materials is poor and the sensitivity is degraded by more than an order of magnitude.

(e) Neutron *coincidence counting* decouples the measurement from variable, room-background neutron sources because the coincidence timing criterion eliminates all background neutrons except for cosmic ray spallation events.

Because of the obvious advantages in cost, reliability, accuracy, and sensitivity, passive neutron techniques should be used for plutonium assay. Active techniques for plutonium are justified only in cases of high neutron background levels from fission products such as ^{244}Cm in the waste.

PASSIVE WASTE-DRUM COUNTER DESCRIPTION

Los Alamos prepared the specifications and conceptual design of the 200-L-drum counter. A commercial nuclear instrument company designed and built the counter (Model JCC-21). After fabrication, the counter was delivered to the Los Alamos National Laboratory Safeguards Assay Group for a program of performance measurements and acceptance testing, installation of the add-a-source, initial calibration, software installation and check-out.

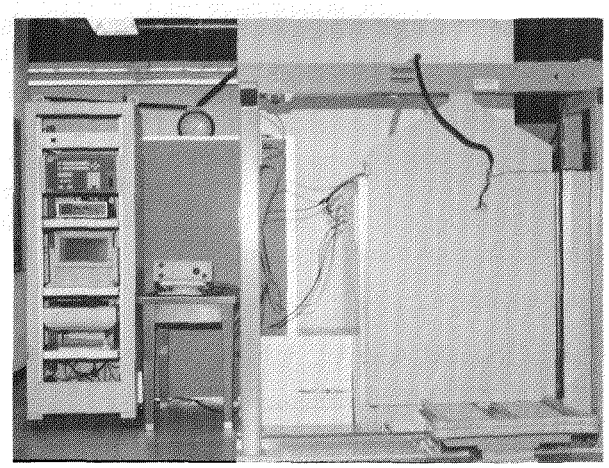

Figure 1
This waste-drum assay system shows the open sample cavity and a 200-L drum.

Figure 1 shows a photograph of the drum counter with the add-a-source neutron shield attached to the lower left side of the detector. The interior well is 711 x 711 x 965 mm high and can easily hold a standard 200-L drum, which can be loaded by rolling it along the fixed platform of rotating wheels as shown in the figure. The door is driven by a motor positioned on top of the counter that moves the door back and forth on its wheels.

The counter has six banks of ^3He tubes — one in each of the four sides and one on the top and bottom. The four vertical side banks each contain ten 914-mm active length ^3He tubes, and the top and bottom horizontal banks each contain ten 533-mm active-length ^3He tubes. The detector banks each require two separate counting channels, each consisting of a preamplifier and discriminator circuit. The electronics is similar to that of the HLNC-II.[9,10] The detector counts the totals and coincidence neutrons from the spontaneous fission of the even isotopes of plutonium. Each of the six banks of ^3He tubes is embedded in a 100-mm-thick slab of high-density polyethylene (CH_2). Each bank is also shielded on the outside by another 100-mm-thick slab of polyethylene. Within the six detector banks, the ^3He tubes are centered 4.16 cm from the inside edge of the polyethylene.

TABLE I. Detector Performance Characteristics (date: 90-08-29)

Parameter	WDAS
Efficiency (no sample)	18.6%
Die-away time (center)	80 μs
Gate setting	128 μs
High voltage	1680 V
Deadtime coefficient *a*	0.71 μs
Deadtime coefficient *b*	0.23 μs
AS reference (91-09-05)	
R(K-182)	1323 counts/s

The cadmium liners that normally cover the detector banks were removed to increase the detector's efficiency and to decrease the *coincidence* neutron background. The cadmium increases the coincidence background from cosmic ray spallation reactions, and its removal improves the sensitivity of the system for low-background applications. Removing the cadmium reduces the shielding for external neutrons by ~16%.

The efficiency of the system was measured by using a calibrated ^{252}Cf source in the detector. The efficiency and other operational parameters[7] are listed in Table I.

The detector uses the same basic electronics and amplifiers as does the HLNC-II. The deadtime coefficient δ is given by

$$\delta = (a + bT \times 10^{-6})\ \mu\text{ s},$$

where T is the measured totals rate in counts/s and a and b are constants given in Table I. The corrected counting rates are

$$T(\text{corr}) = T\, e^{\delta T/4} \text{ and } R(\text{corr}) = R\, e^{\delta T}.$$

To determine sample positioning effects, we counted a ^{252}Cf point source at a variety of vertical and radial positions in an empty drum. The vertical profile measurements were made at a radius of 20 cm from the center of the 200-L drum. The outside edge of the drum has a radius of 28 cm, and the 20-cm radius is approximately the volume-averaged mean radius. That is, the drum volume inside 20 cm equals the volume outside 20 cm.

Figure 2 shows the normalized vertical totals and reals rates for the ^{252}Cf source. The dips at the top and bottom are

caused by the gaps in the detector coverage at the ends of the detector banks.

For the radial profile, the ^{252}Cf source was positioned at four different radial positions and three different vertical positions. Figure 3 shows the radial profile for the average of the three vertical positions. The vertical positions were 15, 35 and 55 cm above the bottom of the drum.

ADD-A-SOURCE (AS) METHOD

The objective of the method is to measure how the matrix perturbs the counting rate when a small ^{252}Cf source (~3 x 10^4 n/s) is placed near the outside of the sample and to use the information to correct for the matrix. For the present case, we positioned the AS neutron source at the bottom-center of the 200-L drum. Figure 4 shows a schematic diagram that illustrates the technique in which the AS neutrons originate from ^{252}Cf and the sample neutrons originate from plutonium.

The sample matrix primarily has two effects on the neutrons: (1) energy reduction by scattering reactions and (2) absorption of the low-energy neutrons. The counter is designed with the optimum moderator (CH_2) thickness to be relatively insensitive to the energy reduction; however, as the hydrogen density in the drum increases, the absorption process significantly reduces the measured neutron signal.

To correct for the matrix perturbation on the neutron signal, the AS method measures each drum both with and without the ^{252}Cf source on the bottom of the drum. The measured quantities are

T_0, R_0 = totals and reals rates from ^{252}Cf for an empty drum,

T, R = totals and reals rates from a sample drum without ^{252}Cf,

$T(Cf)$, $R(Cf)$ = totals and reals rates from a sample drum with the ^{252}Cf.

The net ^{252}Cf reals rate for the ^{252}Cf and a loaded sample drum is

$$R(Cf) - R = R(net).$$

We use the ratio of reals rates from the empty drum (after source decay correction) and the net loaded drum to make the matrix correction as follows:

$$[(R_0 e^{-\delta r})/R(net)] - 1 = x,$$

and the correction factor (CF) is defined as

$$CF = 1 + f(x),$$

where $f(x)$ is a polynomial function of x based on empirical measurements. The measured R for a drum is corrected to give

$$R(corrected) = R(measured)\ CF.$$

The functional relationship between the AS perturbation (x) and the volume-averaged sample perturbation $f(x)$ was determined empirically by measuring a large variety of matrix loadings with the AS on the bottom of the drum. A separate neutron source was counted at nine positions in the drum to give a *volume-averaged* matrix effect. The average of the nine positions was then ratioed to the empty drum case to give the

TABLE II. Californium-252 Counting Rates for Add-a-Source and the Average over the Matrix Volume (AS Source K-182 on 91-08-10)

	Volume Average (G370)				Add-a-Source			
Sample	T_{av}	R_{av}	T_0/T	R_0/R	T_{av}	R_{av}	T_0/T	R_0/R
Empty Drum	6439	1073	1	1	7450	1354	1	1
Vermiculite (dry)	6466	1089	0.996	0.985	7308	1301	1.019	1.041
Paper (ρ = 0.11)	6492	1053	0.992	1.019	7225	1231	1.031	1.101
Boron Glass	5896	1042	1.092	1.031	6314	1159	1.181	1.168
CH_2 (ρ = 0.060)	6425	1033	1.002	1.039	7173	1205	1.039	1.124
CH_2 (ρ = 0.154)	6125	898	1.051	1.195	6451	925	1.155	1.464
CH_2 (ρ = 0.159)	6006	861	1.075	1.257	6390	906	1.166	1.494
CH_2 (ρ = 0.225)	5451	637	1.181	1.685	5733	715	1.299	1.894
CH_2 (ρ = 0.308)	4067	358	1.583	3.000	4872	515	1.529	2.630
CH_2 (ρ = 0.464)	3561	268	1.811	4.001	4545	459	1.639	2.951
CH_2 (ρ = 0.604)	2285	128	2.818	8.396	3822	341	1.949	3.971
CH_2 + Fe + Al Mix	6254	1002	1.031	1.071	6768	1097	1.101	1.234

volume-averaged perturbation

$$[R'_0(\text{empty vol.})/R'(\text{matrix vol.})] - 1 = y(\text{vol. avg. perturbation})$$

where R'_0 = reals rates averaged over the volume of an empty drum and R' = reals rates averaged over the volume of the drum with matrix material.

Table II lists the totals and reals rates and ratios for the volume-averaged case and the AS case. A typical drum contained ~190 L of matrix material. A plot of the volume-averaged perturbations (y) vs. the AS perturbation (x) is shown in Figure 5. The data point with the highest AS perturbation (~300%) corresponds to a drum loaded with CH_2 beads (ρ = 0.60 g/cm^3). This has the same neutron shielding as a drum containing H_2O with ρ = 0.72 g/cm^3, and it is more opaque to neutrons than a concrete drum.

A third-order polynomial was fit through the y vs. x data to give the predicted volume-averaged matrix perturbation $f(x)$ based on the AS measured perturbation

$$y = f(x) = a_0 + a_1x + a_2x^2 + a_3x^3$$

where a_0 =-0.00426
a_1 = 0.2111
a_2 = 0.5417
a_3 = 0.07537.

The totals rate ratio could be used for the AS correction as well as the R ratio, and the feasibility of using the totals (T) ratio was evaluated. The AS perturbations (x) derived from the R ratios are ~3.2 times larger than the totals perturbation. There is good agreement between the totals and reals perturbations except for the cases in which the matrix absorbs *thermal neutrons* such as those from boron glass and iron. The measured R values are independent of thermal-neutron absorption *in the drum* because a thermal neutron in the drum takes too long to ever reach the ^{3}He tube within the coincidence gate interval (128 μ s). However, the totals rate T has no time limits, and the thermal-neutron absorbers reduce the T values.

To evaluate the error in using the AS correction for the matrix materials listed in Table II, we used the fitted function $f(x)$ to give

$$CF = 1 + f(x).$$

All of the measured R values were corrected by CF and compared with the empty drum case.

The results are listed in Table III and illustrated in Figure 6. The CF-corrected reals deviate from the empty drum with a standard deviation of only ±1.0%. These same drums (except for the boron glass) were used to determine the $f(x)$ function so the results show the scatter of our CF calibration. However, after the CF calibration was established, a drum filled with vermiculite plus CH_2 beads (ρCH_2 = 0.308 g/cm^3) was measured as an unknown and the corrected response (R • CF) was within 3% of the empty-drum case. A typical drum of organic waste is expected to have a hydrogen loading that is equivalent to ρCH_2 = 0.1 g/cm^3, and thus the correction factor will be much smaller than the present case with ρCH_2 = 0.3 g/cm^3.

Future work will include measuring drums of other matrix materials to help establish the accuracy of the AS method for a variety of matrices.

TABLE III. Add-a-Source Matrix Correction for 200-ℓ Drums

Sample	Volume Av R_0/R	Relative R	CF	Relative R(corr)
Empty Drum	1.000	1.00	0.996	0.996
Vermiculite (dry)	0.985	1.015	1.005	1.020
Paper (ρ = 0.11)	1.019	0.981	1.023	1.003
Boron Glass	1.031	0.970	1.048	1.016
CH_2 (ρ = 0.060)	1.039	0.963	1.030	0.992
CH_2 (ρ = 0.154)	1.195	0.837	1.217	1.019
CH_2 (ρ = 0.159)	1.257	0.796	1.241	0.988
CH_2 (ρ = 0.225)	1.685	0.594	1.671	0.993
CH_2 (ρ = 0.464)	4.001	0.250	4.020	1.005
CH_2 (ρ = 0.604)	8.396	0.119	8.380	0.997
CH_2 + Fe + Al Mix	1.071	0.934	1.076	1.005
			1σ =	1.0%

TABLE IV. Los Alamos MOX Pellets Specifications

		August 30, 1991											
		Wt % (Relative to total plutonium mass)											
ID	g Pu	238	239	240	241	242	^{241}Am	P (mW/g Pu)	g ^{239}Pu-eff	g ^{240}Pu-eff	Alpha	MOX Ratio U/Pu	Enrich (%)
A1-066	0.1526	0.0856	88.4296	10.3053	0.8844	0.2951	1.8465	5.0603	0.9552	0.0168	0.9729	61.3413	0.7400
A1-081	0.5077	0.0856	88.4296	10.3053	0.8844	0.2951	1.8465	5.0603	1.2561	0.0559	0.9729	17.5092	0.7400
A1-078	0.8061	0.0856	88.4296	10.3053	0.8844	0.2951	1.8465	5.0603	1.4778	0.0888	0.9729	10.0922	0.7400
A1-089	0.2267	0.2354	77.8275	18.8824	1.8130	1.2417	3.8233	8.6038	0.9880	0.0489	0.8665	39.7135	0.7400
A1-119	0.2651	0.0519	87.1700	11.8495	0.7160	0.2126	1.4045	4.440	0.7709	0.0327	0.7521	3.1112	92.8100

Our present AS mechanical system measures primarily the bottom half of the drum, so we have assumed that the matrix in the bottom region represents the entire drum. If this assumption is too limiting, the AS mechanism could be designed to move up and down the side of the drum to interrogate it more uniformly. The software and the Teleflex cable for the AS drive system can be adapted to the more complete scanning of the drum as is done with ^{252}Cf shuffler systems.[3]

TABLE V. MOX Precalibration Results (91-09-05): Reference source K-182

Sample[a]	^{240}Pu-eff (g)	net T (s^{-1})	net R (s^{-1})	σ_R (s^{-1})	CF	$CF \cdot R$ (s^{-1})	$R/g\ ^{240}Pu$
Room background	0	2.6	0.08	—	—		
66 + 81 + 78 + 89 + 119	0.243	87.2	4.34	0.04	1.000	4.34	17.9
66 + 81 + 78 + 89	0.210	76.5	3.86	0.03	1.000	3.86	18.4
66 + 78 + 89 + 119	0.187	65.8	3.34	0.03	1.000	3.34	17.9
66 + 89 + 119 + 81	0.154	54.3	2.75	0.03	1.000	2.75	17.8
(66 + 81 + 78 + 89 + 119) CH_2	0.243	85.6	3.78	0.06	1.194	4.51	18.6
(66 + 81 + 78 + 89) CH_2	0.210	75.1	3.27	0.04	1.190	3.89	18.5
K-182 (AS empty drum)	NA	7307	1324	5.4	NA	NA	NA
K-182 (AS no drum)	NA	7440	1323	5.5	NA	NA	NA

[a]The pellet standards were distributed in height between 15 and 65 cm and the average of three radial positions (12, 20, and 25 cm) was used to obtain the T and R values.

PLUTONIUM PRECALIBRATION

Calibration measurements obtained by using mixed-oxide (MOX) pellets were made at Los Alamos. The calibration range of interest for the waste drums is from zero to a few grams of plutonium. The specifications for the MOX pellets that we used are listed in Table IV. The calibrations were performed in both an empty drum and the low-density (ρ = 0.154 g/cm^3) CH_2-filled drum. The measured rates from the CH_2-filled drum were multiplied by the AS correction factor (CF) to give the empty drum equivalent rates. Because of the geometric variation of the counting efficiency, we positioned the standards at the nine positions that were used for the volume- averaged rates.

Table V gives the volume-averaged reals rates for the standards, and Figure 7 gives a plot of R vs. the ^{240}Pu-eff mass where

$$^{240}\text{Pu-eff} = 2.52\ ^{238}\text{Pu} + {}^{240}\text{Pu} + 1.68\ ^{242}\text{Pu}.$$

There is negligible multiplication in the standards, so we fitted a linear calibration line that goes through the origin. The Deming-fitted calibration line is

$$R(\text{corr}) = a\,m$$

where m = ^{240}Pu-eff mass and a = 18.28 ± 0.1 counts/(s • g ^{240}Pu-eff).

When matrix material is in the drum, the measured reals are corrected by

$$R(\text{corr}) = R(\text{meas})\ \text{CF}$$

before fitting to the calibration line. The CF correction factor is applied to *both* the calibration standards and the assay samples. Thus, any error in the CF factor is limited to matrix differences between the standards and the unknowns.

For normal detector operation, there is no significant neutron multiplication (M = 1), and the assay results are based on the CF-corrected reals rates (no multiplication correction). However, if a high-mass multiplying sample is measured, the normal neutron coincidence counter software can be used and the multiplication-corrected result is available. For this type of application, we have measured the multiplication constant (ρ_0) using the small pellets listed in Table IV. The result was

$$\rho_0 = (R/T)(1 + \alpha) = 0.097$$

where α (= 0.922) is the ratio of (α,n)/spontaneous-fission neutrons. The coincidence gate was set at 128 μ s.

DETECTABILITY LIMIT

The detectability limit d (in grams of ^{240}Pu) at 3 standard deviations above background was calculated for the counter by using the MOX calibration curve and the equation

$$d = (3/a)[(B + ad)/t]^{1/2}$$

where a = response of counter in counts/(s • g ^{240}Pu) = 18.28
B = room-background rate = 0.06 counts/s
t = counting time = 1,000 s.

For the coincidence mode, d = 1.57 mg of ^{240}Pu; however, the detectability limit depends on the background of the installation location. Figure 8 shows a graph of the detectability limit vs. the neutron coincidence background for the waste drum system.

The detectability limit is a function of the neutron coincidence background, and we have reduced our background by a factor of ~1.8 by eliminating the cosmic ray spallation events with high multiplicity. The cosmic ray events can be counted as prompt charged-particle reactions in the detector tubes or as spallation source neutrons that extend in time over the slowing-down time of the detector body. The predelay (4.5 μ s) eliminates the first category because they are short lived and the predelay vetoes them from the coincidence gate. The spallation neutrons fall within the coincidence gate but often with high multiplicity. We use the data collection software to isolate the high multiplicity events and to eliminate them from

the data averages. We are currently using statistical techniques to accomplish this. In the future, we will investigate the use of multiplicity electronics to eliminate these types of cosmic ray events.

Our statistical filter for background reduction consists of a 3-σ rejection threshold from the average of multiple, short data intervals. The normal counting time for a drum is 600 s, and we divide this into 20 intervals of 30 s each. If any interval is more than $\pm 3\sigma$ out of the average, we reject that interval from the average. This type of filter does not interfere with the data collection for drums with significant plutonium content.

If the totals rate is used to determine the detectability limit, we have $a = 359$ and $B = 2.6$ counts/s. These rates give $d = 0.4$ mg of ^{240}Pu-eff. However, plutonium storage in the vicinity of the counter will increase the totals background rate but not the coincidence background rate. This will increase the detectability limit in the totals mode. Another problem with using the totals rate for determining the detectability limit is that the background totals rate varies with the number and location of drums in the measurement room. Thus, it might be impossible to determine if a small increase in the totals rate came from the drum inside the detector or if the increase came from a change in the room background. However, the totals rate can be used to screen drums that have less than a minimum plutonium content.

The neutron coincidence background originates from cosmic ray spallation reactions, and the frequency of these reactions is a function of the elevation and the overhead shielding. Figure 9 shows a plot of the *relative* cosmic ray origin neutron flux as a function of elevation.[11] We see that the cosmic ray–neutron flux decreases by a factor of ~7 in going from Los Alamos (7500 ft.) to sea level.

HYDROGEN DETERMINATION

Because the neutron scattering, moderation and absorption in the drum are dominated by the hydrogen content, we can use the AS measurement to determine the approximate hydrogen content in a drum. Figure 10 gives the AS perturbation (x) as a function of the hydrogen density (ρH). For comparison, full density ($\rho = 1$) H_2O has $\rho H = 0.11$ g/cm^3.

The presence of thermal-neutron absorbers such as boron in the matrix has almost no effect on the measurement because the AS perturbation (x) is based on the ratio of R values. The 128-u s coincidence gate for R eliminates all neutrons that are at thermal energy inside the drum because the flight time to the ^{3}He tubes is longer than the coincidence gate.

The method of neutron moderation has been used in many fields (for example, borehole logging) to determine the amount of hydrogen in a sample. The present application of AS to determine the hydrogen is new in that it uses neutron coincidence counting. This gives an important improvement to the hydrogen measurement because the results no longer depend on the impurities that absorb thermal neutrons because the coincidence timing criterion eliminates those neutrons from consideration.

SUMMARY

The drum assay system provides a sensitive (18.6% efficiency) and accurate method to measure plutonium in 200-L waste drums. Other samples, such as boxes that fit into the sample cavity, can be measured, as well as the drums. The sensitivity of the system for our design-basis matrix is ~1–2 mg of ^{240}Pu-eff for coincidence counting depending on the cosmic ray spallation background at the measurement location. If we use the singles counts for screening low levels of plutonium, the sensitivity is improved by a factor of ~3. The accuracy will depend on the particular matrix type and the plutonium mass level. For the present design target of ~1 g of plutonium in a combustible matrix, the expected accuracy is 3–10% for a 10-min. assay. The statistical precision is 1.7% for 1 g of reactor-grade plutonium measured for 10 min.

The detector has been optimized to be insensitive to matrix changes. The detector wall thickness was chosen to give approximately the same counting rate for an empty drum and a drum containing 20 kg of combustible wastes such as paper and rags. As the matrix density increases, the AS correction is effective for correcting the measurement back to the calibration condition. The AS correction significantly improves the final assay accuracy, as illustrated in Figure 6. The AS feature also gives the capability to flag outlier samples that contain an unexpected matrix. If neutron-shielding material is present in the drum, the AS procedure picks up the condition with good sensitivity. The AS-generated flag works even for cases for which part of the SNM is inside the shield and part is outside the shield in the same drum.

ACKNOWLEDGMENTS

I thank S.-T. Hsue, N. Ensslin and D.W. Miller for contributing to the design and testing of the original passive drum counter. M.C. Miller, W.C. Harker and M.S. Krick contributed to the field testing and software development. The design and assembly of the AS system were performed by K.E. Kroncke and J. Baca.

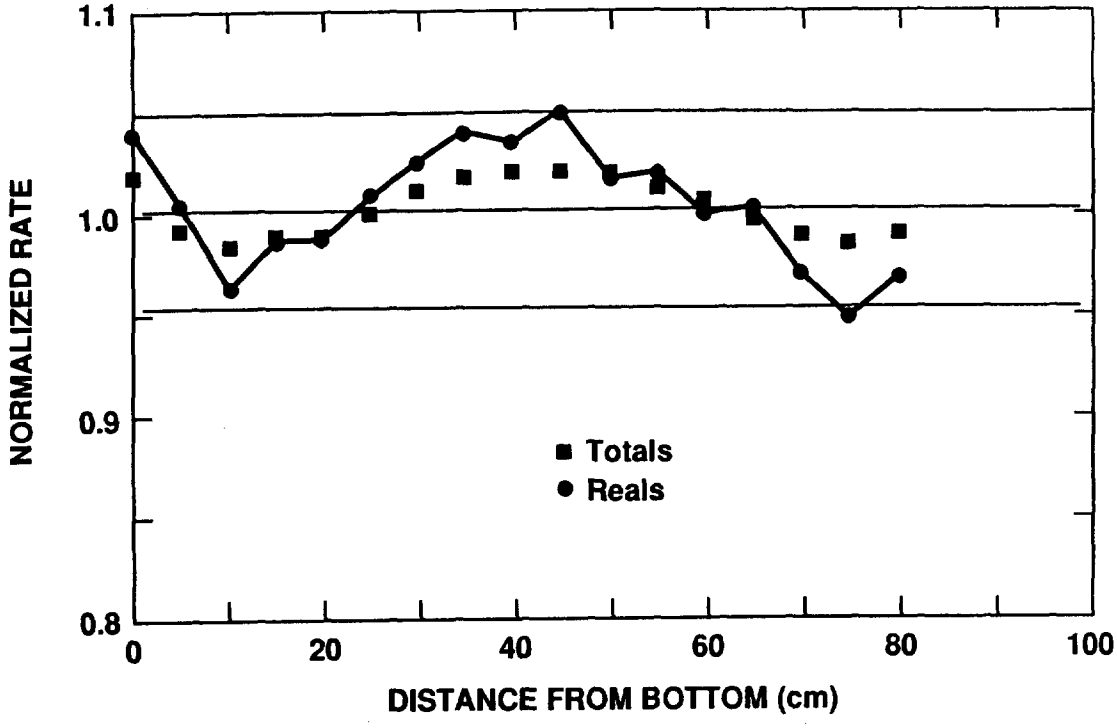

Figure 2

Totals and reals vertical response profiles measured by using ^{252}Cf at a radius of 20 cm in an empty 200-L drum.

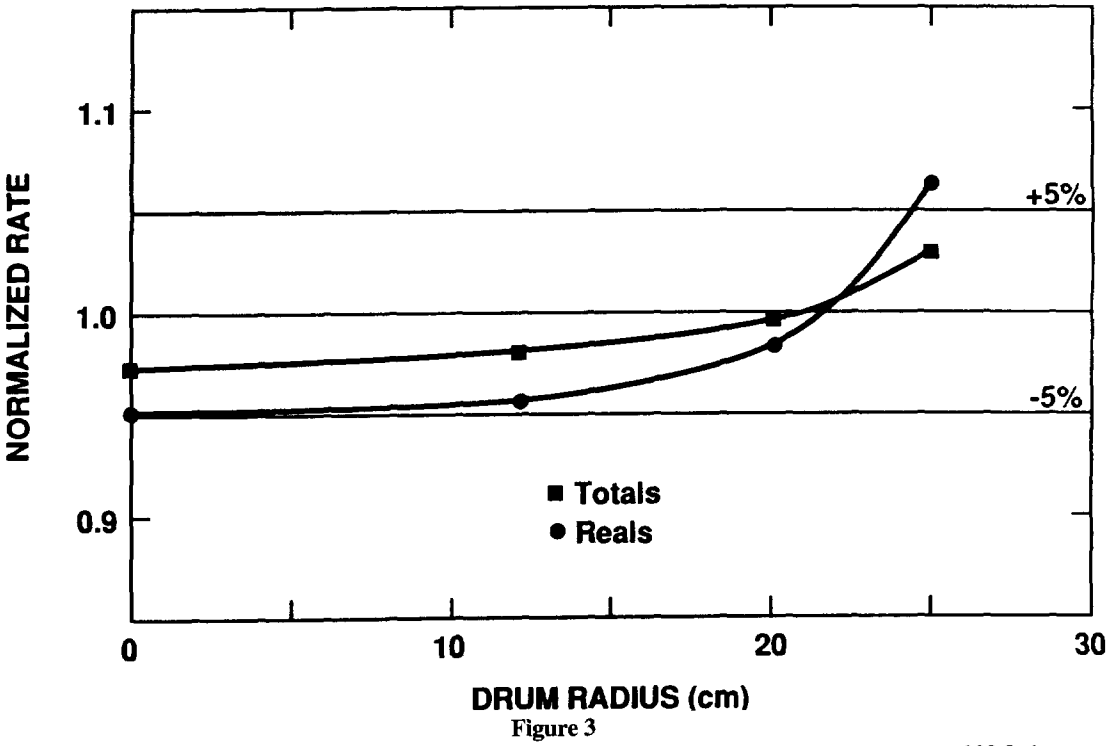

Figure 3

Totals and reals radial response profiles averaged over the heights of 15, 35 and 55 cm in an empty 200-L drum.

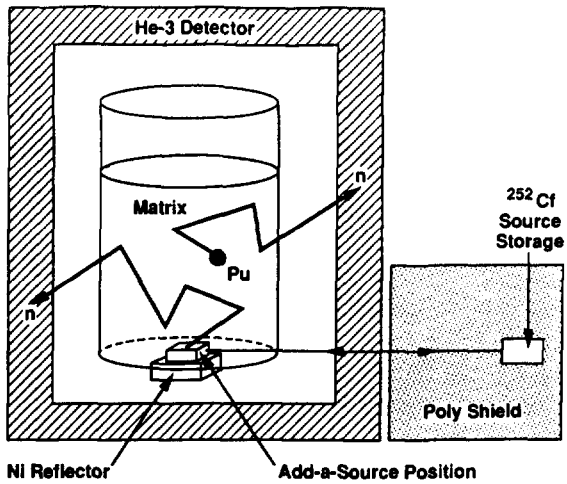

Figure 4

Schematic illustration for the "add-a-source" concept showing the Teleflex cable transfer system that moves the ^{252}Cf source from the shielded storage position to the matrix interrogation position.

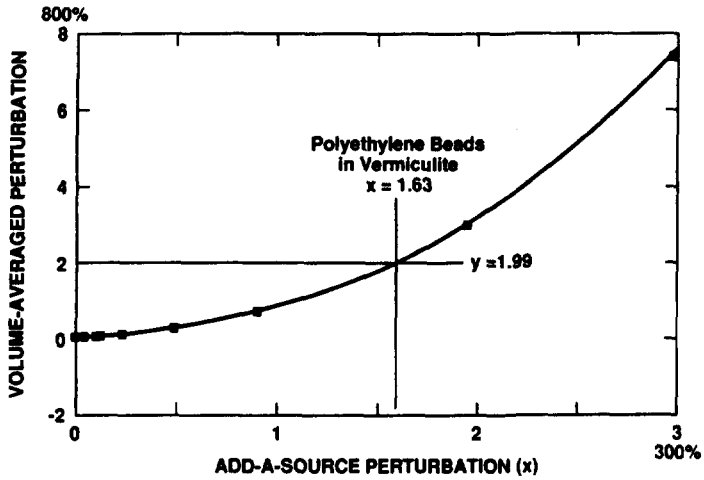

Figure 5

The "add-a-source" perturbation (x) in R vs. the volume-averaged perturbation (y) in R' for a variety of matrix materials in 200-L drums. The CH_2 beads in vermiculite ($\rho = 0.308$ g/cm^3) was run as an unknown.

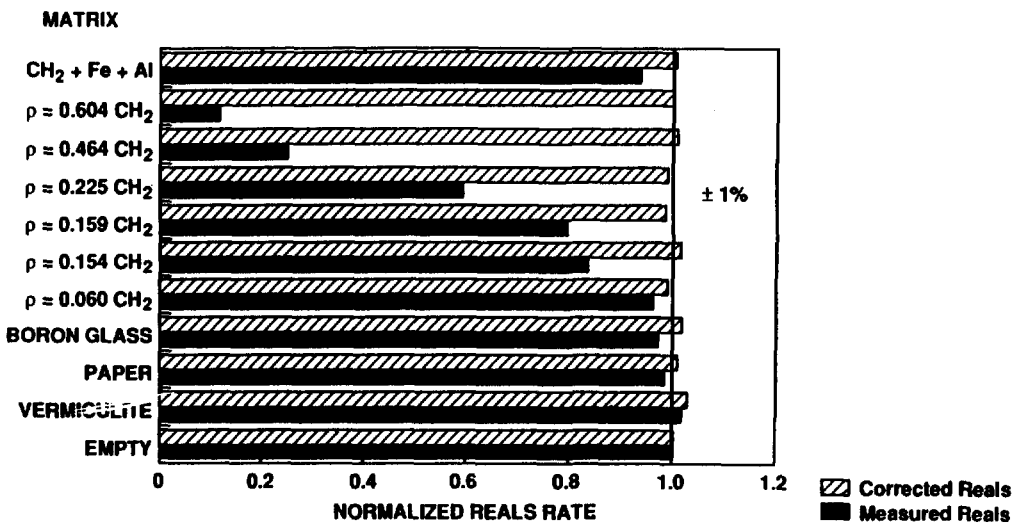

Figure 6

The measured reals and the "add-a-source" CF-corrected reals for various matrix materials in 200-L drums.

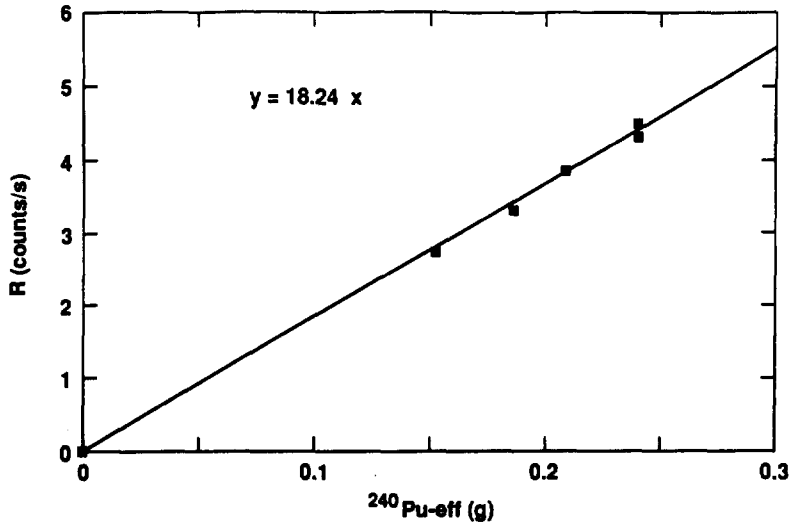

Figure 7

Preliminary calibration curve for (CF) *R* vs. the ^{240}Pu-eff mass for MOX pellets at Los Alamos.

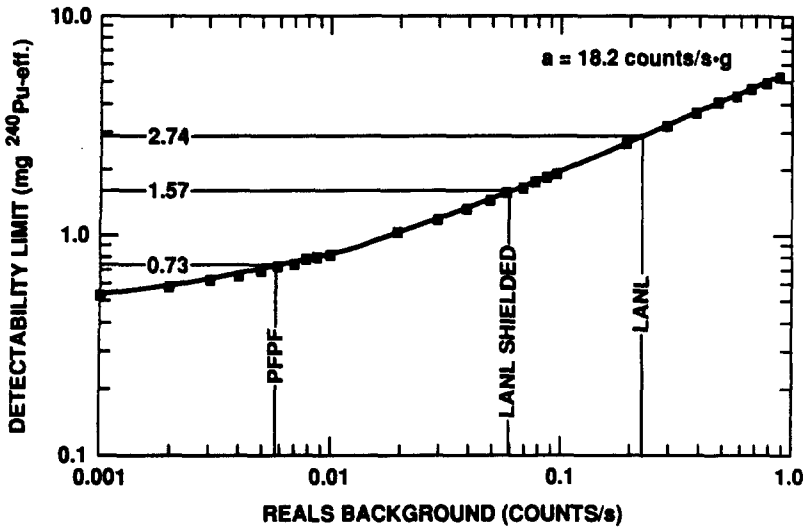

Figure 8

Calculated detectability limit vs. neutron coincidence background for a 1000-s measurement time.

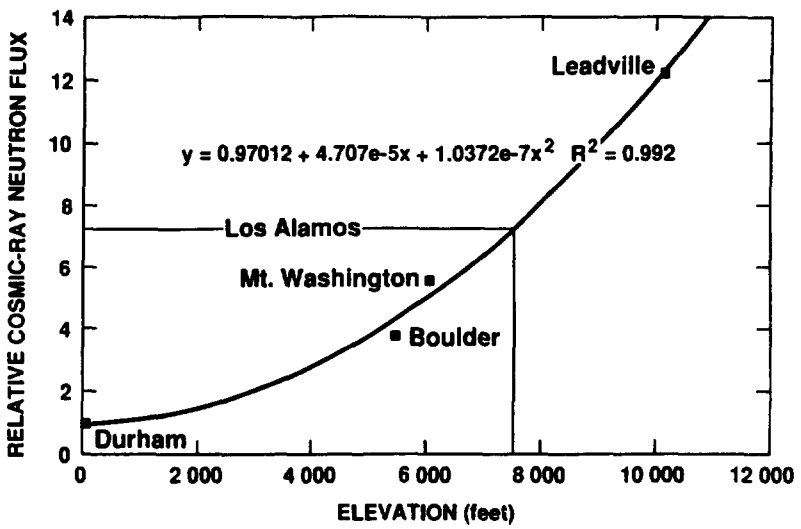

Figure 9

Measured cosmic-ray neutron flux[9] as a function of elevation above sea level.

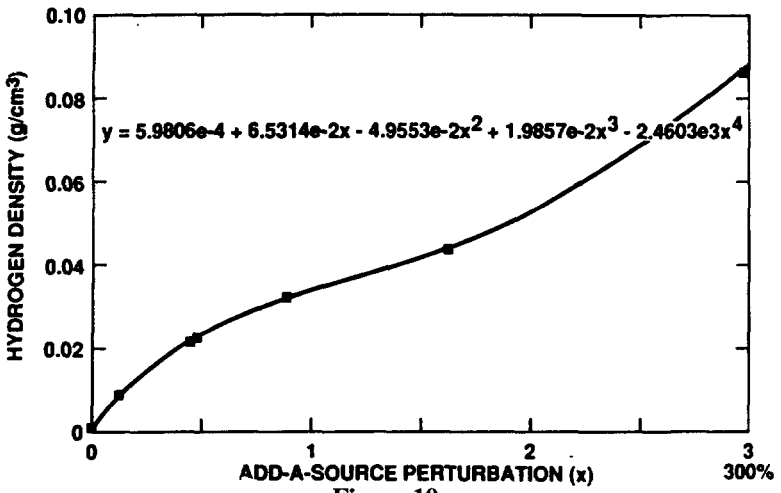

Figure 10

"Add-a-source" perturbation (x) as a function of hydrogen density in 200-L drums containing CH_2.

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H.O. Menlove received his Ph.D. in Nuclear Engineering from Stanford University in 1966. Prior to working at Los Alamos, Menlove had considerable experience in the areas of neutron and fission physics as well as gamma-ray spectroscopy. He spent a year at the Kernforschungszentrum in Karlsruhe, Germany, supported by a Fulbright Award. His recent work has been in the areas of instrumentation for international safeguards, neutron activation analysis techniques, the application of nuclear methods to the nondestructive assay of fissionable materials and the investigation of neutron emission from cold fusion experiments. Menlove has served as the International Safeguards Group Leader at Los Alamos National Laboratory, and he is currently a Los Alamos Fellow working in the area of Nuclear Safeguards research and development.

Swedish Experiences In Implementing National And International Safeguards

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ABSTRACT

International Atomic Energy Agency (IAEA) safeguards has been applied in Sweden since the early 1970s, and bilateral safeguards since mid 1950s. The Swedish State System for Accountancy and Control (SSAC) includes all regulations that follow from prevailing Swedish legislation and obligations regarding the peaceful uses of nuclear material, including NPT-safeguards, bilateral and multilateral undertakings. The system has been developed by the Swedish Nuclear Power Inspectorate (SKI), as being the national safeguards authority, in cooperation with the Swedish nuclear industry. This paper presents the background to and experiences from the implementation of the SSAC and the IAEA safeguards system, gained by the Swedish Nuclear Power Inspectorate and the Swedish nuclear industry, respectively. Joint approaches and solutions to some significant safeguards issues are discussed. The cooperation between the nuclear industry and the authority in R&D activities are also discussed, in particular with respect to the Swedish Support Programme to IAEA safeguards where the nuclear industry is actively involved by offering facilities for instrument testing and training of IAEA inspectors. The cooperative system between the National Safeguards Authority and the nuclear industry is emphasized, and some of the difficulties encountered in the system also are discussed.

INTRODUCTION

The utilization of nuclear energy in Sweden depends on Swedish legislation, bilateral agreements with countries supplying nuclear material or equipment and other arrangements adhered to by the Swedish government. Sweden became a member of the Treaty of Non-proliferation of Nuclear Weapons in 1970 and signed a Control Agreement with the International Atomic Energy Agency (IAEA) in 1975. Sweden has bilateral cooperation agreements, or the equivalent, with several countries. All these legal documents emphasize the peaceful uses of all nuclear material or equipment in Sweden. All the bilateral agreements and the NPT Safeguards Agreement with the IAEA include a large number of demands for accountancy and control of all nuclear material within Sweden. Periodic reporting of the material or equipment supplied under each separate agreement is required in addition to the reports to the IAEA. Physical control of the material is, however, always performed by the IAEA. IAEA safeguards is a provision in all bilateral agreements. Bilateral requirements are terminated in these agreements as long as IAEA performs its safeguards system in a satisfactory way.

The Swedish Nuclear Power Inspectorate (SKI) has been appointed by the government as the national authority for utilization of nuclear energy, excluding radiation protection. Accordingly, the SKI has been given the authority to issue all regulations and guidelines for the utilization of nuclear energy, including those required for Sweden to fulfill all undertakings in international treaties and bilateral cooperation agreements with arrangements adhered to by the government. All regulations related to safeguards are assembled in the Swedish State System for Accountancy and Control (SSAC). This means that the SSAC does not only cover undertakings made for NPT-safeguards, but also all other undertakings made, primarily in the bilateral cooperation agreements and otherwise the implementation of Swedish legislation. The SSAC includes guidelines for accountancy records, reporting system and provisions for material control. The SSAC regulates all relevant safeguards matters within Sweden with the nuclear facilities dealing only with the SKI and the SKI dealing with all international undertakings. Consequently, all international reporting to the IAEA and to bilateral parties is made by the SKI. The overall organizational structure is shown in Figure 1.

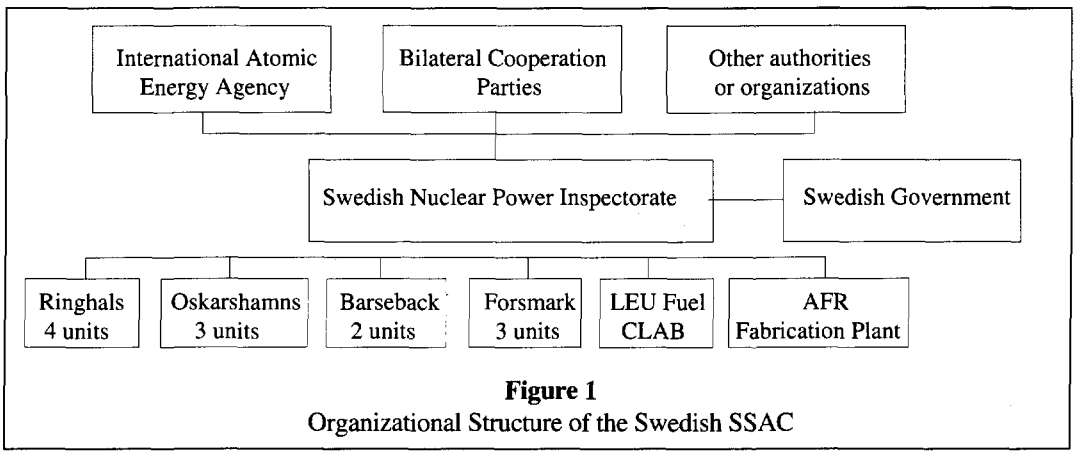

Figure 1
Organizational Structure of the Swedish SSAC

INTERACTION BETWEEN THE AUTHORITY AND NUCLEAR FACILITIES

Ultimately, all demands of nuclear material accountancy and control are directed to the nuclear industry. The nuclear facilities need to provide a plan for organization and routines that can handle the requirements in the SSAC and provide the information required. The regulatory system is derived, to a high degree, in collaboration between the SKI and the nuclear facilities. Regulations or guidelines are always discussed with the facilities before being issued, and the facilities will be formally invited to comment before any new rule is decided. The objectives of guidelines or regulations cannot be questioned once there is a formal agreement on the international level. However, the objective could be met in a number of ways, and the SKI and the facility cooperate in order to find the most effective solution for all parties: The aim of the SKI being to meet the Swedish policies and to fulfill undertakings made, and the aim of the operator is to reduce intrusion or work load. In most cases, acceptable solutions are found. As an example, when criteria for (revised) data base requirements were established, representatives from the nuclear industry and the SKI cooperated. As a result, the established data base criteria were easily accepted by all operators.

The principles for interactions between the national safeguards authority and the nuclear facilities are based on a model with open constructive interaction. Experience has shown the importance of mutual understanding of objectives, aims and difficulties for the parties concerned, i.e., the SKI and the operators. With such an understanding, it has been possible to design and implement an effective and efficient national safeguards system. Formal and informal discussions are held in an open atmosphere where matters of concern are discussed before any formal decisions are taken by the SKI. It has been considered important that organizational structure and working principles of the SKI favor interaction according to these principles. In order to further increase the efficiency of the system, an independent examination has been performed where the interactive processes between the SKI and the nuclear facilities have been examined. Problems that may reduce efficiency and thereby the effectiveness of safeguards were addressed, identified and possible to correct thereafter.

On the formal level, the SKI has a Safeguards Advisory Committee with members from the Parliament, other authorities and the nuclear industry. The Committee discusses the SSAC and its consequences for the nuclear industry. Advice from the Committee is seriously considered by the SKI before formal decisions in related issues are taken.

SAFEGUARDS IMPLEMENTATION AT A NUCLEAR POWER PLANT

Sweden has 12 nuclear power reactors located at four different sites. Nine units are ABB Atom designed BWRs, and three units are Westinghouse designed PWRs. In addition there is an "away from reactor storage" (CLAB) where irradiated fuel from all units are stored awaiting final deposition in deep geological storages. Although the place for the geological storage is not yet determined, the design of the storage has reached an advanced stage.

The nuclear power plants (NPPs) are free to design safeguards systems individually provided the guidelines and requirements in the SSAC will be fulfilled. In practice, the safeguards systems applied are similar at all sites, and the same general conclusions can be drawn on operability.

At the NPP, the safeguards accountancy system is part of the system used by the operator to generate all work permits for handling nuclear fuel. For a number of reasons, the NPP is obliged to have strict knowledge and control of all fuel assemblies and rods stored at each time and place. The safeguards system has been designed in a way that it includes all data relevant to safeguards, as well as safety or other internal aspects. The system is fully computer controlled, including routines for cross checking and interlockings. Updating of the safeguards system is thereby made any time there is a change registered such as location or handling of fuel.

The computerized records systems include information for calculation of burnup, residual heat, nuclear loss and production. The systems also calculate the fuel content of the nuclides U-235, U-236 and Pu-238–242. It should be noted that reporting of isotopic composition is not included in the agreement with the IAEA (except, of course, for U-235). Information about void history and control-rod-history is also included in the system.

Nuclear material used at a NPP is always subject to conditions of the bilateral cooperation agreement with the

supplying country, the so called origin of the material. Normally the nuclear material will be subject to conditions of *one* agreement, but it may well happen that nuclear material is subject to the conditions of *several* bilateral agreements. It is normal that a reactor core contains fuel assemblies of different origins, and that different conditions or obligations are attached to the different fuel assemblies. However, on the assembly level, the principle of proportionality is valid; i.e., obligations attached to the fresh unirradiated nuclear material will be valid also for the nuclear material produced or lost during irradiation *in the same proportion* as for the fresh fuel. Any obligation attached to a specific fuel assembly before irradiation will also be attached to the assembly after irradiation. Only if fuel rods from fuel assemblies with different origins are reassembled into a new assembly will there be overlapping and duplicate obligations attached to the resulting assembly. If there is a need to reassemble fuel elements, the operator makes a careful selection of the assemblies in order to avoid creating fuel with overlapping obligations attached.

Within the SSAC it is assumed that the nuclear material quantities included in fresh fuel received from the fuel fabrication plant have been adequately checked at the fuel fabrication plant. Measurements on fresh fuel could be considered duplicates for a nuclear power plant, but the option is still included in the relevant parts of the agreement with the IAEA. However, recently the IAEA has, as part of its flow verification, stated the need to reverify fresh fuel also at the NPP in connection with a physical inventory verification. NDA-measurements at a NPP are concentrated on irradiated fuel. Measurements are made by using the Cerenkov viewing technique and, in special cases, gamma measurement techniques. Each Swedish NPP is equipped with a special measurement position to which assemblies could be brought for gamma measurements, isolated from the high radiation background that will be unavoidable at a normal storage position. Although this equipment is available, the NPP wishes to reduce handling of fuel assemblies to an absolute minimum due to the very small but still existing risk of fuel integrity damage at each handling occasion, in favor of nonintrusive methods.

Surveillance systems utilized at NPPs are seals over the reactor pond and CCTV, primarily the MIVS system. The objective of the surveillance systems is to certify that no unauthorized shipments have taken place in between inspections. However, the system is vulnerable to unintentional disturbances such as loss of overhead light. In such a case, additional inspection efforts are needed. The surveillance systems are serviced by the IAEA every third month, the stated detection time limit for irradiated fuel. NPPs would favor a system where remote controlled or operated surveillance systems are utilized, provided that the same level of safeguards could be obtained. If so, the IAEA inspection frequency could be somewhat reduced.

Generally, normal routine inspections do not impose difficulties for the NPP. Verification after physical inventory taking presents a slightly different situation. The physical inventory verification is, within the Swedish SSAC, performed just before the reactor pressure vessel head is put on place. The verification includes identifying each assembly in the reactor core by number and position. The physical inventory verification inspection is on the critical path of the restart of the reactor. It can be difficult for the operator to predict the correct time for the final verification. Often this happens during weekends or nights. The inspections prolong the outage of the reactor and can impose economical losses for the operator. The inspections have, so far, always been performed at a time chosen by the operator in spite of the inconvenience for the SKI and IAEA inspectors.

In summary, it could be stated that the different components of the safeguards system at a NPP to a large extent would be introduced irrespective of the safeguards requirements. The NPP needs to have good records of burnup, residual heat, nuclide inventory, etc. The data are considered to be very important for traceability of nuclear material during the back-end of the fuel cycle. In Sweden, it is decided that all irradiated fuel will be finally disposed of in a geological repository. Consequently, the knowledge of material quantities disposed will be entirely dependent on the calculations made at the NPP and the traceability of the quantities of individual fuel assemblies to individual disposal containers at the geological repository.

IMPLEMENTATION AT A LEU FUEL FABRICATION PLANT

The ABB Atom fuel fabrication plant produces LEU fuel for both BWRs and PWRs, and is the only fuel fabrication plant in the Nordic countries. The plant feed material is UF^6 with an enrichment up to 5%. At the plant, the UF^6 is converted to UO_2 powder, pressed to pellets that will be loaded into rods and assembled to fuel assemblies. Besides manufacturing LWR fuel, BWR fuel channels and control rods are also manufactured. In addition, the division designs LWR fuel and cores. The annual capacity of the factory is 400 tonnes of UO_2, with an employment of about 550 persons. The factory is highly mechanized and automated. Fuel deliveries are made to Swedish reactors and to several countries outside of Sweden.

A well planned administrative system for the uranium handling is needed at a LEU fuel fabrication plant with many customers and deliveries to several countries. An extremely good records system is needed for the nuclear material for many reasons, such as:

- Economical — uranium is an expensive material,
- Good planning — a necessity for a short throughput time,
- Optimization of enrichment blending,
- Optimization of the ABB Atom owned stock of uranium,
- Ability to provide fast and accurate accounts to the customers,
- Traceability of the material, and
- Safeguards.

Inside the plant, there exists a great variety of uranium compounds of several different enrichments. As the customers own most of the uranium which is supplied from different countries, the variety of origins and obligation codes attached to the material is significant. The implementation of the provisions of bilateral agreements could have been very difficult had not the principle of proportionality been introduced in the bilateral cooperation agreements. Material from different suppliers is bound to be processed in the same production area and is often mixed in order to get the correct enrichments. If the principle of proportionality had not been introduced, all bilateral cooperation agreements would have been applicable to all the material. Within the plant, the factory production area is looked upon as a "black box" concerning nuclear material origins. This means that origins and obligation codes are not applicable for material in the production area and do not follow the material at internal transfers. Only when the material is being delivered to or sent from the fuel plant, are the codes or origins assigned to the material. At that time, the same proportion of supplied feed material will leave the factory as produced fuel.

Nuclear materials accountancy is computerized. Guidelines for the data base design issued by the SKI have been followed in order to facilitate automatic computer communication. The computer system includes safeguards, operational quality control and processing data. The system covers data from UF_6 through the production lines to complete assemblies for delivery. Drawing numbers, material lot numbers, analytical data, etc., are entered into the system. Input of data has been decentralized and often is made by the different operator's staff in the shops or in the analytical laboratory, which makes the system automatically updated and accurate at any time.

The computer system was introduced for several purposes — safeguards being only one. As mentioned, the system is also used for quality control purposes. Actually, the demands from the quality control point of view are often more severe than those for safeguards. One exception is limits of acceptable shipper - receiver differences in enrichment and uranium content of UF_6, where the safeguards requirements are more stringent than the specifications for quality control.

The aim to minimize the quantity of nuclear material unaccounted for cooperates with the economical benefit of taking care of every single gram of the material. Scrap recovery, good cleaning of ventilation systems, filters, production vessels and storage tanks are examples of how this double aim is achieved.

IAEA inspects the plant at least six times a year, according to the 1991-95 IAEA criteria. These criteria, which include verification of about 20% of the domestic material flow, has increased the number of inspections. Changes of the criteria that can influence inspection frequency or the safeguards activities applied need to be carefully explained and described to the operator and in particular to the plant production management. Management needs to understand why changes are issued in order to be motivated to increase the safeguards efforts.

To verify material flow, UF^6 cylinders available in the storage are weighed and checked for enrichment. Fuel assemblies produced and prepared for domestic shipment are measured by using NDA techniques. The measurement of fuel assemblies creates problems as the same personnel and equipment are needed both for production purposes and safeguards inspection activities. Since most assemblies are assembled and shipped from the plant during springtime, inspections during this time period are more intrusive to the operator than at other times. To obtain the verification goal, more frequent inspections with inspection work at odd hours may be necessary during this period.

Once a year, a physical inventory takes place. Normally, the inventory-taking is planned in connection with the summer holidays and fuel fabrication shut down period. The time is chosen primarily to fit the production schedule. During the physical inventory verification, the SKI and IAEA inspectors are allowed to use the plant's rod scanner. Authentication of data can be obtained by using special IAEA and SKI standard rods which are normally sealed and not used by the plant. Other NDA measurements are made by using portable instruments.

When exporting LEU fuel, the SKI will, after a request from the operator, handle all international procedures to obtain the necessary authorizations for export or re-export. The operator makes sure that all necessary information about the nuclear material is available. The SKI interacts with other authorities, both within Sweden and in other countries concerned, making sure that all obligations undertaken in bilateral agreements or treaties are fulfilled. When these procedures are fulfilled and the necessary assurances obtained, the government or, in some cases the SKI, makes a decision about issuing an export licence.

R&D ACTIVITIES

Safeguards require research activities in order to maintain a high level. Technological development, in general, goes quickly and the methods applied in both national and international safeguards need to keep a high standard in order to remain trustworthy. Research activities are needed both in the long- and short-term perspective. Support programs to IAEA contribute, at least presently, to the short-term needs of the Agency. The Swedish Support Programme (the SSP) relates mainly to the practical implementation of safeguards. The contributions of the nuclear industry play a very important role. Participation in training of IAEA inspectors and testing of new techniques are relevant examples.

For the nuclear industry, safeguards is required for continued operation: Effective safeguards with a high level of assurance of the peaceful uses of the nuclear material gives credit to the nuclear industry, and efficient safeguards provides for less interference in the production structure of the plant. For the nuclear industry, it could be a good investment to contribute actively to safeguards research and develop-

ment. For NPPs and AFRs, low intrusiveness and quick verification methods for irradiated fuel are highly desired. The fuel assemblies stored get older and the number increases rapidly. Time-consuming methods for verification may turn out to be impossible to use, and the current level of assurance could then not be maintained.

The SKI and the nuclear facilities discuss, on a continuous basis and in an open manner, the current safeguards system applied both by the SKI and the IAEA. The SKI is thereby in a position to obtain direct information from the operator about advantages or difficulties of the various methods applied and also to obtain operator proposals for approvals. Conversely, the SKI gives information to the operator about new techniques under development and new approaches to current safeguards applications. Active participation of the nuclear facilities in the R&D activities gives very good possibilities to the support program to contribute in the development process of future safeguards.

Participation in R&D activities, particularly in connection with the support program, also gives the nuclear industry a possibility to influence the future direction of international safeguards.

CONCLUSIONS

A high level of national and international safeguards has the same unquestionable value on the national level as for the nuclear industry. The peaceful uses of nuclear material must never be questioned, and the possibility of obtaining international assurance of the peaceful uses is a prerequisite for continued use of nuclear energy and for continued supply of nuclear material and equipment.

The model for cooperation between the SKI as the national safeguards authority and the nuclear industry has been implemented for at least one decade. All experiences obtained support the principle of open interaction in obtaining more effective and efficient safeguards. In the few cases where there are differences of opinions, the mutual understanding of each party helps overlap any difficulty that may arise from the application of an inconvenient method. With this model, Sweden has found a way to certify that safeguards is applied in an effective and efficient way at Swedish facilities and thereby securing the necessary level of assurance and, at the same time, taking due account of the need for integrity and responsibility for the SKI and the operators respectively.

The objectives of safeguards are determined in treaties and bilateral agreements and should not be questioned. The way to obtain these objectives could, however, differ at different facilities. The close cooperation between the SKI and the operators contributes to achieve a solution that would minimize interference and that also would fit well into presently applied systems for production control at each different facility.

Systems for safeguards accountancy and control can be integrated in the normal recording and controlling systems of a NPP or a LEU fuel fabrication plant. In addition, specially designed systems particularly for safeguards are, in most cases, not required.

Nuclear energy cannot be utilized without the general public's acceptance. A high level of international safeguards, with assurances of the peaceful uses of nuclear material used in energy production is a prerequisite for any commercial use of nuclear material. This recognition strongly motivates the nuclear industry to actively participate in obtaining an effective and efficient safeguards system.

Monika Eiborn has a bachelor's degree in mathematics and chemistry, which she received at the University of Gothenburg. She joined ASEA-ATOM, presently ABB Atom in 1970 and has worked in different positions. For two years, 1976-77, she worked with Alfa Laval in Teheran. In 1979, she headed the chemical laboratory at ASEA-ATOM and has been manager for quality control since 1982, first for the production of powder and pellets and later for the entire fuel production. In 1988, Eiborn became manager of safety and safeguards. Her present position at ABB Atom is director of public relations, with simultaneous responsibility for safeguards and security at ABB Atom LEU Fuel Fabrication Plant in Vasteras.

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Measurement Technology At Selected DOE Facilities: A Status Report

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ABSTRACT

There are to be target values established for Department of Energy (DOE) facilities which perform accountability measurements for nuclear materials. As part of the decision process for making a reasonable selection of those target values, information aboutthe status of measurement technology at sites doing accountability measurements on Category I, II and III materials was collected and tabulated. Information about the technology used at seven sites is provided in four tables. Information about some proposed target values is provided in three tables. A comparison of the most accurate accountability assay methods used at the sites and the proposed target values is made in a final table. Additional observations about the individual site information are provided, and selected method literature references are given.

INTRODUCTION

The Office of Safeguards and Security (OSS), U.S. Department of Energy (DOE), will issue guidance for measurement control and for measurement target values accompanying a new Material Control and Accountability (MC&A) Order, DOE 5633.3A.To aid the OSS in understanding the present measurement technology utilized at contractor facilities for accountability measurements, a survey was made, through DOE field offices of seven selected sites. That information was collected and tabulated for use by OSS and is presented, in part, in the accompanying tables.

Requests were made through OSS in September 1990 to Albuquerque, Idaho, Oak Ridge, Richland and Savannah River field offices for information about technology used for accountability measurements. Accountability measurements of Category I, II and III materials were to be included. A list of the measurement techniques used, together with the associated measurement uncertainty (both random and systematic error components, if available) for process and product materials, was requested. It was requested that the list indicate whether the measurement made was online or offline and that it specify the element and chemical form, e.g., Pu - metal, U - oxide, Pu - solid waste, etc., of the material being measured. Materials, such as fuel rods, for which item accountability with confirmatory measurements are done, were not to be included.

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MEASUREMENT SURVEY AND TARGET VALUE SUMMARIES

The information received included all accountability analysis methods for Category I, II and III materials and, in many cases, those for waste streams. OSS is in the process of reviewing available target value listings which are applicable to DOE accountability measurements. Table I contains some proposed target values[1] for the methods used to measure product and process solutions. The proposed target values are for the methods only and do not include sampling or matrix effects. Table II contains information on some of the measurement technologies in place for solutions at the selected facilities. The data in Table II are for accountability solution measurements of process, product and in some cases, waste. Tables II-A and II-B break the data down into smaller pieces which are easier to compare to the proposed target values. Selected analysis methods are referenced under 10 topical headings in the reference section to provide additional information on some of the methods used for analysis at DOE sites.

A few sites are reporting measurement data from combined methods (e.g., volume and assay for tanks, calorimetry and gamma analysis for metal); use of target values for comparison to combined methods may be a consideration for future modifications to target value tables. Table III contains proposed target values[1] for sampling liquids and solids. Tables IV and V contain information on proposed target values and on measurement technology used for solids, respectively. Table VI contains measurement technology information for

nondestructive assay (NDA). Table VII contains measurement technology information from the sites for gases.

The information for both the proposed target values and the site's measurement values includes the associated measurement uncertainty. The random component (repeatability) or precision of the measurement is stated as percent relative standard deviation (%RSD = 100(s/x)). The systematic component or bias is an estimate of the uncertainty of the measurement derived from the calibration process for the measurement technique. Two pieces of information germane to a strict intercomparison of the data were omitted from the original request, i.e., a description of the standards used for calibration of the measurement systems and a statement of the confidence levelof the uncertainty. Site A provided some information on the calibration standards used for the measurement systems. Sites B, C and F included a statement on the confidence level on the uncertainty calculations. Sites B and C used a one-sigma confidence level; site F used a two-sigma confidence level. To directly compare data from site F to sites B and C, divide the data for F by two. Depending upon the final use of the information from the survey, an additional request for these items may be made to all sites.

Table I
Some Proposed Target Values[1] for Solution Accountability Measurements for Process and Product Materials

Measurement Type	*Material Type*	*Precision or % Rel Ran Er*	*Bias or % Rel Sys Er*
Tank Volume	Pu Nitrate	—[a]	—[a]
Titrimetry	Pu Nitrate	0.1	0.05
Coulometry	Pu Nitrate	0.1	0.05
X-ray Fluorescence	Pu Nitrate	0.5	0.5
K-edge Densitometry	Pu Nitrate	0.2	0.2
Spectrophotometry	Pu Nitrate	0.2	0.2
Isotope Dilution MS	Pu Nitrate	0.1[b]	0.1[b]
Titrimetry	U Nitrate	0.075	0.05
Gravimetry	U Nitrate	0.1	0.1
X-ray Fluorescence	U Nitrate	0.5	0.5
Spectrophotometry	U Nitrate	0.2	0.2
Isotope Dilution MS	U Nitrate	0.1[b]	0.1[b]

a. "DWK Workshop on Tank Calibration and the Caldex Exercise," R. Weh, ESARDA Bulletin #10, ISSN 0392-3029, June 1989.

b. Consultants' Meeting on International Standards of Measurement, Recommendations, June 3-5, 1991.

Table II
Solution Accountability Measurements by Selected Sites from the Technology Survey for the OSS

Site	*Measurement Technology*	*Material Description* *Measurement*	*Elem.*	*Chem. Form*	*% Rel Ran Er*	*% Rel Sys Er*
(A)	Manometer	Vol,13-2000L	Pu	Nitrate	1.51-2.12	.32-4
(A)	Ruska Elec.	Vol, 2000L	Pu	Nitrate	0.28	.05
(A)	Drexelbrook Capacitance Probe	Vol, 31-189L	Pu	Nitrate	.06-2.9	.17-2.1
(A)	Sonic Probe	Vol, 87L	Pu	Nitrate	.1	.73
(A)	Vacuum Tube	Vol, 10-20mL	Pu	Nitrate	.01	NA
(A)	Density Meter	Density	Pu	Nitrate	.05	.01
(A)	Diode Array	0.2-200g/L,Vol	Pu	Nitrate(IV)	2.1	.22
	Spectro-	0.2-200g/L,Wt.	Pu	Nitrate(IV)	.65	.2
	photometry	Assay, Vol.	U	Nitrate(IV)	2.7	.38
(A)	CPC	Assay,.8-2.5g/L	Pu	Nitrate	.11	.06
(A)	LANL Soln Assy	Assy,10-5000mg/L	Pu	Nitrate(IV)	25.0	5.0
(A)	X-ray Fluor	Assay, 5-100g/L	Pu	Nitrate(IV)	.15-1.0	NA
(A)	Emission Spec	Impurities	Pu	Nitrate	.02	.001
(A)	Mass Spec	Isotopic	Pu	Nitrate	.1	.03
(A)	Mass Spec	Isotopic	U	Nitrate	.1	.03
(A)	IDMS	Assay & Isotope	U	Nitrate	.83	.19
(B)	Soln Assay Instrument	Assay, with Vol. Sampling	Pu	Nitrate & Chloride	3.9	.66
(B)	Soln Assay Instrument	Assay, with Wt. Sampling	Pu	Nitrate & Chloride	2.2	.54
(C)	X-ray Fluor	Assay, .5-100g/L	Pu	Aqueous	3 (Uncertainty)	
(C)	X-ray Fluor	Assay,100-300g/L	Pu	Aqueous	6 (Uncertainty)	
(C)	X-ray Fluor	Assay, 1-100g/L	Pu	Aqueous	2 (Uncertainty)	
(D)	Density Meter	Density	Pu & U	Nitrate	.10	.10
(D)	Amperometric Titr'n	Assay	Pu	Nitrate	.20	.03
(D)	IDMS	Assay & Isotope	Pu & U	Nitrate	.50	.29
(D)	Alpha Spec	Assay	Pu	Nitrate	2.17	25.0
(D)	Alpha Spec w/ Extraction	Assay	Pu	Nitrate	1.21	7.6
(D)	Mod D&G Titr'n	Assay	U	Nitrate	.20	.17
(D)	Laser Fluoresence	Assay	U	Nitrate	8.5	5.6
(D)	X-ray Diffraction	Assay	U	Nitrate	.83	2.0
(E)	Ruska Elec.	Volume	U	Nitrate	.1-.22	.1-.3
(E)	Rosemount Trans.	Volume	U	Nitrate	7.4	1.2
(E)	Scale, Mettler	Mass	U	Nitrate	.03	.02
(E)	Ruska Elec. w/	Assay,	U	Nitrate	.4	.2
	Mass Spec, IDMS	.5-3g/L	^{235}U		.05	.02
(E)	Ruska Elec. w/	Assay,	U	Nitrate	.4	.2
	Mass Spec, IDMS	100-400g/	^{235}U		.05	.02
(E)	Ruska Elec. w/ Fluorophotometric	Assay, .001-.01g/L	U	Nitrate(IV)	10	1
(F)	X-ray Fluor.	Assay, >3 mg/g	U	Nitrate	1.38, Avg 1.0	
(F)	X-ray Fluor.	Assay, <3 mg/g	U	Nitrate	1.5	1.0
(F)	Mass Spec	Isotopics ≥93.15%	^{235}U	All Solns.	.05, Avg .01	
(F)	Mass Spec	Isotopics ≤93.15%	^{235}U	All Solns.	.45, Avg .2	

Table II-A
Liquid Assay Measurements (Solution Accountability Measurements from the Technology Survey for the OSS)

Measurement Method	*Material Type*	*Precision or % Rel Ran Er*	*Accuracy or % Rel Sys Er*
Alpha Counting	Pu Nitrate	1.21-4.5	1.0-25.0
Solution Assay-NDA (Non-Destructive Assay)	Pu Nitrate & Chloride	2.2-25.0	0.54-5.0
Diode Array Spec (DAS), with Volumetric Sampling	Pu Nitrate	2.1	0.22
DAS, with Sampling by Mass (Wt.)	Pu Nitrate	0.65	0.2
X-ray Fluorescence	Pu Nitrate	0.15-1.38	1.0-6.0
Controlled Potential Coulometry (CPC)	Pu Nitrate	0.11	0.06
Isotope Dilution Mass Spectrometry (IDMS)	Pu/U Nitrate	0.05-0.83	0.02-0.29
Laser Fluorescence	U Nitrate	8.5	5.6
Fluorophotometry	U Nitrate	10	1
Ultraviolet (UV) Fluorescence	U Nitrate	12.1	10.0
Transition Corrected Gamma	U Nitrate	1.32	2.0
DAS, with Volumetric Sampling	U Nitrate	2.7	0.38
X-ray Diffraction	U Nitrate	0.83	2.0
Modified Davies and Gray Potentiometric Titration (Mod D&G Titr'n)	U Nitrate	0.2-0.45	0.1-0.17

Table II-B
Tank Volume Measurements (Solution Accountability Measurements from the Technology Survey for the OSS)

Measurement Method	*Material Type*	*Precision or % Rel Ran Er*	*Accuracy or % Rel Sys Er*
Manometer	Pu Nitrate	1.5-2.12	.32-4.0
Drexelbrook Capacitance Probe	Pu Nitrate	.06-2.9	.17-2.1
Ruska Electromanometer	Pu Nitrate	.28	.05
Ruska Electromanometer	U Nitrate	.1-.28	.05-.3

Table III
Some Proposed Target Values[1] for Accountability Sampling Measurements for Process and Product Materials

Sampling Type	*Material Type*	*Precision or % Rel Ran Er*	*Bias or % Rel Sys Er*
Drill	Pu Metal	—	—
Lathe	Pu Metal	—	—
Proportional	PuO^2 Powder	0.1	—
Aliquant-by Mass	Pu Nitrate	0.2	0.2
by Volume	Pu Nitrate	0.2	0.2
Random	U Metal	0.06	—
Aliquant- by Mass	Uranyl Nitrate	0.05	—
by Volume	Uranyl Nitrate	0.1	—
Mechanical Blend/Grab	UO_2 Powder	0.2	—
Proportional	UO_2 Powder	0.2	—
Pellet	UO_2 Pellet	0.05	—
Gas	UF_6	—	—
Liquid	UF_6	0.2	—

Table IV
Some Proposed Target Values[1] for Accountability Measurements of Solids for Process and Product Materials

Measurement Type	*Material Type*	*Precision or % Rel Ran Er*	*Bias or % Rel Sys Er*
Titrimetry	Pu Metal & Powder	0.1	0.05
Coulometry	Pu Metal & Powder	0.1	0.05
Gravimetry	Pu Powder	0.1	0.1
Spectrophotometry	Pu Powder	0.2	0.2
Titrimetry	U Powder & Pellet	0.075	0.05
Titrimetry	U-Al Alloy	0.15	0.2
Gravimetry	U Powder & Pellet	0.1	0.1

Table V
Mass & Destructive Accountability Measurements of Solids by Selected Sites from the Technology Survey for the OSS

	Measurement	*Material Description*			*% Rel*	*% Rel*
Site	*Technology*	*Measurement*	*Elem.*	*Chem. Form*	*Ran Er*	*Sys Er*
(A)	Sampling, drill	Isotopic Dist.	Pu	Metal	.10	.05
(A)	Scale, load cell	Mass, <23 kg	Pu	Powder	1.0	1.0
(A)	Scale, Analytic	Mass, <23 kg	Pu	Metal	.01	.01
(A)	Scale, Analytic	Mass	U	Alumina	.01-.1	NA
(B)	Ceric Titr'n	Assay	Pu	Metal	.045	.022
(B)	Coulometry (CPC)	Assay	Pu	Metal & Oxide (add .15 for oxide wt)	.2	.12
(B)	Spec III	Assay	Pu	Oxide	.22	.13
(B)	Chem. & Wt.	Assay on Feed	Pu	Metal	.1-.11	.12-.13
(B)	Mod D&G Titr'n	Assay	U	Metal Oxide (add .15 for oxide wt)	.08	.08
(C)	X-ray Fluor.	Assay, on 0.5-0.88g/g	Pu	Oxide	6 (Uncertainty)	
(C)	X-ray Fluor.	Assay, on 0.6-0.84g/g	U	Oxide	2 (Uncertainty)	
(C)	Ceric Titr'n	Assay	Pu	Metal	.043 (Uncertainty)	
(C)	Mass Spec	Isotopics	Pu	Metal & Oxide	.2 (Uncertainty)	
(C)	Scale, Analytic	Mass	Pu & U	All Solids	.01-.001-	1.167-.889
(D)	Amper. Titr'n	Assay	Pu	Oxide	.20	.03
(D)	Mod D&G Titr'n	Assay	U	Oxide	.15	.13
(D)	IDMS	Assay & Isotopic	Pu	Metal	.5	.29
(D)	IDMS	Assay & Isotopic	Pu & U	Oxide	.5	.29
(E)	Scale, Anal w/ Mass Spec, IDMS	Assay & Isotopic	U ^{235}U	Oxide	.4 .05	.2 .02
(F)	Mod D&G Titr'n	Assay	U	Oxide	.45,	Avg .1
(F)	Mass Spec.	Isotopic	U	All Solids	.05,	Avg.
(F)	X-ray Fluor.	Assay	U	Residue & Waste	2.8,	Avg 1.5
(F)	Mass Spec	Isotopics	^{235}U ≥93.15%	All Solns	.05,	Avg .01
(F)	Mass Spec	Isotopics	^{235}U ≤93.15%	All Solns.	.45,	Avg .2
(G)	Scale, Electronic	Mass	U	Oxide	1.1	2.0
(G)	Mod D&G Titr'n	Assay	U	Oxide	.34	.15
(G)	Mod. D&G w/ Gamma Spec.	Assay & Isotopic	U	Oxide	1.8	.24

Table VI
NDA Accountability Measurements of Solids by Selected Sites from the Technology Survey for the OSS

	Measurement	*Material Description*			*% Rel*	*% Rel*
Site	*Technology*	*Measurement*	*Elem.*	*Chem. Form*	*Ran Er*	*Sys Er*
(A)	NDA, Segmented Gamma Scanner(SGS)	Assay, on 0-200g	Pu	Fluoride & Oxide	3.2	NA
(A)	NDA, Calorimeter	Assay	^{238}Pu	Oxide	.23	NA
(A)	NDA, Calorimeter	Assay	Pu	Oxide	.38	.13
(A)	NDA, LANL Solid System	Isotopics	Pu	Oxide & Metal	.4	.05
(A)	NDA, Far Field Gamma	Experimental System	U	Alumina	Dev.	Dev.
(A)	NDA, Cf Shuffler \Delayed Neutrons	Assay	U	Alumina	.3	.2
(B)	Calorimetry & Gamma Spec	Assay & Isotopic	Pu	Metal & Oxide	.3-.5	.2-.6 (add.15 uncertainity for wt. of Oxide)
(B)	Calorimetry & Mass Spec	Assay & Isotopic	Pu	Metal	.3-.4	.15
(C)	Calorimetry & Gamma Spec	Assay & Isotopic	Pu	Metal & Oxide	0.1-5 (Uncertainty)	
(D)	Gamma Spec (Ge/Li)	Isotopic	Pu	Metal & Oxide	.60	6.7
(D)	Calorimetry & Gamma Spec	Assay & Isotopic	Pu	Metal & Oxide	.7	.3
(D)	Gamma Spec (Na/I)	Assay	Pu	Waste	25	25
(D)	Gamma Spec (Na/I) Portable	Assay	Pu	Holdup	78	21
(D)	SGS, Small	Assay	Pu	Waste	1.6	6.7
(D)	SGS, Large	Assay	Pu	Waste Drums	7.4	2.2
(D)	SGS, Slag & Crucible	Assay	Pu	Reactive Scrap	7.6	6.7
(F)	SGS, Small	Assay, Can	U	Ceramic, Ash Carbon, Leach	3.2 @ 208g	2.0
(F)	SGS, Large	Assay, Barrel	U	Paper, Ash Carbon, Leach	4.66 @ 173g	4.0
(F)	Active Well Coincidence Counter	Assay	U	Oxide & Crucible Waste	7.0 @ 8700 g	10

OBSERVATIONS

Site A: Site A provided the most complete information in the survey. Sampling uncertainty for tanks has been determined and listed separately from analysis uncertainty, and many online measurements were identified. Site A is apparently developing the information base to provide propagated error analyses, but the information for sampling and method error combined was not requested and not reported. Measurements on Category IV materials were also included. The methods selected generally appeared appropriate for the material being analyzed and were technologically modern. Overall, the precision and bias numbers were reasonable for the techniques in use. In several methods, the precision and bias were stated as being from traceable standards.

The data on solution measurements for sites A, B, C, D, E and F are given in Table II. The measurements are compared below for site A to proposed target values given in Table I. The values for plutonium analysis by controlled potential coulometry agreed with the proposed target values. The plutonium spectrophotometry analysis values agree with the target bias but not the target precision. The uranium spectrophotometry values agree with neither target value. Although the diode array spectrophotometry (DAS) plutonium analysis values exceed the precision of proposed target values, the method was a great improvement over past methods used at site A for plutonium nitrate in tanks (alpha counting). The DAS method is relatively new and provides better precision and accuracy than the LANL solution assay instrument. The only spectrophotometric method which reached the proposed target value was site B's Spec III system, which was reportedly used for Pu solids (oxide).

Table VII
Accountability Measurements of Gases from the Technology Survey for the OSS

Site	Measurement Technology	Material Description: Measurement	Material Description: Elem.	Material Description: Chem. Form	% Rel Ran Er	% Rel Sys Er
(A)	Calorimetry	Assay	H	Tritium Gas	.32	.48
(A)	Mass Spec.	Isotopic	H	Tritium Gas	.13 to .27	-.06 to -.33
(F)	Gravimetry w/ Impurity Corrections	Assay	U	UF_6 Gas	.11	.1
(F)	Mass Spec	Isotopic	^{235}U ≥93.15%	UF_6 Gas	.05,Avg	—
(F)	Mass Spec	Isotopics	^{235}U ≤93.15%	All Solns.	.45,Avg	.2
(G)	Scales	Mass	U	UF_6 Gas	.0030	.0011
(G)	Mass Spec (Inline)	Isotopic by Process, Interim	U	UF_6 Gas	.18	.0066
(G)	Gravimetry w/ Impurity Corrections	Assay	U	UF_6 Gas (Hydrolyzed)	.013	.025
(G)	Mass Spec	Isotopic by Analytical Lab	U	UF_6 Gas	.032	.015

Site B: Site B provided a good breakdown of their measurement methods. The data presented the precision statement and the bias statement each as a total value for the combined analysis, e.g., calorimetry and gamma isotopics were given with a single bias and precision value. Site B has apparently done propagated error analysis and already reports the data in the combined form. The data were arranged by material type, and only the methods for materials from the requested Categories I, II and III were listed. All of site B's analyses are performed offline, which is reasonable for their process operation which is much smaller in scale than that of site A. Most of site B's accountability measurements are made on solids rather than on solutions. The precision and bias statements for the solution assay instrument, as indicated above, are more similar to the DAS system than to the Spec III system. The traceability for the measurement standards was not requested and not specified.

Site C: Site C provided the error statement with percent uncertainty data for the measurement methods rather than the preferred random and systematic components. Site C will be producing data which will give both random and systematic components to their analytical laboratory measurements in the near future. No indication of sampling studies or sampling errors was included in the analysis methods. The X-ray fluorescence spectroscopy for the tank measurements is considered an old technology which does not compare favorably with state-of-the- practice measurements. All measurements were listed as being made offline; a reevaluation of this practice may be needed on resumption of processing at the site. Site C's analytical laboratory has purchased a controlled potential coulometer for plutonium analysis and standard checks which should give better future traceability. Information on Category IV materials was provided in addition to the I, II, and III Category materials.

Site D: Information from Site D on measurement methods was reasonably complete. The indication from the references for error statements was that studies with traceable materials may not have been performed to establish those values. The amperometric titration and the alpha spectrometry with extraction methods may no longer be in use due to environmental concerns. Site D may be interested in the diode array spectrophotometry system and/or in controlled potential coulometric plutonium determinations for future applications. Site D was the only site to give accountability values for holdup measurements.

Site E: Site E has a single assay accountability measurement, isotope dilution mass spectrometry (IDMS), which has random and systematic errors which reflect state-of-the-practice capabilities. A recent NBL assistance report for the site indicated that significant progress has been made in IDMS capabilities in recent years. There was no indication given of sampling errors or studies to determine sampling error contributions to measurements. The was evidence of propagated error analysis by site E.

Site F: The list provided by site F included Category IV materials in addition to the requested Category I, II and III materials. The gravimetric and the modified Davies and Gray titration determinations of uranium both have higher than normal random error components. Sampling contribution to the measurement error was not indicated in the report. A recent review at the site indicated that the modified Davies and Gray titration was being used to analyze samples from non-homogeneous waste materials. No study has been performed on the effects of sampling on the waste analyses at the site; use of the SGS systems may provide advantages for such waste determinations.

Site G: The scale and balance data provided may includes only the calibration of the weights used for scale calibrations in the plant. According to recent survey reports, the balance control program at site G needs increased attention. The

Table VIII
Most Accurate Accountability Assay Measurements for Uranium and Plutonium by Site Compared to Proposed Target Values[1]

Facility	*Measurement Method*	*Material Type*	*Precision or % Rel Ran Er*	*Accuracy or % Rel Sys Er*
Target	Titrimetry/Coulometry	Pu	0.1	0.05
Target	Titrimetry	U	0.075	0.05
Target	Gravimetry	U	0.1	0.1
Target	IDMS	Pu, U	0.1	0.1
(A)	CPC, Assay	Pu	0.11	0.06
(A)	IDMS, Assay & Isotope	U	0.83	0.19
(B)	Ceric Titr'n, Assay	Pu	0.045	0.022
(B)	Mod D&G Titr'n, Assay	U	0.08	0.08
(C)	Ceric Titr'n, Assay	Pu	0.043 (Uncertainty)	
(C)	X-ray Fluorescence, Assay	U	2 (Uncertainty)	
(D)	Amperometric Titr'n, Assay	Pu	0.2	0.03
(D)	Mod D&G Titr'n, Assay	U	0.15-0.2	0.13-0.25
(E)	IDMS, Assay & Isotopic	^{235}U	0.05	0.02
(F)	Gravimetry, w/Impurity Correction, Assay	U	0.11	0.1
(F)	Mass Spec., Isotopics	^{235}U ≥93.15%	0.05	0.01
(G)	Gravimetry, w/Impurity Correction, Assay	U	0.013	0.025

gravimetric uranium analysis was reported with good random and systematic errors. Theconversion factor for gravimetry is based on an industry average at present; the DOE reference material laboratory (NBL) is working with the sites to provide a more accurate number. The Davies and Gray titration used for oxides in storage is not at the state-of-the-practice for the method. The only online analysis listed was the isotope determination, although pressure and temperature values should factor into volume calculations. No information on sampling error was provided, and no indication of sampling studies was given. No information on holdup measurements was provided by the site.

CONCLUSIONS

Some of the data listed in the tables will be researched further to identify where improvements to measurements may improve safeguards and to pinpoint areas where measurement technology transfer would be appropriate. Table VIII allows a direct comparison of the most accurate accountability measurements made at the selected sites with the proposed target values[1]. The proposed target values do not include some important areas of measurements such as all types of sampling, volume, mass and nondestructive analysis. Errors from sampling and from volume may be important contributors to shipper/receiver (S/R) differences and to inventory differences (IDs), respectively. Only by modeling error contributions from the variety of measurements within the individual MBAs of the facilities can the largest measurement contributors to S/R differences and to IDs be identified.

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Experts in the respective measurement areas were asked to provide bibliographies for another purpose, which listed the basic papers for some of the methods in this paper. Grateful acknowledgement is made to those experts for the reference listings. The selected lists, herein, were derived by me from those bibliographies; I take sole responsibility for that selection. The experts and their respective bibliographic areas are as follows: (1) Wanda Mitchell, New Brunswick Laboratory (NBL) — Modified Davies and Gray Titration for Uranium; (2) Paul Croatto, NBL — Spectrophotometric Determination of Uranium; (3) Larry Callis, Los Alamos National Laboratory (LANL) — Isotopic Mass Spectrometric Measurement of Uranium; (4) John Gramlich, NBL —Isotopic Mass Spectrometric Measurement of Plutonium; (5) Wanda Mitchell, NBL — Ion-exchange/Controlled Potential Coulometric Plutonium determination; (6) Donald Temer, LANL- Spectrophotometric Determination of Plutonium; (7) Sylvester Suda, Brookhaven National Laboratory — Tank Volume Measurements, (8) Tony Ciramella, Mound — Calorimetry; (9) Wayne Ruhter, Lawrence Livermore National Laboratory — Gamma-ray Isotopics; (10) S. -T. Hsue, LANL — Segmented Gamma-ray Scanner for Waste Assay; and (11) Norbert Ensslin, LANL —Neutron Coincidence Counting.

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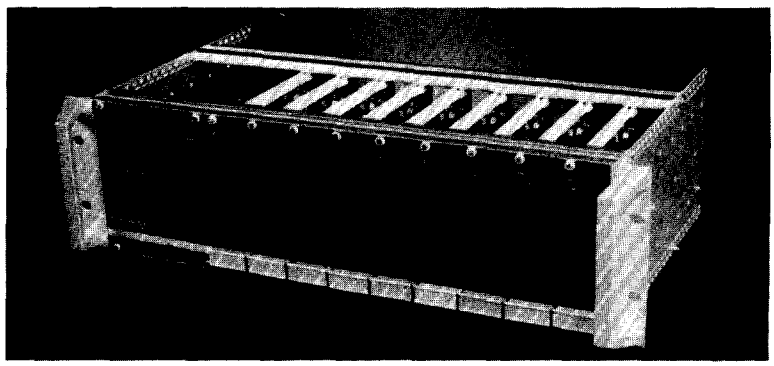

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