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New safeguards challenges

This issue of *JNMM* includes articles on destructive analysis, calorimeters and verification strategy.

Destructive analysis, which involves weighing items, taking samples, and weighing and assaying the samples, is generally more accurate than NDA. Therefore, it is generally used to measure the materials transferred between nuclear facilities. For many years, difficulties have been experienced in measuring plutonium and mixed uranium–plutonium oxides because the samples and the items from which they are drawn tend to gain or lose water relative to each other. Although procedures have been developed to reduce the resulting shipper–receiver differences, the approach presented here should be of interest to those who still must worry about this problem.

Lightweight calorimeters are taking on greater importance for the IAEA. However, the Agency has not had the time or the resources to determine the sensitivity and the stability of the calorimeters which it is now using. Norman Beyer has been able to perform these tests and reports on his results.

A number of INMM members and others are becoming involved in the design of verification techniques for application to nuclear and non-nuclear arms control agreements now being seriously discussed. In some cases, the activities to be verified are quite similar to those with which we are familiar. In some cases, the activities and the information involved may be rather different. Nevertheless, the logical approach to the designs is basically the same. Jonathan Sanborn describes, and illustrates with a simple example, a logical analytical approach to verifying adherence to an agreement which places certain limits on the numbers and locations of conventional warfare elements. As in nuclear materials safeguards, it is important to decide the extent to which the inspectee's possibly false statements, regarding "materials," may be useful to the inspector. The same carefully reasoned approach, often referred to as "game theory," has been applied in the past to nuclear material safeguards by R. Avenhaus and a few others, as Sanborn notes.

Last year, Congress recommended that the United States discuss with the Soviet Union the possibility of a halt to the production of fissile material for nuclear weapons and the transfer of nuclear weapons material from warheads, which are to be eliminated by treaties now under discussion, to safeguarded peaceful activities. The president's report to Congress on the feasibility of verifying such agreements was scheduled to be published near press time for this issue of *JNMM*. An unofficial report on this subject, prepared by a joint committee of American and Soviet scientists, was released last month.

INMM members should study these reports. These initiatives present new challenges to those who have been involved in the development and implementation of national and international safeguards systems. The challenges are not simply technical. It will be necessary to agree on the safeguards objectives and on the degree of assurance desired, on such matters as significant quantities, timeliness goals, and when safeguards may be terminated, before defining what the Agency refers to as the "safeguards approaches" for the different nuclear materials and many different facility types.

The history and the experience of the IAEA will be extremely useful for developing the new systems while the new systems should greatly strengthen the IAEA and the non-proliferation regime.

As technical editor of this publication, I feel that I should express my gratitude not only to the associate editors listed on the masthead, but also to the many others of you who have assisted in soliciting and reviewing contributions.

Some editors carefully protect the anonymity of their reviewers. Sometimes that seems important to me. In other cases, it makes more sense to ask the reviewer to correspond directly with the author. In most cases, a draft needs to be clarified, typos corrected or a technical detail cleared up. Anonymity does not seem to me to be as important as efficiency in such cases. So far, no one has complained.

Of course, we could always use more contributions and suggestions for authors to be solicited. We need your help.

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INMM stands for success

The past year has been another successful one for the Institute. A part of this success results from the leadership of the Executive Committee and the organization of OMSI, our management company. But much of the success of INMM is a result of the dedication of the many volunteers from our membership.

Once again, as we return to New Orleans for our Annual Meeting, the Technical Program Committee and the Technical Working Groups have put together a comprehensive and diverse program that reflects the growing interdisciplinary interests of our membership. It includes more than 200 contributed papers organized into 33 sessions. In addition to our usual sessions on physical protection, international safeguards, materials control and accounting, and waste management, we are adding a second session on arms control-treaty verification (our first arms control session last year was very popular), two sessions on transportation and a session on the environment, safety and health.

The Technical Working Groups have continued to carry out the educational and informational exchange goals of the INMM by conducting several excellent workshops this year. The workshop on "Assessing Safeguards Performance," which was postponed from November because of budget uncertainties, was held in March and attracted 82 participants. A new workshop on "Mass Measurements: Principles and Practices" drew 103 participants and several commercial sponsors. An important regular workshop, "Spent Fuel Management VII," had 145 participants.

Membership continues to fluctuate at around 750 but, for some reason, is not as large as might be expected from the attendance at the Institute's Annual Meetings. Perhaps Charlie Vaughan, the new chairman of the Membership Committee, can help change this statistic — or at least help us to understand it.

JNMM, the Institute's technical journal, appears to have turned the corner. It is attractive, well-respected, and provides an excellent forum for technology transfer in the nuclear materials management community. The many contributed papers — more than half of which are written by nonmembers — cover a wide range of interests.

As you are likely aware, last year the Long-Range Planning Committee recommended that INMM consider modifying its structure to facilitate more fully integrating transportation and waste management (elements of nuclear materials management that have been part of our logo from the beginning) and perhaps other special interests into the Institute's programs. The Executive Committee, after much discussion, is still struggling with how to accomplish this. Such a move could have an important effect on the Institute and warrants careful consideration. Perhaps by this time next year there will be a proposal ready for membership ballot.

Once again, the success of the Institute depends on you as a member. I urge you to take part.

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Note: For a complete report on the activities of the Institute of Nuclear Materials Management, you may request a copy of the INMM Annual Report. Contact Laura Rainey, INMM, 60 Revere Dr., Suite 500, Northbrook, IL 60062 USA; (708) 480-9573.

Chernobyl's literary fallout

The Truth About Chernobyl
Grigori Medvedev
Basic Books, New York, 1991
274 pages

The Legacy of Chernobyl
Zhores A. Medvedev
Norton, New York, 1990
352 pages

Chernobyl
Andrey Illesh
Richardson and Steirman Inc.
New York, 1987
200 pages

Although a bit premature, it is probably safe to say that no event in the 20th century will have such a profound effect on the relationship of mankind to technology as the explosion of the number 4 reactor at the Chernobyl generating station on April 26, 1986. This event, the ultimate nightmare of nuclear reactor engineers, caused the release into the environment of a substantial fraction of the fission product inventory in the core of an RBMK-1000 power reactor at the end of a two-year operating cycle, when the inventory had reached its maximum value.

The radioactive plume from the explosion circled the earth, depositing measurable contamination in practically every country in the Northern Hemisphere. Although the accident immediately caused 31 casualties, its true consequences will be tallied for many years. Tens, perhaps hundreds, of thousands of people living in the vicinity, workers dealing with the damaged reactor and participants in the massive cleanup operation, were exposed to heavy doses of radiation and are at risk from cancer and other health problems in later life. In all, 130,000 residents of the area were evacuated and 15 million acres of farmland and forest were severely contaminated.

Yet, Chernobyl's greatest cost to other counties may well be its effect on public attitudes toward choices of energy technologies for the next century. We are now at a crucial juncture where the possibility of global warming through the continued burning of fossil fuels, with consequent drastic changes in climate, destruction of croplands and increasingly violent and destructive storms, cannot be discounted. Alternative energy sources, such as solar, wind and biomass energy generation, are not yet mature and cost-effective.

Were it not for its real and perceived risks (and in politics perception is reality), nuclear energy would be the logical choice for new electric power generating capacity during the next several decades. The Chernobyl disaster has, effectively, cut the ground from under the advocates of nuclear power, including the writer of this review, who held that the risks it presented were small and acceptable by comparison with the other risks we face in our daily lives.

In the months following the accident, detailed studies were carried out by the International Atomic Energy Agency and others to reconstruct the events that preceded it. As a consequence, the physical and technical details of the accident scenario are well understood. Among the features of the reactor contributing to the accident were the lack of a containment structure; a positive void coefficient which caused the reactor power to increase rapidly as steam bubbles formed in the fuel channels; the design of the control rods, with a graphite tip and a meter of void space at the end, which also caused an initial increase in reactor power as the rods were inserted; and the extremely slow insertion speed. Significantly, none of these flaws exists in power reactors licensed to operate in Western countries.

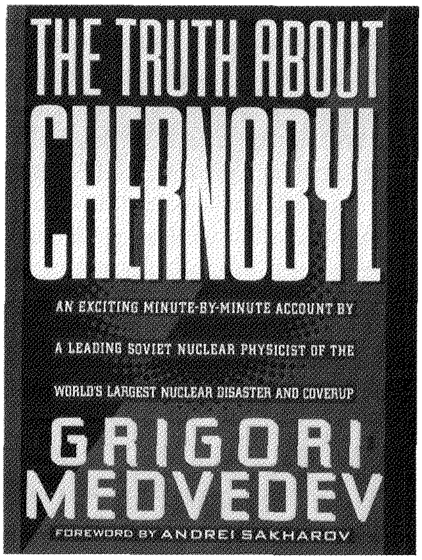
In the five years since the accident, a number of books and publications on the Chernobyl accident have appeared, and many more undoubtedly will appear in the future. Recently, two especially significant books have been published, *The Truth About Chernobyl* by Grigori Medvedev and *The Legacy of Chernobyl* by Zhores Medvedev. These two accounts have already been widely read and commented on and are certain to have a major impact on public opinion in the West. They deal not only with the now well-known technical aspects of the accident but, perhaps more importantly, with those aspects of the sociology of the Soviet system and the human factors, in the Soviet nuclear energy program and at the reactor site, that played a role in the history of the accident. Grigori Medvedev is a reactor engineer who was deputy chief engineer for operations at Chernobyl in the early 1970s, and consequently was acquainted with the managers who were responsible for its operation at the time of the accident.

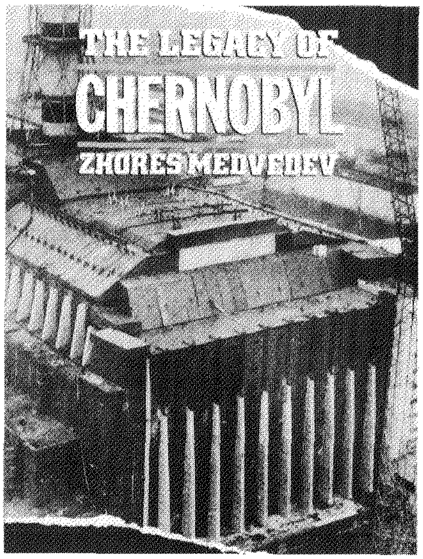
Earlier in his career, Medvedev had received a serious radiation exposure in a laboratory accident (presumably a criticality accident) and spent months in the Moscow hospital, the "Number 6 Clinic," where the victims of the Chernobyl accident were later sent. Within days of the accident, he was sent from Moscow to the reactor site to assess and report on the situation. *The Truth About Chernobyl* discusses the policies and practices in the Soviet nuclear energy program which made the accident possible, or perhaps inevitable. This book examines the protocol of the ill-fated test which was intended to enhance the safety of the reactor, the detailed events in the reactor control room in the hours before and after the explosion and the massive effort immediately thereafter to extinguish the burning reactor and limit the damage. It is an intensely personal and often gripping account of his experiences. He is scathing in his criticism of the responsible managers, both those at the scene and those in charge of the Soviet nuclear power program.

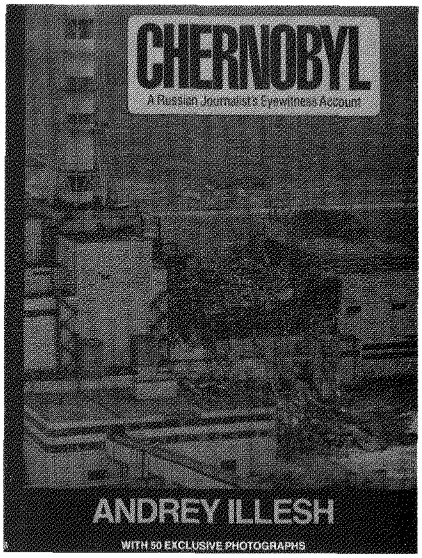
Zhores Medvedev (no relation to Grigori), a biologist, is a well-known critic of the Soviet system. In 1970 he was confined to a psychiatric institute after writing a book critical of the charlatan geneticist Lysenko, who was a favorite of Stalin. After Andrei Sakharov obtained Medvedev's release, he emigrated to England. He was the first writer in the West to publish an account of the radiation accident at the Kyshtym reprocessing plant in the Urals in which a tank containing high-level waste exploded, depositing more long-lived radionuclides in the environment than the Chernobyl event, causing numerous deaths and requiring the permanent evacuation of a large area.

His book, *The Legacy of Chernobyl*, is broader in scope and less subjective than Grigori's account. It covers not only the history of the accident but devotes considerable discussion to the environmental and health impacts of the disaster, provides interesting descriptions of the Soviet nuclear energy program and includes a history of nuclear accidents in the Soviet Union.

The book *Chernobyl*, by Andrey Illesh, is by comparison superficial, but nevertheless interesting in several respects. A deputy editor of the state paper *Izvestia*, Illesh arrived at the reactor site with three photographers 24 hours after the explosion. His account is also very personal, but, predictably, it reflects the official line of the government, placing blame only on the managers at the scene and providing no criticism of the system, top-level managers or the design of the Chernobyl RBMK-1000 reactor. The book combines explanations of the event and its health and environmental effects, intended for popular consump-







tion, with upbeat descriptions of the effort to deal with the consequences of the accident, photographs and interviews with individuals who worked to ameliorate those consequences.

These accounts should be of interest not only to those readers who have an interest in nuclear energy, reactor safety and the environment, but also to those who have an interest in the influence of human factors on safety and emergency management.

Certainly they provide insight into the workings of the Soviet system and the psychology of the Soviet people.

In addition to the fatal design flaws in the reactor, the emphasis in the Soviet system on reaching or exceeding production goals and the almost complete lack of a safety culture were major contributors to the accident. The total "denial reaction" on the part of the responsible managers in the hours after the accident, in which it was asserted that the reactor was intact, and that only an emergency water tank had exploded, caused additional deaths and subjected the population of the nearby town of Pripyat to massive radiation exposures while their evacuation was delayed, incredibly, for 36 hours. Within the Soviet system, this reaction is understandable when we remember that under Stalin the penalty for failure on the part of a manager or official was often summary execution or many years in the Gulag.

In a real sense, the events leading up to the Chernobyl disaster mirror the flaws and inconsistencies in the Soviet system: The disaster itself represents, symbolically, the funeral pyre of a failed social order. In this respect, the press conference called by Mikhail Gorbachev 18 days after the accident was a significant departure characterized by honesty and openness unprecedented in the 69-year history of the Soviet Union.

Still, while these accounts emphasize the many weaknesses in the Soviet system, they also possess a common theme which discloses another aspect of Soviet society, or more accurately, of the Russian people. This is the extraordinary devotion to duty displayed by the thousands of individuals called upon to help control the consequences of the Chernobyl disaster. This applies to the widely known dedication of the fire fighters and operators who, in the hours after the accident, struggled to extinguish the many fires started by the explosion, saving the remaining three reactors from certain destruction, and to countless other individuals who worked at the reactor site for months under difficult and dangerous conditions.

Despite the many failures of a system which has caused almost universal disillusionment and discontent among the population, Soviet citizens will still respond with great selflessness, when necessary, to a grave national emergency.

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Determination of Water in Plutonium Dioxide

■
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■

ABSTRACT

Techniques developed to very effectively apply automatic Karl Fischer reagent titration to the determination of H_2O *in solids were used to determine the moisture content of samples of plutonium dioxide powder under the constraints imposed by the necessity of working in a glove box. The moisture contents of three samples were found to be 0.2934%, 0.7298% and 0.4640%. The estimate of the relative standard deviation of the mean for three determinations on the 0.2934% sample was 0.0091. The method apparently has potential as the basic reference method for the determination of* H_2O *in plutonium dioxide, as a means of standardizing other methods, and as a diagnostic tool.*

I. INTRODUCTION

The interaction between plutonium dioxide and water has been studied by Stakebake[1-4] and others. The exchange of water vapor and plutonium dioxide (PuO_2) and its environment is a possible source of differences in the plutonium content of the oxide as determined by shippers and receivers. In a program on the determination of the moisture content of PuO_2, techniques were developed to very precisely apply Karl Fischer reagent titration to the determination of H_2O in solid materials. Measurements have been made on uranium oxides, titanium dioxide and other metal oxides. This paper reports the determination of H_2O in PuO_2 using an automatic Karl Fischer reagent titrator and modified techniques under the constraints imposed by the necessity of working in a glove box. The work was performed at the Hanford Energy Development Laboratories at Richland, Wash.

II. EXPERIMENTAL

The apparatus and reagents are described in a previous paper.[5] Since the titrations were to be made in a glove box, it was necessary to slightly modify the apparatus. The reaction vessel of the titrator was placed inside the glove box on the base of a magnetic stirrer, and the generator leads and the sensing electrode leads were extended and attached to a "bulkhead" connector mounted on the face of the glove box. Leads connected the connector outside the glove box to the binding post on the base which enclosed the electronics of the titrator. The mixer/mill (used to mill the oxide in methanol to extract the H_2O), without the cover, was installed inside the glove box.

Three samples (about 15 g each) of PuO_2 powder from three different sites (Los Alamos Scientific Laboratories, Los Alamos, N.M.; Rockwell Hanford Operations, Richland, Wash.; and Savannah River Plant, Aiken, S.C.) were used in the determination of water. It was not practical to run replicate samples. Each sample was weighed on an analytical balance. The sample and three tungsten carbide pellets were put into the milling vessel of the mixer/mill, and 25 mL of methanol was pipeted into the vessel from a Class A pipet. The lid of the vessel was sealed, and the sample was milled in the methanol for 15 minutes. The vessel was then set aside for about 42 hours, during which time the solid residue settled to the bottom. The milling and succeeding procedures were repeated for 25 mL of methanol without sample, to prepare a blank.

Calibrated syringes[6] of 1-mL capacity were used to withdraw 0.5-mL quantities of methanol-extracted H_2O mixture from the milling vessels and introduce them into the reaction vessel of the titrator, and 2.5-mL quantities of the methanol blank were introduced from a 5-mL-capacity uncalibrated syringe. A specimen or a blank was introduced into the titration vessel, titration was started, and after the end-point was reached the mass of H_2O titrated as indicated by the counter on the titrator was noted.

The titrator was standardized by using a mixture of methanol and water. The mixture was prepared at the National Bureau of Standards (now the National Institute of Standards and Technology) by mixing 2 mL of distilled water with 250 mL of methanol. Ten milliliters of the mixture was injected into each of seven evacuated test tubes through rubber stoppers by using a 10-mL capacity "gastight" syringe which had been rinsed with methanol and heated in an oven at about 84°C. After filling, molten paraffin was poured into the concavity in the stopper, and then the stoppered end of the test tube was dipped into the paraffin as a precautionary measure to further seal the hole made by the syringe needle and to immobilize the stopper. The titer of the mixture was determined by using a titrator standardized[5] with distilled water.

III. RESULTS AND DISCUSSION

The moisture content, % H_2O, of the samples of PuO_2 was calculated[5] by using the equation

$$\% H_2O = (VC/10^6 m_g) x \{[Z(A_s/v_s) - (A_b/v_b)] / [l - (ZC/10^6 \rho) (A_s/v_{s]})]\} x100 \qquad (1)$$

where V is the volume (25 mL) of methanol used for extraction, C is the standardization factor for the titrator (μg/μg), m_g is the mass (g) of thePuO_2 sample, Z (dimensionless)[7] takes account of the fact that the volume of a methanol–H_2O mixture is less than the sum of the volumes the components would occupy separately, A_s is the titration value (μg of H_2O) for the methanol-extracted H_2O mixture, v_s is the volume (mL) of the specimen, A_b is the titration value for the methanol blank, V_b is the volume of the blank and ρ is the density of water (g/cm^3). Z is calculated by using the equation

$$Z = 1 - (1.985x\ 10^7) xCx[(A_s/v_s) - (A_b/v_b)] \qquad (2)$$

where the units of the numerical coefficient in the second term are mL/μg. The results are listed in Table 1.

Table I

Results for Karl Fischer Titration Determinations on PuO_2

sample no.	% H_2O	mean H_2O
1	0.2979 0.2887 0.2935	0.2934
2	0.7355 0.7240	0.7298
3	0.4777 0.4502	0.4640

The results indicate that the techniques described in a previous paper[5] for the application of automatic Karl Fischer titration to the determination of H_2O in solid materials, modified in the present case, produced very satisfactory results despite the constraints imposed by the necessity of working in a glove box. The estimate of the relative standard deviation of the mean is about 1% in the range 0.3 to 0.7 % H_2O, which can be compared with a value of 0.37% at 0.2758% H_2O in titanium dioxide achieved under nearly ideal laboratory conditions[5] by an analyst experienced in the method.

For comparison of the Karl Fischer titration results with those obtained routinely on PuO_2 at the Hanford Development Laboratories, samples (about 200 mg) were analyzed on a moisture evolution analyzer at 400°C "to equalization." The results corresponding to samples 1, 2 and 3 in Table 1 are 857, 7044 and 4997 ppm, respectively. Since the analyzer result was much lower than the titration result for sample 1 and since it was not practical to make a titration determination on another 15-g sample, two more samples from different places in the can were subsequently analyzed on the moisture evolution analyzer. The results, 735 and 750 ppm, were also much lower than the titration result in Table 1. The ratios of the analyzer result to the titration result for samples 2 and 3 are 0.9652 and 1.077; the ratio for largest analyzer value for sample 1 is 0.292. The reason for this discrepancy was not established.

The work reported here has demonstrated that the techniques developed for the optimum application of automatic Karl Fischer reagent titration to the determination of H_2O in solid materials, modified for the present case, can be used successfully under the constraints imposed by a glove box by an operator with no prior experience with the method.

IV. ACKNOWLEDGMENTS

I am grateful to R. L. Moore and G. J. Alkire of the Hanford Energy Development Laboratories, who made it possible for the experimental work to be done there; to M. C. Burt, who contributed in many ways to the success of the effort; to W. B. Larson, who did the actual titration work in the glove box and the moisture evolution analyzer measurements; and to P. S. Schaus for consultation and for making the PuO_2 available.

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Frank E. Jones is a physicist and independent consultant, having retired from the National Bureau of Standards (now the National Institute of Standards and Technology) in 1987. He has been actively engaged in tank volume calibration for more than 10 years. He designed, directed and participated in the first definitive tank calibration at the Savannah River Site as well as many other tank calibrations. He also performed a definitive in-tank measurement of solution density. He served as deputy office chief in the NBS Nuclear Safeguards Programs, authored more than 50 technical papers, holds two patents and lectures on various subjects. Jones earned a master's degree in physics from the University of Maryland and has done doctoral work in meteorology at the same university. He was a consultant to the writing group for American National Standard ANSI N15.19, "Volume Calibration Techniques for Nuclear Material Control."

Evaluation of the Fast-Response, Small-Sample Calorimeter

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ABSTRACT

This paper describes an evaluation of the measurement reliability of a portable, fast-response, small-sample calorimeter. The main thrust of the study was to determine the measurement confidence to be expected over the long-term, since only short-term tests, under laboratory conditions, had previously been made of the instrument. An initial series of measurements was made of a small group of well-characterized plutonium samples varying in size from approximately 0.1 to 10.0 g and covering the capacity of this small-sample calorimeter. The major effort consisted of a study conducted over a period of 16 months during which 15 different 3-g size plutonium samples were periodically received and measured calorimetrically. These results were compared with careful chemical and mass spectrometric analyses made during the same period. A third part of the evaluation consisted of a study to examine the reliability of the calorimeter when operated with the new and more sophisticated controller called the PC-driven DAS (i.e., Personal Computer Driven Data Acquisition System). The controller provides improved handling of the measurement sequence and has the capacity to mathematically predict the thermal equilibrium endpoint of a measurement. Endpoint prediction, if accurate, can considerably reduce the measurement time. So, to test the accuracy, a 3-g sample was repetitively measured over a period of seven weeks to compare predicted endpoint values to final endpoint values. Conclusions reached from the three parts of the study indicate the following:

1) Samples ranging in size from 0.1 to 10 g of plutonium are measurable, but the best accuracy and precision is obtained with the 3- to 10-g size. 2) Over the long term, 3-g-size samples can be measured at a precision of ±0.5%. 3) Endpoint prediction by the PC-driven DAS yields reliable values and allows a measurement to be completed in 45 minutes.

I. INTRODUCTION

This paper describes an evaluation of a portable calorimeter used to non-destructively measure the mass of small samples of plutonium (i.e. samples containing less than 15 g of plutonium in a volume not greater than 12 cm^3). The primary goal of the study was to establish the response to be expected when the instrument is used for a measurement program protracted in time. It has been a number of years since the original instrument of this type was reported upon by its builders (Beyer et al.),[1] who subsequently patented the design.[2] The goal of the original design was to provide a portable, fast-response, air-chamber instrument for traveling inspectors which would approach the high accuracy and precision usually associated with the bulky, slow responding, conventional calorimeter with its large water-bath heat sink. The design of the instrument used for this study was based on the original design but was built specifically for use by traveling inspectors of the International Atomic Engergy Agency (IAEA). Details of the instrument are presented in the reports by Roche and Perry,[3,4] who designed and built this instrument. Their evaluation could not be protracted over a realistic time period prior to delivery to the IAEA. For various reasons, the IAEA also was unable to evaluate the instrument in the laboratory or under in-the-field conditions. Therefore, the investigation reported in this paper was carried out with the purpose of providing an evaluation which was needed before the instrument could be used for routine measurements. For the sake of completeness, the report includes brief discussions covering measurement principles, features of the apparatus and theory of operation which have been previously described.[1-4]

II. PRINCIPLES OF THE MEASUREMENT

The radiations emitted during the decay of plutonium are principally alpha particles accompanied by some relatively low energy photons. The alpha particles are of such low penetrating capacity that greater than 99.9% of their energy is

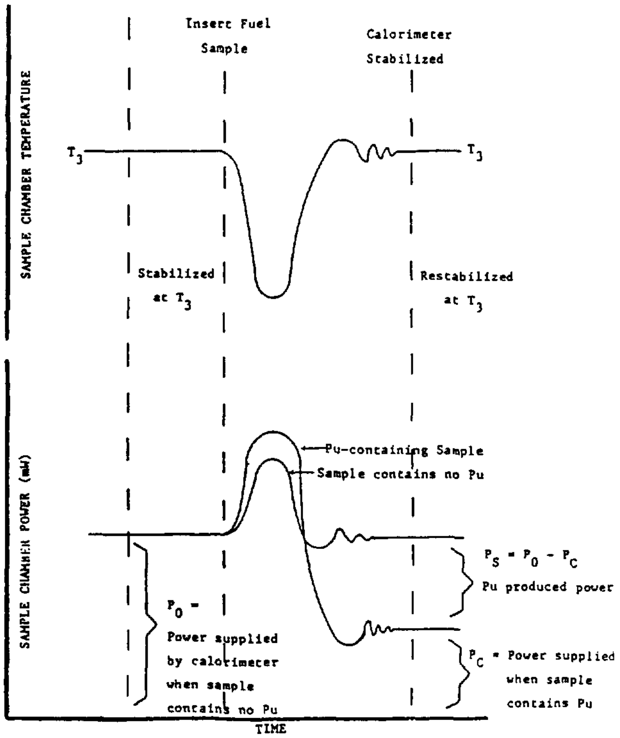


Figure 1
The measurement-chamber temperature and power relations in the fast-response, small-sample calorimeter

degraded to thermal power upon emission. Basic to the calorimeteric measurement of the mass of plutonium contained in a sample is the ability to measure this thermal power, commonly referred to as the sample power (P_s), which is directly related to the mass of plutonium in the sample.

III. THEORY OF OPERATION OF THE EQUIPMENT

Measurements of P_s (milliwatts of power, mW) are made in the calorimeter measurement chamber (CMC). The CMC can be described as a small oven with a heater that maintains a constant temperature. Under this condition of constant temperature, P_s is measured as the difference between the heater power required when the CMC is empty and the power required when it contains a heat-emitting sample of plutonium. This relationship is clarifed in Figure 1.

The effective specific power (ESP), characteristic of the sample material being measured, is used to convert P_s to grams of plutonium. The ESP (expressed as milliwatts/gram of plutonium) is a function of the abundance of the plutonium isotopes and the americium-241 in the sample and of their associated thermal constants.

IV. DESCRIPTION OF THE APPARATUS

The original version of the fast-response, small-sample calorimeter is a portable instrument which is housed in two packages: (1) a measurement module consisting of the CMC and the sample preheater and (2) a data-aquisition system (DAS) consisting of a microprocessor which acts as a controller and data processor. The total weight of the two packages in this portable version is 18 kg.

The DAS is an important part of the instrumentation. There are two types of DAS modules that can be used with the calorimeter: the portable version and the personal computer driven version. The main function of both of them is to monitor the power supplied to the measurement chamber, collect this data, carry out the conversion from sample power to grams of plutonium and provide a printout of results. The newer and less portable DAS, which is called the personal computer driven DAS (PC-driven DAS), has a more sophisticated data-handling program and the capability of predicting the thermal equilibrium endpoint (i.e., steady-state T_3).

The measurement module, which is the same for both versions, is housed in a 30 cm x 41 cm x 26 cm aluminum case and has a total weight of 13 kg. The heart of this unit is the CMC, which is comprised of four temperature-controlled concentric cylinders. These act to maintain the central (the sample measurement chamber) cylinder as a constant-temperature oven. All the concentric cylinders are wound with non-inductive heater coils and contain temperature-sensing elements. Each cylinder is set at increasingly higher temperatures as the center is approached ($T_0 < T_1 < T_2, < T_2, < T_3$). Special servo circuits measure and control the electric power supplied to the cylinders to maintain this CMC at a constant temperature. This arrangement is shown in Figure 2. Adjacent to the CMC chamber is the sample preheater. It is used to heat the encapsulated samples to a temperature near that of the central measurement cylinder temperature (T_3), before the samples are inserted. Preheating the sample in this manner greatly reduces the time required for the sample to reach thermal equilibrium and hence shortens the total measurement time considerably.

The portable DAS is housed in a 47 cm x 35 cm x 16 cm case and has a total weight of 5 kg. The PC-driven DAS consists of a small, lightweight interface module, a conventional PC and a printer. This makes the new DAS considerably less portable than the original version, which is briefcase-sized. However, a portable PC can be used if portable safeguards equipment is required. Currently, a table-top PC is being used for laboratory measurements.

The PC-driven DAS is an IBM compatible desk-top PC, 6/10 MHz AT model, with 40 Mbyte SCSI hard drive and two floppy disk drives. When it is interfaced to the calorimeter, it upgrades the instrument to include higher measurement sensitivity together with thermal equilibrium end-point prediction. Input is via the PC keyboard, and output is via a color monitor and/or dot matrix printer.

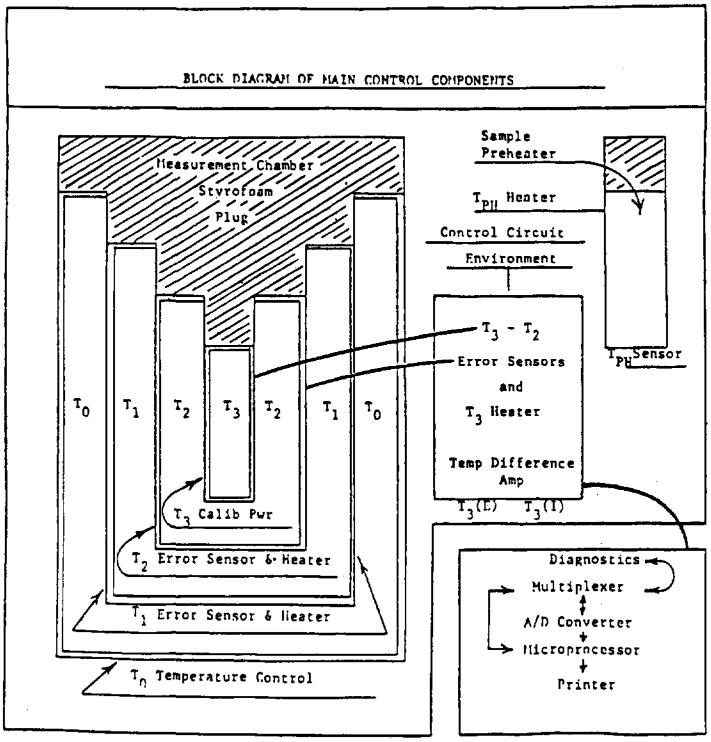


Figure 2
A block diagram of the fast-response, small-sample calorimeter with its measurement and control components

Special sample holders must be used when making measurements with this apparatus. These sample holders provide double encapsulation (as a radiation safety precaution) and are specifically designed with the dimensions required to provide a snug fit in the central measurement chamber of the CMC. Sample holders contain an inner capsule having an inside diameter of 1.8 cm and are 5.0 cm high, and hence they will not accept samples larger than this. The plutonium-bearing samples are placed in this inner capsule, and if possible, to ensure containment from a safety standpoint, the actual sample (i.e., metal, powder, pellets, etc.) can be placed in a separate container (i.e., tube, bottle, bag, etc.) before it is inserted in the capsule. The inner capsule is then closed by a special cap and sealed with latex or epoxy sealer. After being sealed, the capsule is then inserted into the sample holder, which has a special "O ring"-sealed screw cap. Thus, double, or often triple, encapsulation is accomplished.

V. MEASUREMENT PROCEDURE

A. Summary of the measurement

There are four main steps for measuring a sample of plutonium with the calorimeter:

1. The effective specific power (ESP), characteristic of the sample material, is calculated and entered into the memory of the DAS.
2. The baseline power (P_o) is measured after placing an empty sample holder in the CMC.
3. The system power (P_c) is measured after placing a sample holder, which is loaded with plutonium sample, in the CMC.
4. The specific power (SP) is calculated as the difference $P_o - P_c$. This relationsip is shown diagrammatically in Figure 1. P_s is then converted to grams of plutonium by using the ESP (mW/g of Pu) characteristic of the sample. These calculations and a printout of results are done automatically by the DAS, which remembers the values of P_o, P_c and the ESP. The magnitude of P_c will always be less than P_o because the plutonium in the sample supplies thermal energy to the CMC during a measurement.

B. Details of the measurement

Each measurement step contains special measurement sequence criteria programmed into the DAS controller to ensure the proper collection of data.

An accurate calculation of the ESP for a sample was accomplished by using the program provided in the memory of the DAS. The calculation of the ESP, which is the sum of the thermal power per gram contributed by each heat-emitting isotope in a sample, required the analyst to enter the isotopic abundance data for each isotope of plutonium and for the americium-241, present in the sample, together with dates of abundance measurements and the current date, which are used to make decay corrections. The isotopic abundance data must have been previously measured by other techniques (e.g., mass spectrometry, gamma ray and/or alpha particle spectrometry).

A special sequence is followed to assure the validity of the measurement of P_o and P_c. Measurement values of P_o or P_c are valid only after the chamber has stabilized at T_3 and thermal equilibrium (i.e., thermodynamic "steady state" – heat gained equals heat lost) has been achieved. This is accomplished by controllers activated by signals (criteria set by the operator) sent by the DAS to the heater and sensing coils of the CMC. The following sequence takes place to establish a condition of thermal equilibrium after which a power measurement can be made:

1. A set of 125 instantaneous measurements is made of the control power, which has been applied to the CMC to try to bring it to thermal equilibrium. This set of 125 measurements, collected over a period of 1.5 minutes, is called a measurement run.
2. At the conclusion of a run, the average control power and its standard deviation are calculated and the values stored for comparison to future runs.
3. Runs are repeated until the mean of a set of 10 runs has a standard deviation of less than 0.04 mW and the slope of

the set is zero.

If these requirements are met in 10 runs, thermal equilibrium, as defined for this instrument, has been attained, and the measurement of P_0 or P_c is accepted. This sequence usually requires 15 minutes of measurement time.

A baseline power measurement P_0 (i.e., empty sample holder) follows the same sequence as described above (the total measurement time is 15 + 15 = 30 minutes). The measurement time can be shortened by preheating the sample to a temperature close to the equilibrium temperature T_3. Usually, preheating for 15 minutes is sufficient to bring the sample to a temperature close to T_3. Therefore, the total measurement time is 45 minutes when the preheat time is included. However, when one is measuring a group of samples, preheating can be done simultaneously with the measurement of another sample. Therefore, measurement time is 45 minutes only for a single sample or first of a series. If only one P_0 measurement is taken when a series of samples are being measured (e.g., during one day), then the measurement time can be as short as 15 minutes. When high precision and accuracy are required, two measurements of P_0 and P_c are made. P_0 is measured before and after two measurements of P_c and the averages are used to determine P_s. In this case, a total measurement time of 105 minutes is needed for the first of a series and 60 minutes thereafter.

C. Calibration

The calorimeter has been designed so that a calibration can be performed electrically by using internal components of the apparatus. A special heating coil has been wound on the inner cylinder of the CMC, and an accurately known amount of electrical power (i.e., heating power) can be applied to this coil. This power simulates the heating that would be caused by a plutonium sample (i.e., simulated P_s). Under the control of a program incorporated into the DAS, these special heating coils are incrementally heated, and the system is allowed to reach thermal equilibrium after each incremental change. The measuring circuits then use the sense coils to make measurements of the simulated sample power, and a calibration can be established by comparison to the accurately known values of power applied. This type of calibration was performed periodically throughout the measurement program to provide a check upon the uniformity and reliability of the operation of the system. All tests of this type met the acceptance criteria which required that a linear regression analysis of the data yield a slope of -1.000 and a zero intercept equal to P_0 within the uncertainty of the simulated power measurements.

In addition to the internal electrical calibration, as described above, a more conventional calibration was done by using four well-characterized standards which produce values of P_s from 2 to 17 milliwatts. These standards consisted of samples of plutonium for which the isotopic abundance of the plutonium isotopes, the americium concentration and total plutonium assay values and weights had been very accurately measured (i.e., accuracy and precision of the total plutonium content of < ±0.1%) by other techniques. To establish this calibration, a linear regression analysis was made of the values of sample power measured with the calorimeter as a function of the values calculated from the other measurement data (i.e., mass spectrometry, analytical chemistry, etc.). The calorimetric measurements were made by using the technique that produces the highest precision and accuracy. This technique requires duplicate measurements of P_0 and P_c. A linear regression analysis of the data obtained for this calibration resulted as follows:

$$\begin{aligned} Y &= (1.0001)\,X - 0.002\,03 \\ \text{correlation coefficient} &= 0.999\,997 \end{aligned}$$

where Y is sample power (milliwatts), as calculated for the standards based upon other independent measurement data, and X is sample power (milliwatts) as measured by the calorimeter.

VI. MEASUREMENT RESULTS AND CONCLUSIONS

The primary goal of the evaluation was to establish the response to be expected when the calorimeter was used for a measurement program protracted in time. In addition, two other evaluations were made. An initial evaluation was made of the measurement response to different sample sizes, and following the main evaluation, a study was made of the effect of using the PC-driven DAS instead of the portable DAS. Results obtained from these three test programs together with conclusions are presented in this section.

A. Initial evaluation

First a series of measurements were made of a well-characterized group of five samples of metallic plutonium ranging from approximately 0.9 to 10 g of Pu. The book values for these samples had been established prior to the calorimetric measurements by chemical and mass spectrometric analytic techniques. The results compared to book values are shown below in Table I.

Table I

Calorimetric measurement of metallic samples of plutonium ranging from 0.9 to 10 g of plutonium compared to book values

Sample Number	Sample Weight, g	
	Book Value	Calorimetric Measurement
1	10.191	10.233
2	7.111	7.112
3	4.892	4.889
4	1.709	1.698
5	0.916	0.923

After these five measurements, a group of four samples, each containing less than 1 g of plutonium, was measured. Although the fast-response, small-sample calorimeter was not specifically designed for the measurement of samples containing less than 1 g of Pu, samples as small as a few tenths of a gram of plutonium are measurable but accompanied by a reduction in precision. The results of the measurement of this group of samples, which included sample sizes ranging from approximately 0.1 to 0.5 g Pu, are given in Table II. As with the first group, comparison is made to well-characterized book values.

Table II

Calorimetric measurement of Pu samples of 0.1 to 0.5 g compared to book values

Sample Number	Sample Weight	
	Book Value	Calorimetric Measurement
6	0.547	0.542
7	0.483	0.473
8	0.351	0.355
9	0.134	0.139

It can be concluded from the results presented in Table I that agreement between book value and calorimetric measurement of samples, containing from 0.9 to 10 g of plutonium, may vary from less than 0.1% to as high as 0.8% for a small sample like the 0.9-g sample.

As was expected, agreement between book value and calorimetric measurement of samples in the 0.1- to 0.5-g size shown in Table II was not as good as with the larger samples, since the instrument was not designed for measurements in this range. The agreement varied from 0.9% for the 0.5-g sample to 3.7% for the 0.1-g samples.

The difference of approximately 0.4% for the 10-g sample of Table I may have been due to an inaccuracy in the ESP, caused by uncertainties which were known to exist in the isotopic abundance values available for that sample. Because of this case, it may be appropriate to briefly discuss a few error contributors. Probably the worst offenders as concerns ESP error are errors in the isotopic abundance values for Am-241 and Pu-238 which are available to the calorimetry analyst. Some other possible contributors to final error include such things as unnoticed instrument drift causing a shift in baseline power (P_0) measurement while measuring P_c, variation of measurement chamber sensitivity to sample location in the measurement chamber (i.e., heat distribution error), errors in the electrical and/or standard heat source calibration and unknown heat contributors (e.g., fission products) in the sample.

B. Protracted evaluation

In order to evaluate the reliability of the calorimeter under conditions similar to long-term measurement programs, a group of 15 different samples was measured over a period spanning16 months. These samples (each containing approximately 3 g of metallic plutonium) were periodically received, in groups of four to eight, during the 16-month time span. Soon after receipt, they were measured with the calorimeter and then subjected to a destructive assay, using chemistry and mass spectrometry techniques, to establish a book value. The measurements were made under time constraints (e.g., not more than two or three days) to simulate measurement conditions where results are needed as soon as possible. A comparison of the calorimetric measurements to the book values is presented in Table III and Figure 3.

Table III

Calorimetric measurement of 3-g Pu samples compared to book values (measurements protracted over a 16-month measurement period)

Sample Number	Sample Weight, g		Difference (Calor. Meas.-Book Value)	
	Book Value	Calorimetric Measurement	Weight	Percent*
1	2.9957	2.992	(–)0.004	(–)0.13
2	2.9421	2.932	(–)0.010	(–)0.34
3	2.9441	2.947	(+)0.003	(+)0.10
4	2.9965	2.993	(–)0.004	(–)0.13
5	3.0435	3.046	(+)0.002	(+)0.06
6	2.9597	2.956	(–)0.004	(–)0.14
7	2.9224	2.923	(+)0.001	(+)0.03
8	2.9435	2.964	(+)0.020	(+)0.68
9	3.1337	3.139	(+)0.005	(+)0.16
10	3.1225	3.128	(+)0.006	(+)0.19
11	2.9556	2.966	(+)0.010	(+)0.34
12	2.9860	2.992	(+)0.006	(+)0.33
13	3.1316	3.126	(–)0.006	(–)0.19
14	3.1330	3.135	(+)0.002	(+)0.06
15	3.1696	3.187	(+)0.017	(+)0.54

Mean Value of the Percentage Difference = (+)0.104
RSD = ± 0.280

$$\text{*Percent difference} = \frac{\text{(calorimetric measurement) - (book value)}}{\text{book value}} \times 100$$

Figure 3

Comparison of percent difference between calorimetric measurement and book value of metallic, 3-g Pu samples — measurements protracted over a 16-month time frame

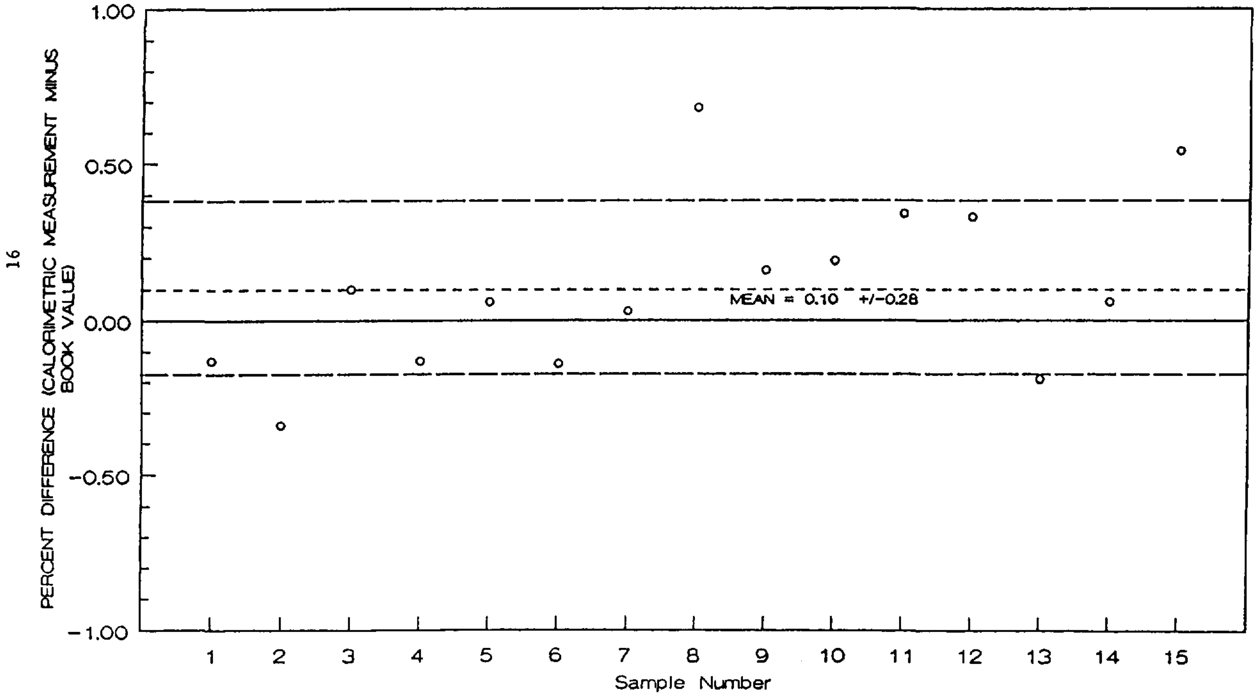


Figure 4

Sample power measurements from predicted equilibrium values of baseline and sample power of a standard sample obtained by using the fast-response, small-sample calorimeter controlled by the PC-driven DAS

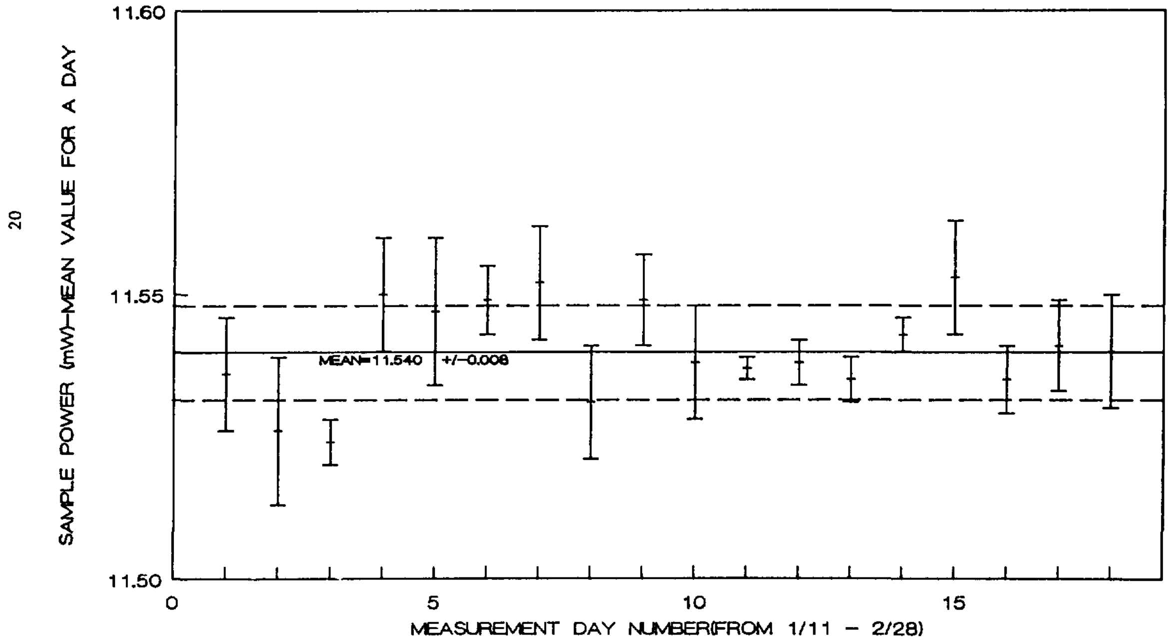


FIGURE 4: SAMPLE POWER MEASUREMENTS USING PREDICTED ENDPOINT VALUES

The results presented in Table III and Figure 3 indicate that a measurement precision of approximately ± 0.% at the 95% confidence level can be expected for long-term measurements of samples (of approximately 3 g of plutonium).

B. Evaluation using the PC-driven DAS

The measurement results presented above under Sections VI. A and VI. B were obtained by using the portable DAS. As mentioned earlier (in Section IV, Description of Apparatus), a more sophisticated but less portable DAS is also available which is called the PC-driven DAS. This newer DAS has better data-handling capability than the portable DAS and can predict thermal equilibrium and endpoint. To evaluate the effect it has upon measurement duration and quality, an additional series of measurements were made using the PC-driven DAS.

1. *Control parameters*

   With the PC-driven DAS, a choice can be made of the operating control parameters which affect the limits of acceptable measurement precision, the duration of the data collection period, and the sensitivity of thermal equilibrium endpoint.

   The first step in conducting the evaluation was to select these parameters to optimize data collection. The most important combinations of parameters were examined, a selection was possible after a few weeks and data collection was started.

2. *Sample power measurement*

   As explained earlier, sample power is measured as the difference between the power at the thermal equilibrium endpoint for an empty measurement chamber (i.e., baseline measurement) and the power measured when the chamber contains a heat-producing plutonium sample. With the new PC-driven DAS, the thermal equilibrium endpoint can be mathematically predicted before the final equilibrium endpoint has been reached. In many cases, this can considerably shorten the total measurement time. For the evaluation, both predicted and final endpoint values were determined by repetitively measuring a well-characterized plutonium standard.

   a. *Sample power from predicted equilibrium*

   A series of sample power measurements, using *predicted* equilibrium endpoints, were made on 18 different days, spread over a period of approximately seven weeks. The mean sample power for each day, together with the measurement uncertainty of that mean, is listed in Table IV. The instrument provides an estimate of the uncertainity (i.e., standard deviation) for each sample power measurement. The mean value obtained by using predicted endpoint measurements for the 18 runs was 11.540 mW, and the standard deviation of this mean was ±0.008 mW. This provides an indication of the repeatability of the instrument when it is operated in the faster measurement mode which predicts final equilibrium. A graphical representation of these values is shown in Figure 4.

Table IV

Sample power measurements of a standard sample using the fast response, small-sample calorimeter controlled by the new PC-driven DAS.

		Sample Power			
		Predicted Equilibrium		Final Equilibrium	
Meas. No.	Date	Mean Value	SD*	Mean Value	SD*
1	1/11	11.536	0.010		
2	1/12	11.526	0.013		
3	1/13	11.524	0.004		
4	1/24	11.550	0.010		
5	1/25	11.547	0.013		
6	1/26	11.549	0.006		
7	2/7	11.552	0.010	11.546	0.009
8	2/8	11.531	0.010	11.550	0.020
9	2/9	11.549	0.008	11.574	0.018
10	2/13	11.538	0.010	11.582	0.013
11	2/14	11.537	0.002	11.549	0.007
12	2/15	11.538	0.004	11.528	0.015
13	2/16	11.535	0.004	11.590	0.029
14	2/21	11.543	0.003	11.577	0.029
15	2/22	11.553	0.010	11.542	0.012
16	2/23	11.535	0.006	11.577	0.017
17	2/27	11.541	0.008	11.560	0.022
18	2/28	11.540	0.010	11.566	0.017
Mean (Nos. 1 – 18) =		11.540	0.008		
Mean (Nos. 7 – 18) =		11.541	0.007	11.562	0.019
		Predicted Equilibrium		Final Equilibrium	

*SD = uncertainity of 1 std. deviation.

   b. *Sample power from final equilibrium*

   Another series of sample power measurements, obtained by using final equilibrium endpoints, were made on 12 different days spread over a period of approximately three weeks and on the same days as the *predicted* endpoint measurements numbered 7 to 18. The instrument also calculates the standard deviation of *final* equilibrium endpoints as done when making *predicted* endpoint measurements. The means of the daily measurement and the uncertainity of those means are listed in Table IV. The mean of these 12 daily runs is 11.562 mW, and its standard deviation is 0.019 mW. These values are graphically shown in Figure 5 with error bars for the daily means. These data provide an indication of the repeatability of the longer measurement when the instrument is allowed to reach the *final* equilibrium endpoint, and a comparison can be made between sample power measurements using *predicted* equilibrium values and *final* equilibrium values.

3. *Measurement time*

The average time to complete a measurement with the instrument adjusted to provide the highest precision possible was

45 minutes	(predicted equilibrium endpoints)
65 minutes	(final equilibrium endpoints)
105 minutes	(portable DAS)

It should be mentioned that the instrument can be adjusted to make measurements in shorter times than those listed above, which are necessary for the highest precision case. However, shorter measurement times are accompanied by a concomitant loss in precision but may in some cases be the preferred mode of operation.

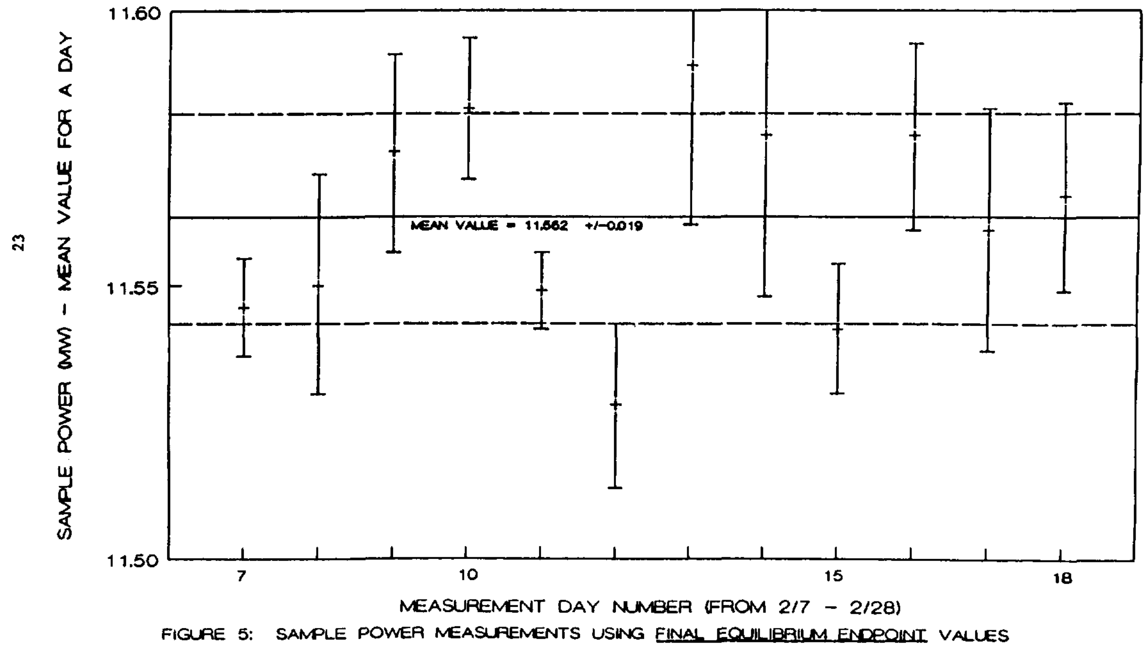
4. *Conclusions concerning the use of the PC-driven DAS*

Comparing the mean values of sample power measurements when equilibrium was predicted with the actual final equilibrium case shows that the predicted value is 0.021 mW low (i.e., 11.562 – 11.541 = 0.021 mW) or approximately 0.18% low. However, it should be noted that the repeatability (or uncertainty of the means) for the predicted endpoint case is ± 0.06%, and for the equilibrium case it is only ± 0.16%. Since these uncertainties overlap, there is apparently no significant difference between the two cases unless adjustments in the measurement circuitry can be found that improve the repeatability of the equilibrium endpoint case. Therefore, the analyst is justified in using the predicted equilibrium endpoint mode of operation and the associated savings in elapsed measurement time (i.e., 45 minutes rather than 65 minutes) if measurement speed is a factor.

The well-characterized standard sample, which was used for this evaluation, was previously used as a control standard with the old portable DAS and was measured periodically during that study. The mean value of these measurements of sample power was 11.561 ± 0.02 mW, which is in agreement with the measurements made during this evaluation of the PC-driven DAS. It can be concluded that the new DAS has not affected the absolute value of the sample power measurement.

Figure 5

Sample power measurements from final equilibrium values of baseline and sample obtained by using a standard sample and the new PC-driven DAS and the fast-response, small-sample calorimeter



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Norman Beyer completed the calorimeter evaluation study while a staff scientist at the U.S. Department of Energy New Brunswick Laboratory (NBL), Argonne, Ill., where he worked from 1986 to 1991. He recently retired from NBL, where he was project leader of the non-destructive assay (NDA) activities. He has been active in NDA and nuclear materials safeguards since the late 1950s, when he joined the staff of Argonne National Laboratory (ANL) and worked as physicist and group leader of the NDA Group.

After serving 18 years at ANL, where his group was responsible for the early development and application of NDA techniques for the assay and accountability of special nuclear materials, he accepted an appointment to the staff of the International Atomic Energy Agency (IAEA) in Vienna. As a senior officer in the IAEA Department of Safeguards, he participated in the development of NDA inspection techniques as well as their application in the role of inspector and was responsible for establishing the IAEA Field Office in Tokyo which he headed for more than two years. He retired from the IAEA in 1986 after serving nearly 10 years with the Agency. Beyer now resides in Elmhurst, Ill., where he is enjoying semi-retirement.

Statistical Concepts of Deceit and Detection in a Verification Regime

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ABSTRACT

A mathematical model of a treaty-verification situation is presented in terms of statistical hypothesis testing and probability theory. A conflict situation is discussed in which the two players (arbitrarily chosen as male) are the party being inspected and the party doing the inspecting. In the case where the party being inspected is complying with the terms of the treaty, it is assumed that his reported declarations are truthful; in the case where he is violating the treaty, he is assumed to falsify his reported declarations to cover up the violations if possible. The model describes a situation in which evidence for treaty compliance or non-compliance is not conclusive, but where the ambiguities can be characterized by using statistical models. Reporting falsification strategies are described for the inspected party, and hypothesis-testing counterstrategies are described for the inspecting party. The concept of a perfect reporting strategy is discussed, and it is shown that in the absence of perfect reporting the data declared by the inspected party may be used against him. The ability of the inspected party to successfully falsify is shown to be dependent on his state of knowledge of the inspector's information. This can be affected, for example, by randomized strategies on the part of the inspector.

I. INTRODUCTION

Under a treaty-verification regime, the inspected party (the inspectee) is responsible for maintaining or creating a defined set of conditions corresponding to treaty compliance. These conditions, for example, may involve the existence of no more than a specified number of treaty-limited items in a defined area or the retention of no less than a fixed amount of nuclear material under an accounting system. The inspecting party (the inspector) makes independent observations to determine whether those conditions prevail or whether, alternatively, another set of conditions (non-compliance) exists. An important feature of verification regimes is a requirement that a set of declarations be made by the inspectee to the inspector regarding the details of the defined conditions, which the inspector can verify. For example, the inspectee may declare to the inspector the specific locations of the treaty-limited items. It is often much more practical for the inspector to attempt to verify the truth of some or all of the inspectee's declarations than to try to verify the conditions of compliance directly.

In the situation we are considering, neither the inspectee nor the inspector *necessarily* has perfect or complete information regarding the conditions that prevail. For example, the inspector may not be able to count precisely the number of treaty-limited items in an area, or he may make a measurement which is subject to measurement error. These uncertainties are assumed to be amenable to statistical characterization.

Two alternatives exist. Either the inspectee is in compliance, in which case he will report truthfully in his declarations to the inspector, or the inspectee is (intentionally) in non-compliance, in which case he will attempt (perhaps among other strategies) to falsify his declarations to the inspector in such a way as to avoid detection. The inspector must attempt to distinguish compliance from non-compliance based on his own (imperfect) observations and the (possibly falsified) declarations of the inspectee. Evidence of falsification in the inspectee's declarations is equivalent to evidence of non-compliance, since the in-compliance inspectee will not intentionally falsify (although he may make errors due to the uncertainty of his own information). This paper presents a model of this situation.

The issue of reporting and falsification is central. The mathematical concepts used below revolve around the following questions:

- What is the capability of the inspector to distinguish compliance from non-compliance using his own observations alone, *without* the declarations of the inspectee?
- Does the requirement for a specific set of declarations *increase* the inspector's ability to

distinguish compliance from non-compliance, given the possibility that the inspectee may be falsifying?

In this model, the first question is a straightforward test-of-hypothesis problem. The second question is more subtle. Obviously, there may be many practical reasons for requiring declarations in a real treaty situation, in terms of confidence-building, effort required to carry out inspections and so on, but the issue examined here is more fundamental. For example, if the information that is reported cannot be verified by the inspector's observations, and is uncorrelated in any way with the inspector's observations, the inspectee can falsify freely, and the answer to the second question posed above will be no (although exactly how the inspectee should falsify may not be obvious). If there is partial correlation between the declared and independently observed information, it may or may not be possible for the inspectee to falsify his declarations in a way that the information adds nothing to the inspector's detection capability. The determination of which situation exists can in theory be made through the mathematics described below.

If the answer to the second question is no, then a *perfect reporting strategy* exists (as defined below), and the inspector may as well ignore the inspectee's declarations and make his compliance/non-compliance decision on the basis of his own independently observed information alone. It is important to emphasize that although a perfect reporting strategy is the best reporting strategy the inspectee can use, it does not ensure that non-compliance will go undetected. The inspector's detection capability depends on the answer to the first question as well. In fact, a perfect reporting strategy may involve reporting truthfully.

If such a strategy is not possible, then the inspector's decision rule (statistic) should incorporate the inspectee's declarations. The discussion will identify detection statistics which are functions of the inspectee's reported data but which have expected values that distinguish compliance from non-compliance regardless of the falsification reporting strategy adopted by the inspectee.

This paper provides an abstract statistical model of the verification situation described verbally above, defines the concept of perfect reporting, identifies conditions where it exists and shows how to achieve it in certain situations. It is easy to show, for example, that perfect reporting is always possible when the inspectee's knowledge includes the inspector's knowledge. When perfect reporting does not exist, it shows that there is at least one statistic that can be used to discriminate between compliance and non-compliance which is "falsification proof." The theory is presented in terms of basic probability theory and discrete-state probability models.

The mathematics of the theory is presented in Section 2. A balls-in-boxes example is given in Section 3 which is designed to be readily grasped and to be completely solvable computationally; it also provides a good illustration of the subtleties of the theory. Some readers may wish to skip to Sections 3 and 4 after reading the first subsection of Section 2. The example shows the utility of randomized strategies (e.g., sampling) on the part of the inspector. Section 4 comments on the possible application of the theory to arms-control verification problems and provides another fairly simple example drawn from an arms-control context. A final section provides conclusions.

II. MATHEMATICAL CONCEPTS AND THEORY

The basic model

We assume a situation in which there are two hypotheses: H_0 (compliance) and H_1(non-compliance).

The inspector wishes to test H_0 against H_1. The inspectee wishes to convince the inspector that H_0 is true when H_1 is in fact true. There are three state-spaces:

$W = \{w_j; j = 1, 2, \ldots N_w\}$: the set of possible events observed by the inspector

$Y = \{y_k; k = 1, 2, \ldots N_y\}$: the set of possible events observed by the inspectee

$X = \{x_i; i = 1, 2, \ldots N_x\}$: the set of reports by the inspectee to the inspector

There are two probability spaces, one under H_0 and one under H_1. $P^0(w \cap x)$ is the probability that the inspector will observe w and the inspectee will (truthfully) report x (when H_0 is true). $P^1(w \cap y)$ is the probability that the inspector will observe w and the inspectee will observe y when H_1 is true. $A = [a_{ij}]$ is the strategy matrix of the inspectee: a_{ij} is the probability that the inspectee will report x_i if he observes y_j. A is only of interest under H_1. The inspector does not know A.

The "inspectability" of the regime will be shown to depend upon the relationship between two sets of vectors: the N_x vectors $P^0{}_i$, whose jth component is the conditional probability

$$P^0{}_i\,[j] = P^0(x_i|w_j)$$

and the N_y vectors $P^1{}_k$, whose jth component is

$$P^1{}_k\,[j] = P^1(y_k|w_j)$$

Basically, if there is a matrix of positive coefficients a_{ij} (the falsification strategy) which will transform the P^1 vectors into the P^0 vectors, a perfect reporting strategy exists. If this is not true, then a linear combination of the frequencies of certain events (which depend on the reported data) can be found with an expected value under H_0 different than under H_1 regardless of the reporting strategy of the inspectee.

The concepts of "uninspectability" and "perfect reporting"

Strategy A induces a probability $P^A(w \cap x \cap y)$ of w being observed by the inspector, y being observed by the inspectee and x being reported if H_1 is true and A is the inspectee's strategy. It is important to note that the inspectee can act only on his own information (not solely on that of the inspector).

Mathematically

$$\begin{aligned} P^A(x_i \cap w_j \cap y_k) &= P^A(x_i | w_j \cap y_k) P^A(w_j \cap y_k) \\ &= P^A(x_i | y_k) P^A(w_j \cap y_k) \\ &= a_{ik} P^1(w_j \cap y_k) \qquad [1] \end{aligned}$$

where P(x|y) indicates the conditional probability of x given y.

Clearly if $P^A = P^0$ for some strategy A, the inspector will observe identical conditions under the two hypotheses and therefore may be unable to distinguish between them. We might call such a treaty regime (defined by the five objects W, X, Y, P^0, P^1) as "uninspectable." In the opposite case, suppose that a treaty regime is such that for any A there is a least one event e_A which has positive probability under P^A but has zero probability under P^0 ($P^A(e_A) > 0$ but $P^0(e_A) = 0$). One might call such a regime "strongly inspectable" because no matter what the strategy of the adversary, there is some likelihood that he will be detected unambiguously or "caught red-handed:" an event can be detected that cannot occur under treaty compliance. Finally, there might be some event $w \in W$ such that $P^1(w) > 0$ but $P^0(w) = 0$; we call this "very strongly inspectable," because the inspector can catch the inspectee red-handed based on his own observations alone.

If the regime is not uninspectable, then the inspector might attempt to distinguish compliance from non-compliance by looking at the log-likelihood ratio statistic

$$\ln\left(P^A(w,x) / P^0(w,x)\right)$$

which would be optimal (according to the Neyman-Pearson Theorem) if the inspector knows the strategy A (which is not necessarily true).

The above can be rewritten in terms of conditional probabilities as

$$\ln\left(P^A(x|w) / P^0(x|w)\right) + \ln\left(P^1(w) / P^0(w)\right)$$

because $P^1(w) = P^A(w)$, as the inspector's observations are not affected by the inspectee's reporting. The second term in the above equation is simply the inspection likelihood ratio test of compliance based on his observations alone; it does not incorporate reported declarations.

If there is a strategy A such that $P^A(x|w)$ and $P^0(x|w)$ are identical, then the inspectee can make the first term zero, so that the reported information is useless to the inspector, and the likelihood ratio reduces to the one term involving the inspector's observations only. Thus if

$$P^A(x|w) = P^0(x|w) \qquad [2]$$

for some w such that $P^1(w)$ and $P^0(w)$ are greater than zero so that the conditional probabilities exist, A will be called a perfect reporting strategy.

Conditions sufficient for perfect reporting

Clearly if a regime is uninspectable, so that $P^A = P^0$, then equation [2] holds, so that uninspectability implies a perfect reporting strategy is possible. This is not a very interesting case, however.

If the inspectee knows everything the inspector knows (mathematically, if the sigma-algebra generated by the y_i contains that generated by the w_i), then perfect reporting is always possible. The inspectee uses the formula

$$a_{ij} = P^0\left(x_i | w(y_j)\right) \qquad [3]$$

where $w(y_j)$ is the event w that the inspectee knows the inspector has observed due to the fact that the inspectee has observed y_j (y_j must be contained in some $w(y_j)$, and the union of these y_j must equal $w(y_j)$). It is easy to show that the perfect reporting condition is satisfied by this scheme, using the following result.

Lemma. The conditional probabilities for P^A and P^1 satisfy

$$P^A(x_i | w_j) = \sum_k a_{ik} P^1(y_k | w_j) \qquad [4]$$

Proof

$$\begin{aligned} P^A(x_i | w_j) &= P^A(x_i \cap w_j) / P^1(w_j) \\ &= \sum_k P^A(x_i \cap w_j \cap y_k) / P^1(w_j) \end{aligned}$$

using equation [1]

$$\begin{aligned} &= \sum_k a_{ik} P^A(w_j \cap y_k) / P^1(w_j) \\ &= \sum_k a_{ik} P^A(y_k | w_j) = \sum_k a_{ik} P^1(y_k | w_j) \end{aligned}$$

Returning to the strategy indicated by equation [3], if we substitute it into [4], we get

$$P^A(x_i | w_j) = \sum_k P^0\left(x_i | w(y_k)\right) P^1(y_k | w_j)$$

But $P^1(y_k | w_j)$ is zero unless $w_j = w(y_k)$, and the sum of all such non-zero terms is one because the union of these y_j must equal $w(y_j)$. So the sum on the right of this equation is just $P^0(x_i | w_j)$.

Thus, some uncertainty on the part of the inspectee regarding the state of knowledge of the inspector is necessary in order to make declaration requirements useful in a substantive way. We can call a regime in which the inspectee's knowledge encompasses that of the inspector an "inspectee-dominant" regime. Thus, inspectee dominance implies the possibility of a perfect reporting strategy. However, inspectee dominance is not a necessary condition for perfect reporting.

The lemma above leads directly to the following:

Theorem. A perfect reporting strategy exists if and only if there exists A = $[a_{ij}]$ such that

$$0 \le a_{ij} \le 1$$

$$\sum_i a_{ij} = 1$$

$$P^0(x_i|w_j) = \sum_k a_{ik} P^1(y_k|w_j) \qquad [5]$$

The proof follows directly from equations [4] and [2].

This result does not go very far. In some simple circumstances, the equations [5] could be used as the basis for a linear-programming-type calculation to find the a_{ij}. The following paragraphs develop a conjecture involving some concepts that are helpful in analyzing the examples to follow.

Definition. If $\{V_1, V_2 \ldots V_n\}$ is a set of vectors, the convex envelope (CE) of $\{V_1 \ldots V_n\}$ is

$$CE\{V_1, V_2, \cdots\} = \left\{ \sum_i b_i V_i ; 0 \le b_i \le 1 \right\}$$

Obviously, the convex envelope is a convex set containing the origin and all partial sums of the generating vectors and includes the "convex hull."

Let $\{P^0_i; i = 1, 2 \ldots\}$ be the vectors whose jth component is $P^0(x_i|w_j)$ and $\{P^1_k; k = 1 \ldots\}$ be the vectors whose jth component is $P^1(y_k|w_j)$.

Conjecture. The necessary and sufficient condition that a strategy exists for perfect reporting in a verification regime $[W, X, Y, P^0, P^1]$ is that

$$CE\{P^0_i; i = 1, 2..\} \subset CE\{P^1_i; i = 1, 2..\}$$

This conjecture has not been proven. The "necessary" part of the theorem is easily demonstrable from equation [5]. The "sufficiency" can be demonstrated under a number of special circumstances (for example, if one assumes the linear independence of the $P^1{}_j$) but is possibly false in general. But the object $CE\{P^1{}_j\}$ can be used, as shown below, for demonstrating the existence of "falsification-proof" statistics.

An "imperfect" strategy

There is a reporting strategy which is suggested by equation [3] that would seem to be a natural candidate for the inspectee to use but which turns out to be suboptimal in general. The inspectee's best guess as to what the inspector is observing is given by the conditional distribution $P^1(w|y)$. If the inspector observes w, he expects to have x reported with a probability $P^0(x|w)$. It is reasonable to suggest that the inspectee use a strategy that combines these ideas as follows:

$$a_{ij} = \sum_k P^0(x_i|w_k) P^1(w_k|y_j)$$

This formula will work in the case described by [3], where $P^1(w|y)$ will be 0 or 1, but will not generally provide perfect strategies when they exist.

Detection statistics

The likelihood ratio $P^1(w)/P^0(w)$ is used on the inspector's observations to distinguish compliance from non-compliance, assuming that these two are simple hypotheses. If perfect reporting is *not* possible, are there ways to use the inspectee's declarations to provide additional information?

Suppose, contrary to the assumption of the above conjecture, that there is some i* such that $P^0{}_{i*}$ is not in $CE\{P^1 j\}$. Because $CE\{P^1 j\}$ is convex, there is a hyperplane separating $P^0{}_{i*}$ and $CE\{P^1 j\}$ in the vector-space. This hyperplane is defined by

$$\{Z : \langle Z, Z^* \rangle = c^*\}$$

where Z* is a vector perpendicular to the hyperplane, c* is a constant and < > indicates inner product. Suppose that an unbiased set of estimates $\{f_{i*j}, j = 1, 2, \ldots\}$ exists of the probabilities $P^0(x_{i*}|w_j)$ that x_{i*} is reported given w_j is observed (i.e., the fraction of times that x_{i*} is reported to the inspector when w_j is observed by the inspector). Consider the statistic

$$S = \sum_j f_{i*j} Z^*_j$$

The expected value of this statistic under H_0 is

$$E_o(S) = \sum_j P^o(x_{i*}|w_j) Z^*_j = \langle P^o_{i*}, Z^* \rangle$$

The expected value under H_1 is

$$E_A(S) = \sum_j P^A(x_{i*}|w_j) Z^*_j$$

according to [4]

$$= \sum_j Z^*_j \sum_k a_{i*k} P^1_k$$

$$= \langle Q_A, Z^* \rangle$$

where Q_A is in $CE\{P^1{}_k\}$ for any strategy A, because it is a partial sum of the $P^1{}_k$ vectors. But since the Z* defines a separating hyperplane, the value c* will always be between $E_0(S)$ and $E_A(S) = \langle Q_A, Z^* \rangle$ for any A. In other words, no reporting/falsification strategy exists under H_1 that can force the expected value of the Z* statistic to the value that occurs under H_0.

Instead of using a single vector $P^0{}_{i*}$, a linear combination of P_i vectors (falling outside $CE\{P^1{}_j\}$) could have been used, and the resulting statistic would have looked like $S_{ij} K_{ij} f_{ij}$.

These concepts are illustrated in the example below.

III. AN ILLUSTRATIVE EXAMPLE

This example may initially appear somewhat contrived, but it serves to make accessible the concepts developed in the previous section.

Two identical objects simply called "items" are confined in three distinct (closed) boxes, one item to a box, so that one box is always empty. In any given period of time Δt, there is a fixed probability $\lambda\Delta t$ that an item will disappear from one box and reappear in the empty box. The number of such changes-of-state follows Poisson laws like those that govern the number of counts recorded by a radiation detector.

The inspectee has control of these boxes, and the treaty regime specifies that the items are not to be removed (if an item is removed, two boxes obviously become empty, and the remaining item continues to move randomly among the three boxes in the same manner that the empty space did when the two items were present). In other words, the regime resembles one in which material is safeguarded from diversion.

The treaty regime specifies that the inspectee will periodically open box 1 and report the contents (full or empty) to the inspector. The inspector will also make his own periodic observation of the content of box 1. For specificity, we will say initially that the inspectee is supposed to make his observation at noon each day, and the inspector makes his observation T minutes later. Both parties know T and λ. The value of λ is such that there will with high probability be a number of changes-of-state between one day and the next, so these observations are effectively independent. The inspector generally cannot reach a conclusion of compliance or non-compliance based on a single observation, but over a period of time data will accumulate to provide the basis for a statement of arbitrarily high confidence.

When the parameter λT is small, the probability of a change-of-state between the two observations is small. If λT is small and the inspectee reports something different than what is observed by the inspector, the inspector will have grounds for suspicion.

The inspector can attempt to reach a conclusion about the number of items in the boxes by looking at his observational data alone. He expects to see the box full two-thirds of the time, and he can perform statistical tests on this frequency statistic to determine compliance. Should he ignore what is reported by the inspectee, or can he use this information?

The inspectee (who has of course stolen one item) faces the following dilemma: should he report truthfully the content of box 1, thus avoiding suspicion that he is falsifying, but confirming the fact that box 1 is empty more than it should be, or should he falsify, and risk provoking the suspicion that he is falsifying?

Cases 1 and 2: perfect reporting possible

The answer to all these questions depends on the parameter λT. The mathematics show that three basic situations exist. As one would expect, when λT is very small (Case 1), the inspectee is forced to be truthful; his declarations will merely duplicate the inspector's observations, or the inspector will know he is falsifying. This being the case, the inspector will look at his own frequency data to draw his conclusion. If λT is large (Case 2), the observations of the inspector and inspectee are effectively independent. This allows the inspectee to falsify without suspicion; he therefore reports, in effect, that he sees box 1 full two-thirds of the time, regardless of what he actually sees. Because the inspector's data and the inspectee's data are independent, the inspector can have no basis to suspect the declarations. Again, the inspector must rely on his own data exclusively. Both of these situations technically constitute perfect reporting strategies, because the inspected data do not impart any new knowledge to the inspector. This is true despite the fact that in Case 1 the inspectee is telling the truth. Table 1 illustrates the mathematics of the situation and presents an A-matrix which satisfies the conditions of equation [5] for perfect reporting in each case.

Case 3: perfect reporting impossible

For λT in an intermediate range, however, it turns out that there is no perfect strategy. The inspectee must either report truthfully, and thus provide the inspector *useful* (non-redundant) information on non-compliance, or falsify in a manner that is detectable. This information is in addition to the inspector's own observations, which is the same information he had previously. Thus this verification regime is superior to the other two situations from the point of view of the inspector.

The mathematics of this situation is summarized in Table 1. According to equation [5] of the previous section, the inspectee's problem is to make the P^0_i vectors out of linear combinations of the P^1_j vectors; these coefficients define his reporting strategy. Figure 1 shows that in this case the P^0_i vectors are not within the convex envelope of the (P^1_j), so that perfect reporting cannot occur.

For this situation, the inspector can use the statistic S (see equation [6]):

S = (.4)(fraction of times empty is reported by inspectee when empty is observed by the inspector) – (fraction of times empty is reported when full is observed)

This statistic has an expected value of 1/10 under H_0 and an expected value of zero or less under *any* reporting strategy by the inspectee under H_1. The detection capability of this statistic will depend on the number of times the observations are made. The situation is illustrated in Figure 1.

Case 3a: perfect reporting possible

It turns out that this situation (the impossibility of perfect reporting) exists for all intermediate values $0 < \lambda T <$ infinity. The situations in which perfect reporting is possible are therefore in a sense trivial. An example of non-trivial perfect reporting is possible if we modify Case 3 so as to allow the inspectee access to additional information which he is not forced to declare.

Suppose the inspector requires the inspectee to report on the condition of box 1 as the inspectee sees it at noon. He (the inspector) will look at 12:20. However, the inspectee is *also* allowed to see box 1 at some time between 12:00 and 12:20, say at about 12:12. The inspectee is thus allowed to possess more information than he reports. Perfect reporting is then possible, as shown in Case 3a and Figure 2; the inspectee is then in a position to simulate perfectly what should be in a report *based on a 12:00 observation.* The strategy is: report empty when he observes empty 72% of the time; report full when he observes empty 28% of the time; empty when full 6%; and full when full 94%.

Case 4: perfect reporting impossible

Case 1 ($\lambda T << 1$) may also be modified so that the inspector randomly samples the days on which he chooses to look at box 1. We can assign him some probability, say $s = 0.2$, that he will look at box 1 each day. This situation is realistic, as this type of approach is used to conserve inspection effort. The inspector can observe 3 situations:

w_1 = box 1 was found full
w_2 = box 1 was found empty
w_3 = box 1 was not sampled

As in case 1, the inspectee observes and reports either full or empty for box 1. The calculations result in the following:

$$\begin{array}{cccc} & P^0 & & \\ & w_1 & w_2 & w_3 \\ x = e & [1, & 0, & .33] \\ x = f & [0, & 1, & .67] \end{array} \qquad \begin{array}{cccc} & P^1 & & \\ & w_1 & w_2 & w_3 \\ y = e & [1, & 0, & .67] \\ y = f & [0, & 1, & .33] \end{array}$$

The inspectee's problem is to decide what x values to report for specific y values. It is clear by examining the vectors that there is no perfect strategy: linear combinations of the two y vectors that add up exactly to the x's. This indicates that indeed such a randomized approach is efficient on the part of the inspector. In a sense, by cutting his inspection effort in half and requiring the inspectee to report, he obtains half the data that he got before *plus* some useful information from the declarations. This of course is not true if the inspectee knows when the inspector will sample.

The dilemma of the inspectee is that if he falsifies to show that the occupancy of box 1 is 2/3 and not 1/3, he faces a probability of s/3 of being caught red-handed. If he reports truthfully, he provides data to the inspector that box 1 is full only 1/3 of the time. It turns out that perfect reporting is possible under such a sampling scheme only for λT = infinity.

One could continue to analyze these types of situations under complex combinations of the sampling and timing possibilities considered above. All the rather convoluted logical considerations discussed are captured in the mathematics of the linear dependence of the P^0 and P^1 vectors.

IV. ARMS-CONTROL VERIFICATION

Arms-control agreements reflect the general structure of reporting and verification posed in this paper. The technical substance of such treaties is either (a) that the inspectee agrees to an upper bound on the number of treaty-limited items (TLIs) in his possession or (b) that the inspectee agrees that he will not remove material or items from a defined accounting regime. Verification of either type of treaty is not practicable without declarations by the inspectee. In the first case, the presence of a treaty-limited item not declared by the inspectee indicates a violation. In the second case, the absence of an item or the absence of a quantity of material declared to be present indicates a violation. In both cases, the defined number of items or quantity of material is generally conserved under conditions of compliance (provided legitimate destruction is taken into account), while the conservation is violated under non-compliance. In at least some instances, there are defined areas or locations where the items in question are declared to be or are declared not to be, and the items can pass in time from one location to another.

If there is no ambiguity or uncertainty at all about either sides' information regarding the number, amount, or location of treaty-limited items, the theory described here will probably provide few new insights. Under such circumstances, there are no really useful reporting falsification strategies, and if one is caught, one is caught "red-handed," i.e., unambiguously. The problem for the inspectee in this case is to *minimize this* probability of detection. In fact, this is the best type of situation from the point of view of the inspector.

But there are circumstances for which such ambiguity may be a real fact of life, either because the technical means of determining the numbers or amounts may be imperfect or because the conditions of the treaty will permit only partial declarations or limited means of verification. In such circumstances, the ideas of the theory presented here may be useful.

Consider a verification regime of type (α) in the above paragraph, where a fixed number of TLIs are moved among a number of well-defined areas. The security interests of the inspectee preclude a regime in which he is required to continually reveal the location of all his TLIs. Therefore, the inspectee agrees to declare the location of the TLIs periodically and with some delay. Assume that he reports every 12 hours on the location of the TLIs at a point in time 12 hours previous. Assume also that an observation satellite (controlled by the inspector) images one of these well-defined areas every 12 hours (synchronous with the reporting schedule), attempting to see whether a TLI is in the area. The choice of location is random. For simplicity, we assume only one TLI can be in one area at a time.

The detection capability of the satellite is not perfect. With each observation there is the possibility of a false negative (no TLIs are seen when one is present) or a false positive (a TLI is detected when one is absent). These possibilities are regarded as being statistically determined rather than being affected by actions of the inspectee (camouflage, for example).

The inspectee knows which area the satellite has imaged. He must decide (12 hours later) whether to declare to the inspector that there was or was not a TLI in the area under the satellite. It may seem as though the inspectee should always tell the truth, but this strategy would reveal a higher occupancy to the inspector than the inspectee wishes to admit.

In fact, the mathematics of this situation is very similar to that of the illustrative example. The situation is illustrated in Table 2. The basic parameters are (1) the probability of a false positive (given no TLIs in the area), (2) the probability of a false negative (given a TLI is in the area), (3) the average occupancy under compliance (the number of allowed TLIs divided by the number of areas) and (4) the average occupancy under non-compliance (the actual number of TLIs divided by the number of areas). The situation where the false positive and false negative probabilities are very small (Case 5) corresponds to the $\lambda T << 1$ situation discussed previously (Case 1); the inspectee must tell the truth. The situation in which the false positive and negative probabilities are both 1/2 is somewhat similar to the $\lambda T >> 1$ situation (Case 2) above, in that the inspectee can falsify freely. In this case, the inspector obviously has no real observational capability at all. The regime is uninspectable. Cases 5 and 6 both represent perfect reporting strategies.

Again, intermediate values of parameters produce a situation in which *perfect* reporting appears to be impossible. However, a strategy very close to perfect is illustrated in Case 7, where the conditional probabilities generated by the reporting falsification scheme are good to almost three places. There are 50% more TLIs under the non-compliance hypothesis, but the false positive probability is assumed to be high: 0.15. The strategy is to tell the truth when the satellite images an area with no TLIs, but to declare that no TLI is present about 23% of the time when the satellite is over an area that does contain a TLI. In effect, the inspectee is hoping the inspector will take these to be false positives.

As with the previous example, a number of variants can be explored, some of which favor the inspectee, some the inspector. Suppose the inspectee has some knowledge (but not perfect knowledge) of where the satellite will image, and suppose the inspectee has imperfect knowledge of the imaging capability of the satellite? More realistic and complex examples would require a higher order of computational sophistication and perhaps further development of the theory.

The problem of falsification of reported material accounting data can also be treated using the concepts similar to those presented here[1,2] and with similar results in terms of computation of falsification and detection strategies. However, a different mathematical approach must be used to extend the discrete-state theory used here; this involves extensive calculations beyond the scope of this paper.

V. CONCLUSIONS

On the basis of a small amount of fairly simple theory, this paper introduces a number of ideas that may be conceptually useful in designing or evaluating inspection regimes. It formalizes the inspector–inspectee relationship mathematically. It shows that the inspectee's own information can be used against him by the inspector if it is reported, even falsely, to the inspector. It shows that the inspectee's information about the inspector's knowledge can be used to deceive the inspector. It provides indications of how randomized strategies, which generate information known to the inspector but not to the inspectee, limit the ability of the inspectee to falsify. It demonstrates the existence (at least in some circumstances) of falsification-proof tests. All of these strategies indicate that the inspector–inspectee conflict is waged with bits of information.

The paper leaves untouched a large number of questions: In the case where perfect reporting is impossible, what is an optimal reporting falsification strategy, and how would it be computed? What is an optimal detection counterstrategy? Are there simple conditions that will guarantee the impossibility of perfect reporting?

Table I

Basic Probabilities, Cases 1–3

[Note: $b = e^{-\lambda T}$; e = empty; f = full; w = inspector's observation; y = inspectee's observation; x = reported declaration; a = inspectee's strategy matrix]

$P^0(w \cap x)$

	w=e	w=f
x=e	(1 + 2b)/9	(2-2b)/9
x=f	(2 - 2b)/9	(4+2b)/9

$P^1(w \cap y)$

	w=e	w=f
y=e	(4+2b)/9	(2-2b)/9
y=f	(2 - 2b)/9	(1 + 2b)/9

$P^0(x \mid w)$

P^0_e =	(1 + 2b)/3	(1 - b)/3
P^0_f =	(2 - 2b)/3	(2 + b)/3

$P^1(y \mid w)$

P^1_e =	(2 + b)/3	(2 - 2b)/3
P^1_f =	(1 - b)/3	(1 + 2b)/3

Case 1: $\lambda T << 1, b = 1$

$$P^o_e = [1,0] \xleftarrow{1} P^1_e = [1,0] \qquad a = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$P^o_f = [0,1] \xleftarrow{1} P^1_f = [0,1]$$

The inspectee must report the box is full when it is full, and report empty when it is empty.

Case 2: $\lambda T >> 1$, b = 0

$$\begin{tikzcd}
P_e^o = [1/3, 1/3] & P_e^1 = [2/3, 2/3] \arrow[l, "0.5"'] \arrow[dl, "0.5"'] \\
P_f^o = [2/3, 2/3] & P_f^1 = [1/3, 1/3] \arrow[l, "1.0"]
\end{tikzcd}$$

$$a = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 0 & 1 \end{bmatrix}$$

Half the time the inspectee sees the box empty, he will call it full. When he sees it full, he will call it full. (Alternatively, he could also call the box full when it is empty, and empty when it is full.)

Case 3: b = 1/2

$$\begin{array}{cc}
\begin{array}{c} \quad\text{e}\quad\text{f} \\ P_e^o = [2/3, 1/6] \end{array} & \begin{array}{c} \quad\text{e}\quad\text{f} \\ P_e^1 = [5/6, 1/3] \end{array} \\
? & \\
P_f^o = [1/3, 5/6] & P_f^1 = [1/6, 2/3]
\end{array}$$

No linear combinations of the P^1 vectors can generate the P^o vectors (see Figure 1)

Basic Probabilities, Case 3a

[Note: b = $e^{-\lambda T}$; d = $e^{-\lambda t}$ where
T = 20 min. (noon to 12:20) and
t = time between inspectee's and inspector's observation = 8.3 min.]
then b = 1/2 and d = 3/4

$P^o(w \cap x)$

	w=e	w=f
x=e	(1+2b)/9	(2-2b)/9
x=f	(2-2b)/9	(4+2b)/9

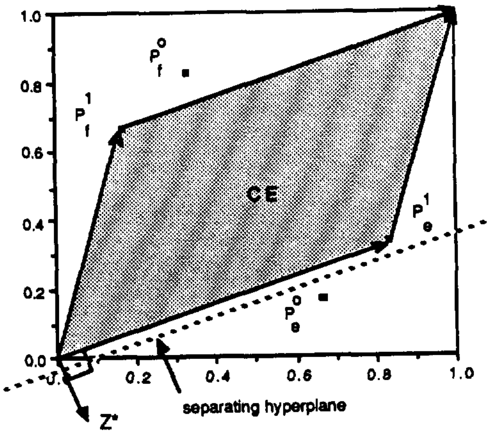
$P^1(w \cap y)$

	w=e	w=f
y=e	(4+2d)/9	(2-2d)/9
y=f	(2-2d)/9	(1+2d)/9

$$\begin{tikzcd}
P_e^o = [2/3, 1/6] & P_e^1 = [11/12, 1/6] \arrow[l, "0.72"'] \arrow[dl, ".28"'] \\
P_f^o = [1/3, 5/6] & P_f^1 = [1/12, 5/6] \arrow[l, "0.94"] \arrow[ul, ".06"]
\end{tikzcd}$$

The inspectee will report empty when he observes empty 72% of the time; full when empty 28%; empty when full 6%; and full when full 94%.

Figure 1
Graphical Analysis of Case 3



P^o_e is outside the convex envelope (CE) of P^1_e, P^1_f, and therefore it can be tested via a linear statistic. In this case, Z* = [2/5,–1] is perpendicular to the hyperplane that separates the two objects, so the test statistic is
S = (2/5)(fraction of times empty is reported when empty is observed) – (fraction empty is reported when full is observed).

Figure 2
Graphical Analysis of Case 3a

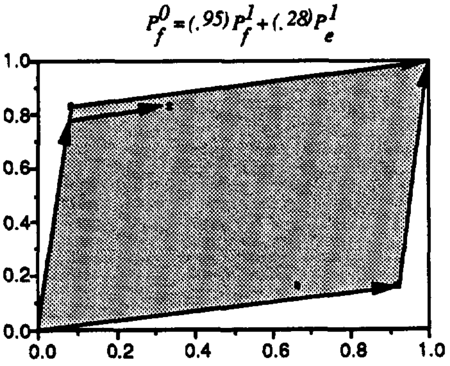


Table II

Basic Probabilities, Cases 5–7

[Note: p = TLI present under satellite; a = TLI absent; w = inspector's observation; y = inspectee's observation; x = reported declaration; α = false positive probability; β = false negative probability; G = occupancy under H_0; F = occupancy under H_1]

$P^0(w \cap x)$

	w=p	w=a
x=p	$(1-\beta)G$	$G\beta$
x=a	$(1-G)\alpha$	$(1-G)(1-\alpha)$

$P^1(w \cap y)$

	w=p	w=a
y=p	$(1-\beta)F$	$F\beta$
y=a	$(1-F)\alpha$	$(1-F)(1-\alpha)$

Case 5: α,β = 0, G = .1, F = .2

$$\begin{tikzcd}
P_p^o = [1,0] & P_p^1 = [1,0] \arrow[l, "1"'] \\
P_a^o = [0,1] & P_a^1 = [0,1] \arrow[l, "1"']
\end{tikzcd}
\qquad
a = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The inspectee must report the TLI present when it is present, and report it absent when it is absent.

Case 6: α,β = 0.5, G = .1, F = .2

$$\begin{tikzcd}
P_p^o = [0.1.0.1] & P_p^1 = [0.2,0.2] \arrow[l, "1/2"'] \arrow[dl, "1/2"'] \\
P_a^o = [0.9,0.9] & P_a^1 = [0.8,0.8] \arrow[l, "1"']
\end{tikzcd}
\qquad
a = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 0 & 1 \end{bmatrix}$$

Half the time the inspectee sees the TLI is present under the satellite, he will call it absent. If it is absent, he will call it absent.

Case 7: α = 0.15, β = 0.05, G = .1, F = .15

$$P_p^o = [0.386, 0.006] \qquad P_p^1 = [0.5, 0.009]$$

$$P_a^o = [0.614, 0.994] \qquad P_a^1 = [0.5, 0.991]$$

Using the matrix

$$a = \begin{bmatrix} .772 & .228 \\ 0 & 1.00 \end{bmatrix}$$

the P^0 vectors can be obtained from the P^1 vectors *almost* exactly.

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2. Sanborn, J.B. "Falsification and Detection Strategies in Material Accountancy Verification", Brookhaven National Laboratory, Report No. BNL-52040, to be published.

Jonathan Sanborn has a Ph.D. in applied mathematics. He joined the Technical Support Organization of Brookhaven Laboratory in 1977; soon thereafter he was sent to the IAEA as a cost-free expert to work in the Systems Studies Section. Upon returning to Brookhaven, he became involved with studies of international safeguards and domestic material accounting systems. More recently he has been working on arms-control problems associated with the Chemical Weapons Convention. He has recently returned from three months as part of the U.S. delegation to the Conference on Disarmament.

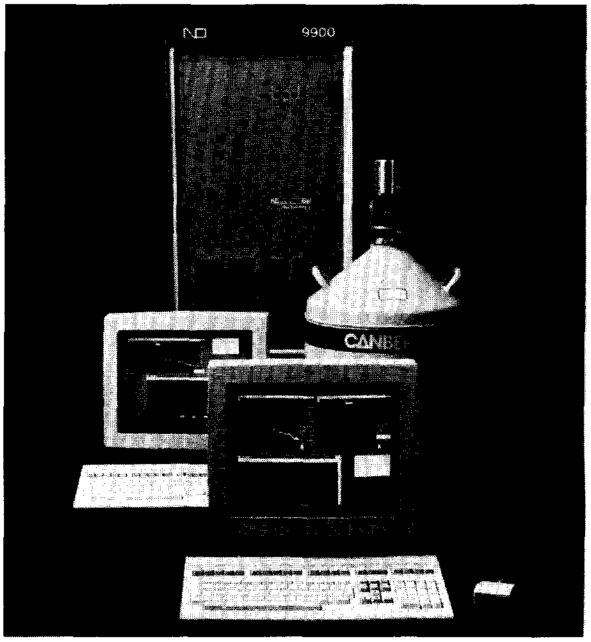
Introducing the X:Genie Network System

Canberra Nuclear announces the the X:Genie Network System for workstation style graphics in a multi-user system. The standard X-windows user interface allows the operator to view multiple windows at one time, each running different applications. Multichannel Analyzer (MCA) windows allow the operator to control data collection devices and to view spectra and associated parameters. Therefore, experiments can be controlled, applications executed or data reviewed from any X-terminal connected to the system. Application programs, such as the ABACOS-PLUS whole body counting package, can interact with MCA windows to facilitate calibration, operator feedback and ease of use, providing the optimum user interface environment.

The X:Genie's flexible architecture allows multiple X-terminals to be connected to an ethernet LAN, which supports decentralized data collection stations, without the overhead of a multi-CPU environment.

Data acquisition on an X:Genie System is performed through either the Q-Bus ADC interface (ACQH) or the 556 Acquisition Interface Module (AIM). The system is fully compatible with all DEC VAX computers.

For more information, contact Canberra Sales at 1-800-243-3955.



Lixi Offers Portable Linescan Technology

Lixi Inc. is now offering its line-scan technology in a portable form. The purpose of line-scan (linear array X-ray) is to provide the user with macro imaging of larger size products inspecting areas up to 9 inches and 18 inches wide very quickly. This makes Lixi Line-Scan systems highly useful to a broad cross-section of industries, such as PC boards, food, composites, medical devices, plastics and similar products that are too large for efficient inspection with microfocus X-ray.

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Since these are portable systems, other departments can also make use of them, thereby maximizing the utilization of a single X-ray system. Incoming inspection, R&D, QC lab and final inspection are just some of the many uses of Lixi Line-Scan X-ray within a plant.

The Lixi linear X-ray detection technology (line-scan) scans an object passing across a 9- or 18-inch-wide area. The imaging quality remains consistent across the entire width because of the higher resolution and higher dynamic range of Lixi systems. The portable systems are available open or enclosed. For more information, contact Lixi Inc., 1438 Brook Drive, Downers Grove, IL 605115; phone (708) 620-4646.

New RAM FLAT Compactor Handles 85-Gallon Drums

The newest RAM FLAT compactor, the Model 85AR, is engineered specifically for compacting hazardous materials within an 85-gallon drum. The compactor was developed by S&G Enterprises in response to hazardous waste safety standards that require packing dry waste or leaking 55-gallon drums and their contents into 85-gallon drums.

The model 85AR can compact within any type of 85-gallon drum, including reconditioned, fiber, plastic and metal, to reduce waste bulk and disposal costs. Shipped prepared for normal or explosion proof service, the model 85AR can deal with any hazardous or low-level radioactive wastes requiring compaction. With a simple change of the compaction head, the RAM FLAT Model 85AR can crush 85-gallon drums, turning them into 5-inch metal pancakes for easy disposal.

For more information, contact Grasso Hillmer, 1505 11th Ave., P.O. Box 318, Grafton, WI 53024; phone (414) 375-1015.

CALENDAR

August 11 - 14, 1991
15th Biennial Topical Meeting on Reactor Operating Experience: Nuclear Power Plant Operations — Ready for 2000, Seattle, Wash. *Sponsor:* American Nuclear Society Reactor Operations Division , ANS Eastern Washington Section. *Contact:* T.T. Claudson, Battelle PNL, Battle Blvd., Richland, WA 99352; phone (509) 375-2878.

August 20 - 22, 1991
Packaging and Transportation of Radioactive Waste Seminar, Las Vegas, Nev. *Sponsor:* US Ecology Inc. *Contact:* Peggy Thompson, US Ecology Inc., 9200 Shelbyville Road, Suite 300, P.O. Box 7246, Louisville, KY 40257-0246; phone (800) 999-7160.

September 15 - 18, 1991
American Society for Non-destructive Testing 50th Anniversary Fall Conference and Quality Testing Show, Sheraton Boston, Boston, Mass. *Sponsor:* American Society for Non-destructive Testing Inc. *Contact:* ASNT Marketing Department; phone (614) 274-6003.

September 17 - 19, 1991
Variance Propagation and Systems Analysis Workshop, Los Alamos, N.M. *Sponsor:* U.S. Department of Energy Safeguards Technology Training Program. *Contact:* Patricia Andersen, MS E 541, Los Alamos National Laboratory, Los Alamos, NM 87545; phone (505) 667-7777.

September 29 - October 4, 1991
Focus: '91 Nuclear Waste Packaging, Plaza Suite Hotel, Las Vegas, Nev. *Sponsor:* American Nuclear Society Fuel Cycle and Waste Management Division and the ANS Las Vegas Section; Cosponsored by the Materials Science and Technologies Division and ASM International. *Contact:* Technical Program Chair David Stahl, SAIC — Suite 407, 101 Convention Center Dr., Las Vegas, Nev. 89109; phone (702) 794-7778.

September 29 - October 4, 1991
Fourth International Conference on Facility Operations-Safeguards Interface, Albuquerque, N.M. *Sponsor:* American Nuclear Society Isotopes and Radiation Division, ANS Fuel Cycle and Waste Management Division, Trinity Section of ANS, and the Institute of Nuclear Materials Management. *Contact:* ANS Meetings Dept., 555 N. Kensington Ave., La Grange Park, IL 60525; phone (708) 579-8258.

October 1 - 3, 1991
Emerging Technologies for Hazardous Waste Treatment, Atlanta, Ga. *Sponsor:* American Chemical Society, Division of Industrial and Engineering Chemistry. *Contact:* Dr. D. William Tedder, I&EC Symposium Chair, School of Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0100.

October 1 - 3, 1991
32nd Conference on Analytical Chemistry in Energy Technology, Gatlinburg, Tenn. *Sponsor:* Oak Ridge National Laboratory, U.S. Department of Energy. *Contact:* R.D. Laing, Oak Ridge National Laboratory, P.O. Box 2008, MS 6127, Oak Ridge, TN 37831.

October 1 - 3, 1991
Packaging and Transportation of Radioactive Waste Seminar, Richland, Wash. *Sponsor:* US Ecology Inc. *Contact:* Peggy Thompson, US Ecology Inc., 9200 Shelbyville Road, Suite 300, P.O. Box 7246, Louisville, KY 40257-0246; phone (800) 999-7160.

October 15 - 18, 1991
1991 Annual Calorimetric Assay Training School, EG&G Mound, Miamisburg, Ohio. *Sponsor:* U.S. Department of Energy. *Contact:* Lina Di Girolamo, EG&G Mound, Miamisburg, Ohio 45343; phone (513) 865-3753; fax (513) 847-5264.

October 23 - 25, 1991
Potential of Small Nuclear Reactors for Future Clean and Safe Energy Sources, Tokyo Japan. *Sponsors:* Tokyo Institute of Technology, Atomic Energy Society of Japan. *Contact:* Hiroshi Sekimoto, Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Okayama, Meguro-ku, Tokyo 152, Japan; phone (03)3726-111.

November 19-21, 1991
Pollution Control Equipment Matchmaker and Seminar, London, England. *Sponsor:* U.S. Department of Commerce. *Contact:* Molly Costa, U.S. and Foreign Commercial Services, U.S. Department of Commerce, Room H2116, Washington, D.C. 20230; phone (202) 377-4231.

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