JNMM

Journal of Nuclear Materials Management

Published by the Institute of Nuclear Materials Management ▪ Volume XX, Number 2 ▪ February 1992

JNMM is published four times a year by the Institute of Nuclear Materials Management, Inc., a not-for-profit membership organization with the purpose of advancing and promoting efficient management and safeguards of nuclear materials.

SUBSCRIPTION RATES: Annual (U.S., Canada and Mexico) $100.00, annual (other countries) $135.00 (shipped via air mail printed matter); single copy regular issues (U.S. and other countries) $25.00; single copy of the proceedings of the annual meeting (U.S. and other countries) $65.00. Mail subscription requests to *JNMM*, 60 Revere Drive, Suite 500, Northbrook, Illinois 60062 U.S.A. Make checks payable to INMM.

ADVERTISING, distribution and delivery inquiries should be directed to *JNMM*, 60 Revere Drive, Suite 500, Northbrook, Illinois 60062 U.S.A. or contact Vickie Zombolo at (708) 480-9573, Fax (708) 480-9282. Allow eight weeks for a change of address to be implemented.

ISSN 0893-6188

CONTENTS

Volume XX, Number 2 • February 1992

PAPERS

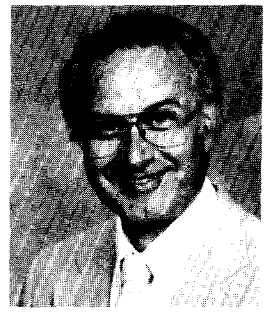
FEATURES

EDITORIALS

INMM NEWS

ANNOUNCEMENTS & NEWS

INMM adds new divisions



Fellow members and friends of the INMM, I hope you had a marvelous holiday and are looking forward to a busy and productive new year, as I am. The coming year should be one of great opportunity for the Institute as well. The efforts in the United States to reconfigure, and probably downsize, the DOE complex and the rapid changes in the former Soviet Republics should require even more of the nuclear materials management technology held primarily by the members of INMM — safeguards, materials measurement, transportation and waste management.

In keeping with all of the amazing changes in the world and the resulting opportunity for growth of the Institute, at the November Executive Committee meeting we redesignated our four Technical Working Groups (the TWGs) to be divisions, which better describes their function, and created two new divisions. So we now have six divisions in the INMM — Physical Protection, Materials Control and Accounting, Transportation, Waste Management, Nuclear Nonproliferation Safeguards, and Arms Control and Verification. The divisions will retain all of the functions of the TWGs but will have increased responsibility for stimulating technical sessions at the Annual Meeting. I will continue to appoint division chairs, but the Executive Committee will confirm the appointments (let's hope we can do it better than the U.S. Senate seems to be able to do). Current TWG chairpersons have been confirmed as division chairs.

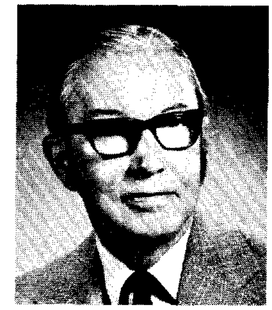
You can read more about the role of the technical divisions, as well as that of the several standing committees and technical committees, elsewhere in this issue. Please take time to read the article and learn about the structure of your Institute. If you have questions, please call me or any member of the Executive Committee. Also call if you discover an area in which you want to serve.

Speaking of changes, OMSI, the management company that has taken care of our day-to-day needs and arranged the logistics of our Annual Meetings so well for the past 10 years, has new owners and a new name — The Sherwood Group, Inc. We will miss John Messervey but are looking forward to working with the new owners, John Waxman and Greg Schultz, and a continuing great relationship with Barb Scott, our executive director, and Laura Rainey, our administrative director. Mary Dulabaum is the new associate editor of this journal, the *Journal of Nuclear Materials Management (JNMM)*.

I hope you have a good and satisfying new year. See you in Orlando!

Darryl B. Smith
Los Alamos National Laboratory
Los Alamos, New Mexico U.S.A.

President's report discusses verification techniques



The Treaty on Elimination of Intermediate Range Nuclear Forces in Europe was signed and came into effect two years ago. The START treaty was signed in 1991 and will become effective shortly. President Bush and former President Gorbachev recently agreed to eliminate thousands of tactical nuclear weapons, and both countries are in the process of halting the production of fissile materials for weapons.

In 1990, the U.S. Congress suggested that, if the President determines "that future international agreements should provide for dismantlement of nuclear warheads and a ban on the further production of fissile material for weapons, then the Congress urges the President to seek to establish with the former Soviet Union republics a joint technical working group to examine and demonstrate cooperative technical monitoring and inspection arrangements that could be applied to the design and verification of these potential provisions." It instructed the President to prepare a report, by April 30, 1991, on the onsite monitoring techniques, inspection arrangements and national technical means of verification that the United States could use to verify the following: dismantlement of nuclear warheads, should that be agreed on; a mutual US - USSR ban, leading to a global ban, on the production of fissile materials for weapons; and the end use or ultimate disposal of any plutonium or highly enriched uranium recovered from the dismantlement of nuclear warheads. The unclassified executive summary of this report, dated July 1991, was released in October.

The report "addresses onsite monitoring techniques, inspection arrangements, and national technical means of verification that could be used to monitor compliance if a decision to pursue such arms control measures were made. The status, role, potential use and possible further development of these verification techniques and inspection arrangements are examined. The report also identifies other impacts, including the risk of compromising sensitive, nuclear weapons-related information."

The report goes on to state the following:

"This report does not address the policy issues of whether it would be in the U.S. national security interest to seek agreements with either the Soviet Union or other nations that would require the dismantlement of nuclear weapons, the disposition of the returned nuclear materials, and/or controls on the production of plutonium or highly-enriched uranium that could be used to build additional weapons. That issue can only be decided on the basis of strategic, military and political judgements, including a net assessment of the objectives and capabilities of other nations relative to U.S. security, which lie beyond the scope of this report.

If a proposed agreement provides for dismantlement of specified numbers of weapons or for specific reductions of weapons material inventories, the following issues would need to be addressed: 1. Actual and appropriate nuclear weapons are dismantled. 2. Nuclear materials recovered from dismantled weapons are not used for prohibited purposes. 3. Prohibited existing facilities are shut down. 4. Allowed production and processing facilities are not used to produce prohibited materials or warheads. 5. Clandestine/prohibited production and processing facilities do not exist.

Assessing the adequacy of potential verification measures is extremely difficult. Standards for verification would depend not only upon the objectives and details of specific agreements, but also on their geopolitical context."

Many of the techniques will be familiar to those who have been involved in developing IAEA safeguards: (1) verification of materials accountancy and (2) containment and surveillance to maintain continuity of knowledge. The subject is complicated, for example, by the size of the peaceful and military programs in the two countries, the fact that it would be difficult, if not impossible, to verify the present inventories of weapons and materials, and that the continuing production of tritium and fuels for naval reactors would be permitted. This will obviously be a challenge for safeguards technologists as well as for the political leaders.

As was reported at the annual meeting in 1990, a committee of the Federation of American Scientists has been working with colleagues in the Soviet Union for several years on verification technologies which might be needed in future arms control agreements. As soon as the U.S. Congress passed the legislation discussed above, a delegation from the Federation went to Moscow to discuss verification of a ban on the production of fissile materials for weapons, dismantlement of nuclear warheads and disposal of the recovered materials with the Committee of Soviet Scientists for Global Security and the Center for Program Studies of the USSR Academy of Sciences. After further discussion and the exchange of drafts, their report was issued in May 1991. This report discusses the same issues as those discussed in the President's report.

Interested Institute members should obtain and study the documents which

Continued on page 5

Chapters: Central Region

The annual meeting of the Central Region Chapter was held on Oct. 25, 1991, in Oak Ridge, Tenn. The meeting was attended by 55 persons representing DOE (two field offices and OSS), NRC license, six DOE contractors, and four other organizations.

The opening session of the meeting focused on DOE and NRC performance requirements and provided a forum for the meeting participants to discuss DOE and NRC perspectives on, and facility experience in, implementing the performance requirements. The following 13 technical reports were presented:

Meeting the Material Control Requirements of the Material Control and Accounting Reform Amendment, Terry W. Lewis, Nuclear Fuels Services, Erwin, Tenn.;

Performance Testing to Validate System Capabilities, B. Tatum Fowler, Martin Marietta Energy Systems, Y-12 Plant, Oak Ridge, Tenn.;

NRC's Approach to Safeguards Performance-based Requirements, Philip Ting, U.S. Nuclear Regulatory Commission, Rockville, Md.;

DOE Material Control and Accountability Performance Requirements Development, David W. Crawford, U.S. Department of Energy, Germantown, Md.;

Measurement Technology in the Weapons Complex — A Status Report, Wanda G. Mitchell, U.S. Department of Energy, New Brunswick Laboratory, Argonne, Ill.;

Plutonium-238 Confirmatory Measurement Experiences, Allen R. Campbell, EG&G Mound Applied Technologies, Miamisburg, Ohio;

Gravimetric Gas Determination for Volume Calibration, Philip W. Gibbs, Westinghouse Savannah River, Aiken, S.C.;

Estimation of Residual Uranium Holdup at the Oak Ridge K-25 Site, Richard L. Mayer, Martin Marietta Energy Systems, K-25 Site, Oak Ridge, Tenn.;

Data Base Management for the NDA Measurement Program, Julianne Bailey, Martin Marietta Energy Systems, K-25 Site, Oak Ridge, Tenn.;

Central Accountability System, Linda A. Hairston, Westinghouse Savannah River, Aiken, S.C.;

Automatic Material Identification and Surveillance System, L.L. King, Westinghouse Electric, Baltimore, Md.;

Lesson Plans and MC&A Training, John L. Hehemeyer, EG&G Mound Applied Technologies, Miamisburg, Ohio; and

Pros and Cons of Using In-house Technical Expertise for the Development of Safeguards Plans and Assessments, James O.V. Nations, Martin Marietta Energy Systems, K-25 Site, Oak Ridge, Tenn.

Bruce W. Moran
Program Chair
Martin Marietta Energy Systems
Oak Ridge, Tenn., U.S.A.

Corrections

The November 1991 issue of *JNMM* incorrectly identified the Chair of the Arms Control session at the 32nd INMM Annual Meeting, held in New Orleans. The well-attended Arms Control session was chaired by Joe Indusi, Brookhaven National Laboratory.

Also, in Dr. William A. Higinbotham's editorial on "Improving IAEA Safeguards," copy was omitted in his discussion of why there was more widespread agreement on the important issues from the 84 signatories attending the Fourth Review Conference of the Nuclear Non-Proliferation Treaty. In addition to the reasons he listed were Iraqi development and concern about North Korea, which signed the NPT but has continued to postpone ratification and the end of the Cold War.

Chapters: Japan

The 47th Executive Committee Meeting was held in Tokyo on Oct. 18, 1991, and the chapter's business plan and financial budget for the 1992 fiscal year were discussed and confirmed.

1991 Business Plan

1. The Japan Chapter's 13th Annual Meeting will be held at Gakushi Kaikan in Tokyo on June 11, 1992. Details of the meeting will be discussed by the Annual Meeting Program Committee. At the 47th Executive Committee Meeting, Mr. Hiroshi Okashita, treasurer, was appointed as a chairman of the 13th Annual Meeting. The Program Committee and the committee members are being organized.
2. Japan chapter's business meeting will also be held at the same time as the 13th Annual Meeting.
3. The Chapter will organize a group tour for participants to the 33rd INMM Annual Meeting in Orlando, Fla. While there, the chapter will make observation tours to some interesting nuclear installations in July 1992.

Membership in the Japan Chapter as of Nov. 16, 1991, totals 152.

Dr. Mitsuho Hirata
Chairman, INMM Japan Chapter

Editor's Note (continued)

are mentioned here. Copies of "Report to Congress: Verification of Nuclear Warhead Dismantlement and Special Nuclear Material Controls, Executive Summary", July 1991, may be obtained from the President's Office, the U.S. Department of Energy, or the U.S. Congress. "Ending the Production of Fissile Materials for Weapons: Verifying the Dismantlement of Nuclear Warheads" may be obtained from the Federation of American Scientists, 307 Massachusetts Ave., Washington, D.C. 20002.

Dr. William A. Higinbotham
Brookhaven National Laboratory
Upton, New York U.S.A.

INMM restructures its organization

The Institute of Nuclear Materials Management (INMM) has amended its organizational structure in a move to help the organization evolve with the diversification of the nuclear safeguards community and respond to the changing needs and interests of the INMM membership.

The Executive Committee voted at its November meeting to reconfigure the Institute's special interest subgroups, formerly known as Technical Working Groups (TWGs.) The Institute's special interest subgroups are now called "divisions." At the same time, two new divisions were added to the four that existed as TWGs. The INMM Divisions are Waste Management, Materials Control & Accounting, Physical Protection, and Transportation, plus the newly formed divisions for Nuclear Non-Proliferation/International Safeguards and Arms Control/Verification.

The Technical Working Groups were established in the late 1970s by an Ad Hoc Committee consisting of D.W. Wilson, D.M. Bishop, T.A. Gerdis and chaired by G. F. Molen. The original recommendation by the committee included working groups in the areas of Physical Protection, Measurements and Measurement Control, Accountability and Materials Management, System Studies and International Safeguards. Waste Management and Transportation were added later. The TWGs were originally formed "to provide a forum for review and discussion of current technical issues related to nuclear materials management and safeguards."

The change to divisions was made to more accurately reflect the function and permanence of these groups. The divisions will have increased responsibility for stimulating and organizing technical sessions at the annual meeting and generating papers for this journal. Divisional chairs will be appointed by the INMM chairman, as were TWG chairs, but they will now be confirmed by the INMM Executive Committee. All TWG chairs have been confirmed by the Executive Committee as division chairs.

A survey conducted at the July 1991 Annual Meeting in New Orleans revealed the need for additional special interest groups under the umbrella of the Institute. More than 500 attendees, two-thirds of them INMM members, listed areas in which they currently work. The results were as follows:

- 11% Arms Control
- 14% Containment & Surveillance
- 18% Environmental Safety & Health
- 26% International Safeguards
- 47% Materials Control & Accounting
- 28% Physical Protection
- 18% Security
- 12% Transportation & Packaging
- 14% Waste Management

The numbers total more than 100% because of multiple areas of involvement. Other areas of involvement listed include Measurement Technology; Technology Transfer; Human Resources, Non-Destructive Assay, Power Generation, Management and Safety.

In another change, the name of the committee charged with interacting with government agencies, particularly the Nuclear Regulatory Commission, has been changed from "Safeguards" to "Government Liaison" to better describe its function.

The chart on page 7 outlines INMM's organizational structure. Members may affiliate with one of five active INMM chapters; however, approximately 60% of INMM members are with a chapter. The Executive Committee, consisting of five officers and four members-at-large, serves as a focal point for members, standing committees, technical committees and technical divisions. The Executive Committee provides guidance to the headquarters staff, which in turn provides administrative support and membership services. The Executive Committee and headquarters staff are listed on page 1 of this journal.

If you are interested in participating or serving on any of the divisions or committees, contact Executive Director Barbara Scott at INMM headquarters, (708) 480-9573.

Executive Committee Officers

Chairman — Darryl Smith, Los Alamos National Laboratory, (505) 667-6394

Vice Chairman — Dennis Mangan, Los Alamos National Laboratory, (505) 845-8710

Secretary — Vincent J. DeVito, consultant, (614) 947-5213

Treasurer — Robert U. Curl, EG&G Idaho Inc., (208) 526-2823

Members-at-Large — Patricia Baird, Martin Marietta Energy Systems, (615) 574-5343; John Lemming, EG&G Mound Applied Technologies, (513) 865-3689; Joseph Indusi, Brookhaven National Laboratory, (516) 282-2975; Elizabeth Ten Eyck, (301) 492-3344; Obie Amacker, Pacific Northwest Laboratory, (509) 376-2819.

Committee Chairs

Annual Meeting Arrangements — Deanna Osowski, Westinghouse Hanford Co., (509) 376-4312

Exhibits — Open

Technical Program — Charles E. Pietri, U.S. Department of Energy, (708) 972-2449

Registration — Gary J. Carnival, EG&G Rocky Flats Inc., (303) 966-2403

Local Arrangements — Deanna Osowski, Westinghouse Hanford Co., (509) 376-4312

Bylaws & Constitution — Roy Cardwell, consultant, (615) 986-7347

Chapters

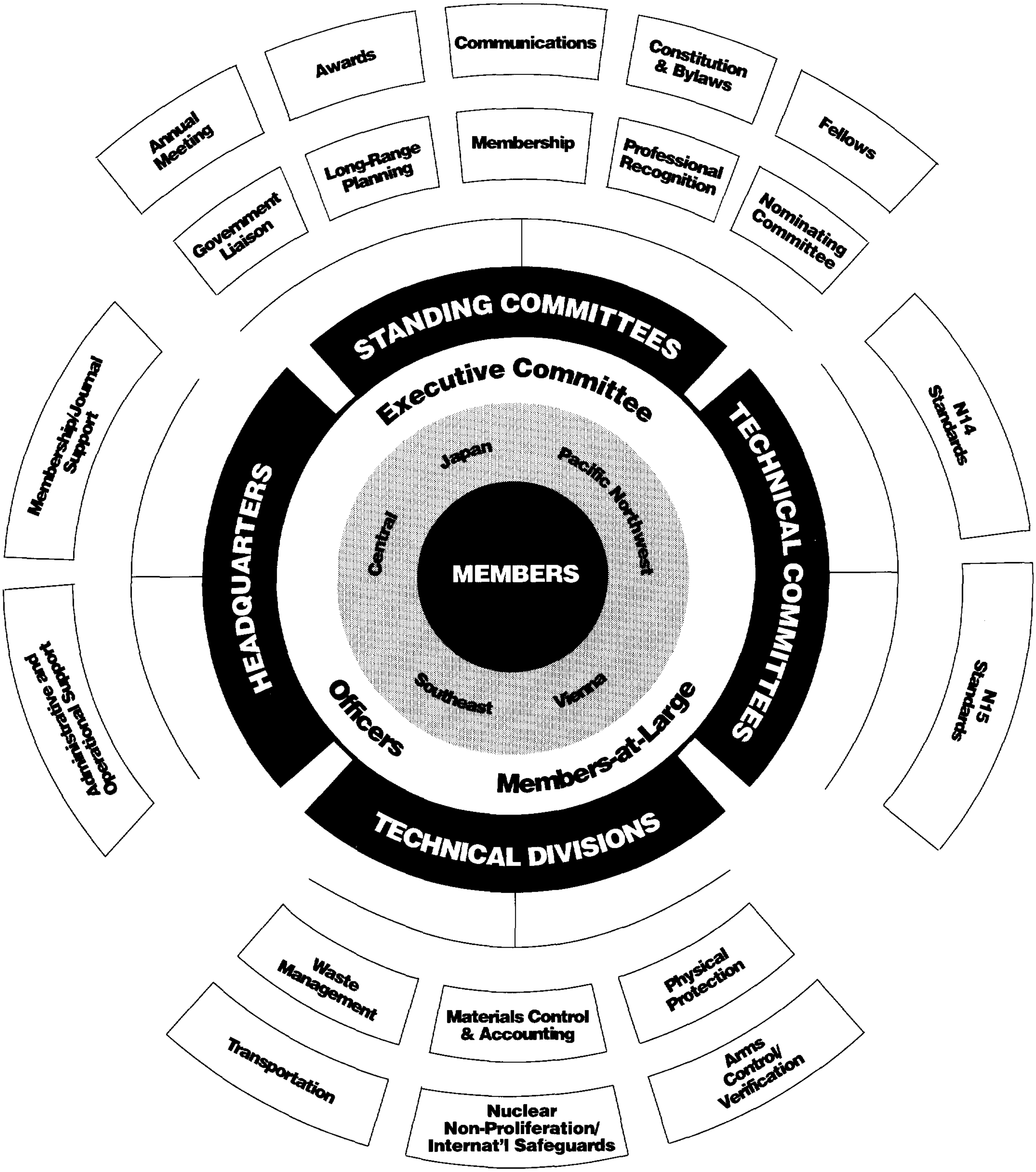
Central — Walter Strohm, EG&G Mound, (513) 865-3462

Pacific Northwest — Brian Smith, Battelle Laboratory

Southeast — Fran Davis, Westinghouse Savannah River Co., (803) 725-5009

Japan — Mitsuho Hirata, Japan Atomic Energy, (03) 593-2551

Institute of Nuclear Materials Management
Organization



Vienna — Tom Shea, International Atomic Energy Agency, (011) 43-1-236000

Fellows — Glen Hammond, (301) 253-3372

Awards — Yvonne Ferris, EG&G Rocky Flats, (303) 966-4867

Communications — Laura Thomas, (505) 845-4713

Government — John Matter, Sandia National Laboratories, (505) 845-8103

Journal Technical Editor — William Higinbotham, Brookhaven National Laboratory, (516) 282-2908

Long Range Planning — Jim Tape, Los Alamos National Laboratory, (505) 667-6394

Continued on page 10

Putting risk in perspective

Technological Risk
H. W. Lewis
W. W. Norton: New York, 1990.

Man and Risks, Technological and Human Risk Prevention
A. Carnino, J.-L. Nicolet and J.-C. Wanner
Marcel Dekker: New York, 1990.

Citizens of the world's developed countries today lead lives that are far safer than could have been dreamed of only one or two generations ago. The risks from infectious diseases (AIDS excepted) are minimal compared with the risks people faced a half century ago. For example, modern workers are protected from occupational diseases such as black lung and asbestos-related health effects, which only recently disabled tens of thousands of individuals. The amount of lead in the environment has been drastically reduced within a few years, and the risks to individuals in air or surface travel (per mile traveled) are a fraction of those existing only a few years ago.

Hand-in-hand with these substantial reductions in the risks which individual citizens bear, there has been a fundamental change in public policy in the extent to which individuals or organizations are held responsible for the possible harm inflicted by their activities on individuals or the environment. Examples are the release of toxic chemicals, transportation accidents and oil spills. As an example of the extent of the evolution in public policy, one can consider the Johnstown flood, a man-made disaster that occurred just a century ago. The flood, which claimed 2,000 to 3,000 lives and caused enormous property damage, was the direct result of the negligence of a small club of millionaires who had utilized a high, badly designed and poorly maintained earth-fill dam to create a hunting and fishing playground for themselves. Subsequent to the disaster, a court ruled that the flood was an "act of God" and that the hunting club was therefore not responsible for the flood's consequences (in fairness to the club members, it should be noted that they voluntarily contributed a few thousand dollars for the relief of the victims).

It is ironic that at the same time that this progress has been made in reducing risks to individual citizens, most individuals have acquired a greatly increased sensitivity toward risks, real or imagined. These perceptions of risk have often been inflated by the tendency of the news media to publicize and exaggerate them, and risks have often been manipulated by opportunistic politicians or other individuals pursuing private agendas. The concerns of the public about risk have, of course, driven public policy in the direction of major risk-reduction efforts, which is all to the good, but much of this effort has been misdirected, or in extreme instances, has been almost irrational.

Within the framework of quantitative risk assessment, the fixation of the public and their political leaders upon the remote risks from, for example, saccharine and other food additives, Alar and nuclear energy, while ignoring and accepting grave risks from tobacco, alcohol, bad driving practices and self destructive life styles, is totally incomprehensible. The reason for this is that nothing in our educational system, even at the university level, has prepared members of the public to assess risks quantitatively or to even address them in any rational approach. The downside consequences of this are numerous:

- *The expenditure of vast resources to eliminate risks which are minimal compared with those we accept as part of our daily lives, if they exist at all.* The best example of this is the effort expended to eliminate asbestos in office buildings and schools.
- *The misdirection of resources.* This includes the expensive practice of defensive medicine, in which physicians order batteries of diagnostic tests as a protection against possible malpractice actions, excessive awards by juries in liability actions and excessive legal fees. (So far, of the funds expended in settling claims for health problems resulting from asbestos exposure, 39 percent has gone to victims and 61 percent has gone for legal fees.)
- *The discouragement of technological innovation and, in some cases, the unavailability or extremely high cost of previously available products.* This is particularly true in the area of pharmaceuticals and in the production of aircraft for general aviation, where perceived future liabilities have so discouraged production of these aircraft that the industry has essentially vanished.
- *The near paralysis of programs for providing future sources of electrical energy.* This is particularly unfortunate in view of the fact that we are currently devouring the earth's petroleum resources within a generation or two, polluting the atmosphere and probably initiating a global warming which may have unknown, and possible catastrophic, consequences. This includes the abandonment and dismantling of the Shoreham power reactor, built at a cost of nearly $6 billion, and our inability to arrive at any politically acceptable solutions for dealing with nuclear waste. The nuclear waste problem deserves special mention since it is probably the extreme example of an instance where the perceived risks outweigh by many orders of magnitude those that can be arrived at by any rational process. It is well established that radioactive wastes from the reprocessing of spent fuel decay in a few hundred years to a level of activity

less than that of the uranium that was mined to produce the fuel, and that with the multiple barriers that will be used to sequester the waste, its escape into the environment during time spans of thousands of years is extremely improbable. However, the assertion (actually a slogan, devoid of factual content) that there is no possible way to deal with nuclear waste has been accepted as a fact by a large segment of the public. In this respect, it is worth noting that the oldest man-made structure in the world, the 5,000-year-old neolithic temple at Brugh na Boinne (Newgrange) in the Boyne valley in Ireland, has remained intact despite total neglect over practically all of its history and invasions by several unrelated cultures. This structure, with a corbel roof made of heavy stone slabs which has prevented water seepage, would have made a suitable repository for nuclear waste.

The solution to these problems is, evidently, educational programs which will prepare individual citizens to make rational decisions concerning risk when they participate in decision-making processes involving choices of future technology or other matters of public policy. These decisions must consider not only the avoidance of future pain but also the necessity for future benefits.

The book *Technological Risk* is an informative and interesting introduction to the subject. The author, Harold W. Lewis, is a professor of physics at the University of California at Santa Barbara. Aimed at the general reader, *Technological Risk* provides a commonsense approach to understanding the principal sources of risk in our society, the estimation of their magnitudes, the uncertainties associated with those estimates and the assessment and management of these risks. In particular, the reader is given, in a straightforward narrative, a clear comparison of the magnitudes of the risks individuals may be subjected to, either by necessity or by their own choice, from, for example, smoking, highway accidents, commercial air travel, high-level nuclear waste and asbestos in public buildings.

The book is divided into three sections, the first devoted to concepts of risk and its assessment and management, including the origins of our public policies on risk management; the second to specific sources of risk including toxic chemicals and carcinogens, air and highway safety, ionizing radiation and nuclear energy, and other topics; and the third to enough of the fundamentals of probability theory and statistics to enable the reader to follow the discussions of the quantitative evaluation of risk. The histories of several man-made disasters, including Chernobyl, Bhopal and the Challenger accident, are treated briefly. The reader is left wishing that the author had provided more details about these events.

The book *Man and Risks, Technological and Human Risk Prevention* is directed at the specialist but is also of interest to the general reader. It was first published in France under the title "Catastrophes? Non Merci!" The authors, A. Carnino, J.-L. Nicolet, and J.-C. Wanner have all played prominent roles in technology management in France, in particular, in the area of safety in complex organizations, including nuclear energy. This book leads the reader through the structure and characteristics of machines in complex systems, the functions of human operators and their interactions with such systems, some examples of malfunctions of complex organizations (Bhopal, the Challenger accident, the TMI accident and the tragic collision of two trains on a single track in France), the principles of reliability management in a complex organization, and the operational approach and tools necessary to achieve this goal. It is evidently aimed at managers in organizations who are charged with managing and minimizing risk and with mitigating the consequences of system failures.

In the space of this review, it would be impossible to do justice to the many topics covered in this book — only a few highlights will be touched upon.

One interesting topic is the characteristics of human operators as they apply to system reliability. Certain fundamental features of the human mind which play a key role in the man/machine interaction are discussed. For example, it is pointed out that the central nervous system is a single-channel device that addresses only one task at a time (the capability of mothers of small children to handle several problems at one time notwithstanding). Consequently, multiple tasks, for example, listening to a lecture and taking notes, are done on a time-sharing basis. An important fact is that in the event of sensor overload, the brain will sort incoming stimuli. This implies that if an operator is saturated, data may be ignored, in particular, the sounding of an alarm.

The adaptation of the operator to the work load is discussed. An individual performing a non-demanding task, for example, driving a car in light traffic in good weather on an interstate highway, will be in what is effectively a "reflex mode" in which attention can be devoted to other activities such as conversation and listening to the radio. Conversely, if the difficulty of the task is high, for example, driving on an icy road at night, full attention is required, and the effort and consequent fatigue are far greater, as is the probability that an error will be committed. For any operator, there will be some "maximal" value for the work load beyond which the operator will suffer a sudden drop in performance and the risk of wrong maneuvers or errors will be high. This maximal point is not fixed but depends upon the mental and physical condition of the operator at any particular time.

Another important consideration is the constant need of the human mind for information. It is well-known, for example, that boredom, inattention and a lack of vigilance may occur when reactor operators spend long periods in control rooms when nothing is happening. The providing of sufficient information, such as analog displays of the system status, and the scheduling of activities that will maintain operator vigilance without resorting to useless "busy work" are interesting problems.

The authors categorize and discuss in detail the errors that human operators may commit and provide examples of how certain of these errors can be contributed to the accident sequence at TMI and Chernobyl. They emphasize, above all, the fallibility of the human operator and the inevitability of errors.

In the chapter on reliability management in the organization, the authors present a number of principles, which, although almost self-evident when presented, are fundamental to the minimization and mitigation of risk. Among these are the principle of isomorphism, which says that at all times there should exist a complete set of documents which accurately describe the physical properties of the system, and that the concepts held by personnel, management and operators, should also correspond totally to the true status of the system. Examples of accidents which occurred due to a lack of adherence to this principle (e.g., train collisions) are presented. The importance of paying attention to "weak signals," i.e., incidents which are effectively precursors to major accidents, and the use of "experience feedback" to head off such accidents, are emphasized. In this instance, the authors point out that in the case of the Challenger explosion a number of problems with the O rings that failed had previously been observed, but no systematic program to deal with this problem had been adopted. The importance of having a flexible crisis management structure which can deal with unanticipated, as well as predictable, events is stressed.

The final chapter, "Operational Approach and Tools," provides some specific examples for implementing a risk management program in the organization, including detailed protocols for performing audits of the system. Also described are computer programs developed by COGEMA, in France, for diagnosing problems and accessing the procedures and documents required for dealing with the problem, and for organizing the plant rounds carried out periodically by the operational staff of a nuclear power reactor.

Man and Risks contains a wealth of ideas on the sources of malfunctions in complex organizations and on the organizational structure and procedures required to minimize the risk of their occurrence and to deal with their consequences if they should occur. This book should be a useful resource for individuals who are concerned with safety in technology or with emergency management, as well as those concerned with the role of human factors in any situation.

Walter Kane
Brookhaven National Laboratory
Upton, New York U.S.A.

Membership — Charlie Vaughan, General Electric Co., (919) 675-5656

Professional Recognition — Paul Ebel, BE Inc., (803) 259-2346

Standards

N-14 — John W. Arendt, Oak Ridge Associated Universities, (615) 483-6622

N-15 — Sharon Jacobsen, Martin Marietta Energy Systems, (615) 574-8707

Technical Divisions

Physical Protection — James D. Williams, (505) 845-8766

Materials Control & Accounting — Rich Strittmatter, Los Alamos National Laboratory, (505) 667-7903

Transportation — Open

Waste Management — E. R. Johnson, E.R. Johnson Associates Inc., (703) 359-9355

Arms Control/Verification — Open

Nuclear Non-Proliferation/Int'l Safeguards — Cecil Sonnier, Sandia National Laboratories, (505) 844-2124

Headquarters

Executive Director — Barbara Scott

Administrative Director — Laura Rainey

Accounting Services — Gloria Buzanis

INMM Journal Managing Editor — Greg Schultz

INMM Journal Associate Editors — Mary Dulabaum, James Rayball

The Third U.S. - German Workshop on Near-Real-Time Accounting for Reprocessing Plants

M. J. Canty
Jülich Research Centre
Jülich, Germany

E. A. Hakkila
R. R. Picard
Los Alamos National Laboratory
Los Alamos, New Mexico U.S.A.

R. Weh
Gesellschaft für Nuklear-Service mbH
Hanover, Germany

ABSTRACT

The discussions of the third workshop on near-real-time accounting (NRTA), sponsored by the U.S. Department of Energy and the German Bundesministerium fur Forschung und Technologie, are summarized. Other approaches to estimate the in-process inventory on a timely basis were also discussed. Since the first of these workshops in 1986, the IAEE and Euratom have begun to use NRTA at reprocessing facilities, and considerable experience has been obtained in designing and implementing the technique. Topics discussed include practical performance of NRTA techniques in the United Kingdom, Germany and Japan; progress in statistical analysis and applications; techniques being developed for inspector measurements; process monitoring to verify facility design features of safeguards concern; and authentication of information provided by facility instrumentation used by the inspectors.

INTRODUCTION

The one-month timeliness goal for detecting the loss of nuclear material from sensitive bulk-handling facilities can only be met by techniques that can determine in-process inventory without shutting down the process. Techniques proposed to determine this inventory in reprocessing plants include running book inventory (RBI), cumulative flux, adjusted running book inventory (ARBI), and near-real-time accounting (NRTA). Over the past 14 years, intensive effort on the part of safeguards experts and the inspectorates has developed and refined the concept of NRTA as it can be applied to reprocessing plants. Experimental work on NRTA has been carried out by the U.K. scientists at the Dounreay fast breeder reprocessing plant, by Japanese scientists at the Tokai reprocessing plant and by German researchers at the Karlsruhe reprocessing plant.

In an effort to bring technology developers together to discuss progress in the field, the U.S. Department of Energy (DOE) and the German Bundesministerium fur Forschung und Technologie (BMFT) have sponsored a series of workshops on the topic of NRTA. The first workshop was held in Hanover, Germany, in May 1986,[1] and the second was held in Los Alamos, N.M., in December 1987.[2] This third workshop was organized to review accomplishments during the past three years and to identify possible areas of future concern. The workshop was co-chaired by E. A. Hakkila of Los Alamos and R. Weh of GNS. Progress made since the first workshop can be summarized by looking back at the summary report from the first meeting,[1] which stated, "Neither EURATOM nor the International Atomic Energy Agency (IAEA) inspectorates have made official or binding statements as to the acceptability of the method for future facilities." Today both inspectorates are planning to use NRTA at the BNFL reprocessing plant at Sellafield, and the IAEA is planning to use it at the Japan Nuclear Fuel Services (JNFS) plant at Rokkasho-mura.

This third workshop was organized to include informal discussion on practical performance of NRTA, quality of measurements, statistics as applied to NRTA, design verification and authentication.

The workshop program is shown in Table 1.

PRACTICAL PERFORMANCE OF NRTA

Although mainly NRTA concepts had been discussed in the course of the previous workshops held at Hanover and Los Alamos and technical conditions had been presented, this third workshop contained contributions that reflected the considerable experience gained in the application of NRTA.

T. L. Jones of AEA-Technology (UKAEA) Dounreay described the United Kingdom's current reprocessing plant safeguards research and development (R&D) program and the work of the ESARDA Reprocessing Input Verification (RIV) working group. The United Kindgom's program includes work on the problems associated with design verification in reprocessing plants. In particular, it was determined that areas where the UKAEA could best assist the IAEA included identification of the areas of the plant in which the available effort should be deployed and training. As a result, two workshops have been held, based on United Kingdom plants currently under construction, in the development of hardware to assist in verification and in the maintenance of continuity of knowledge of verification. The United Kingdom is continuing to emphasize the practicality and benefits, in cost and timeliness, of the verification of plant analyses (VOPAN) technique for the verification of analyses made by the operator.

Very encouraging results were presented from an international exercise in volume calibration with a lutetium tracer carried out under the auspices of the German support program in collaboration with the ESARDA RIV working group.

In a second task, the attention of the workshop was drawn to the residence time (inventory as a function of throughput) of plutonium in reprocessing plants. The residence time varies from a few days for the smaller plants to about 20 days for the very large plants currently being constructed. The significant point is that the residence time is less than the timeliness criterion for the detection of prompt diversion. Recognition of this feature, together with the observations that the plant cannot be made to operate to throughput and product quality specification without its proper working inventory of material and that the inventory is continuously flowing forward, should enable greater reliance to be placed on the simpler means, such as the RBI, of accounting for the nuclear material. The emphasis on the forward flow and the working inventory of nuclear material is useful in identifying those parts of the plant upon which to concentrate design verification resources.

In Japan, where NRTA has been consistently examined since 1978 (TASTEX),[3] field tests carried out with the IAEA have yielded valuable experience and have led to R&D work on the solution of identified subjects. E. Omori of the Power Reactor and Nuclear Fuel Development Corporation (PNC) reported on the practical application of NRTA at the Tokai Reprocessing Plant (TRP). He explained volumetric and analytical methods of determining plutonium in tanks and pointed out effects that could result from evaporation and an increase in the temperature of the solution due to mechanical circulation during homogenization and output sampling. Special attention is given at TRP to the unmeasured inventory determination. An examination of the cumulative material unaccounted for (CUMUF) trend (demonstrated with Campaign 90.1) showed that morning pump holdups and evaporation effects will have to be taken into account for correction. Further investigations identified the purpose of locating measurement bias, error propagation and statistical evaluation techniques in preparation for another field test in the years 1993-94.

At the Karlsruhe reprocessing plant (WAK), tests in conjunction with NRTA have been carried out for a number of years. Because this facility is not endowed with modern process control equipment, due to its age, and is only comparable to commercial facilities to a certain extent because of its pilot nature, the NRTA work was limited to individual components and parameter studies. J. Lausch explained the error contribution of different methods of determination for nuclear material and the impact of level reading, offset in terms of time, and sampling. He established that the error for volume determination is not negligible. Much of the work introduced by Lausch was carried out with the Karlsruhe Nuclear Research Centre (KfK), for example, in the PRODES project, a data acquisition and process control system, and KALA, a laboratory automation system.

An interesting version of NRTA was presented by D. Sellinschegg of the IAEA. Using the example of the plutonim fuel production facility (PFPF) at Tokai, he demonstrated that this method could also be applied in facilities other than reprocessing plants, i.e., not only in bulk handling but also in item facilities. Previous practical application also confirms experience gathered in other facilities that the model assumptions initially taken as a basis will have to adapt to the real conditions by way of extended practical trial runs. The main error contribution of PFPF was again a too optimistic estimation of measurement errors as well as an unexpectedly high unmeasured holdup in the gloveboxes of the fabrication area. Sellinschegg pointed out the excellent cooperation between the operator and the IAEA, with the result that — by adding the appropriate instrumentation, correcting the facility model and adapting the software — the IAEA safeguards goal could be achieved with justifiable effort.

The adjusted running book inventory (ARBI)[4] approach was described by G. Hough, and some of the important main conclusions of the extensive study were the following:

- NRTA should include any material balance procedure that is designed to improve the timely detection of losses of nuclear material.
- The ARBI error model is different from the CUMUF model and provides for a process variance term for unmeasured inventory that eliminates the need to estimate the inventory in equipment that is difficult to measure.
- Up to 15% of the inventory (about 30 kg of a 200-kg inventory) can be unmeasured without significant loss of detection sensitivity by using test statistics designed to attenuate the process variance of the unmeasured inventory.
- The B-statistic, which is based on the Bartlett test, was more effective than other test statistics (Page, CUMUF, GEMUF) for detection of both protracted and abrupt diversion, especially when the test is applied to rolling sets of the ARBI data. Doubling the process variance of the unmeasured inventory decreased the detection sensitivity (using the B-statistic) less than when the measurement errors are doubled, which means that it may be better to include an inventory unit that has a large measurement variance in the unmeasured inventory.
- There is a tradeoff between detection time and the magnitude of the diversion rate that is detectable; i.e.,

it takes longer to detect a small diversion rate than it does to detect a large one.

- A plant with large systematic errors will require frequent inventories, and a plant with small systematic errors may achieve the same detection sensitivity with significantly less frequent inventories.
- The B-statistic is comparatively simple to apply to ARBI data without the need to perfom complex transformations or Monte Carlo simulations.
- When applied to historical data at Dounreay, there are indications that systematic errors do not necessarily propagate as long-term variance components, as is often assumed.

The planned Japanese reprocessing plant at Rokkashomura is already being used in the design phase for simulating NRTA.

Kawada of JNFS presented the latest facility design and a process and measurement simulation model used for NRTA.

An evaluation of the results presented permits the conclusion that the experience gained thus far will allow for the useful application of NRTA in commercial-scale facilities as well. A prerequisite here will, however, be a careful mathematical representation of the process and its mode of operation as well as a realistic error model. The sequential test statistics have been examined to an extent that investigations of proven methods can be limited. The fact that many of the results reported upon could potentially be used to locate weaknesses in the process control should encourage plant designers, designated operators and safeguards personnel to enter into contact as early as possible.

STATISTICAL ASPECTS

R. Avenhaus presented a decision-theoretical analysis of the common optimization criteria for characterizing the timeliness of detection of anomalies associated with various sequential statistical tests for the evaluation of material balances.[5] Beginning with a general model of the test procedure as a two-person, noncooperative game in extensive form, he was able to demonstrate that the use of the average run length as a measure of timeliness, i.e., as criterion for the determination of best tests, is equivalent to an exponential time dependence in the inspector's and operator's payoff utility for detection and non-detection of diversion.

In a second paper (not presented orally), Avenhaus discussed those sequential statistical tests commonly used in NRTA applications that are based on independently transformed material balances (MUF) statistics. He discussed various approaches — Kalman filter, MUF residuals, independently transformed (ITMUF), and standardized and independently transformed (SITMUF) — and demonstrated their formal equivalence.

R. Picard outlined his work on large-scale error propagation codes.[6] Aspects of automating the entire propagation process — from establishing an accountancy database to interfacing that database with a computational engine to ensuring that the engine has all needed capabilities — were summarized. Complications introduced by NRTA (in contrast to conventional accounting) were also addressed.

R. Seifert discussed the current status of the NRTA software packages MEMO and PROSA.[7] Both packages run on personal computers. MEMO[7] determines the statistical measurement model (dispersion matrix) and provides input to PROSA, which performs the sequential statistical evaluation.

In his second presentation, Seifert discussed the use of PROSA[8] in the establishment of detailed measurement models for real plant data. The appearance of an alarm in one of the statistical tests applied to real data is taken as an indication of an inadequate measurement model.

In the final presentation, M. Canty reviewed his recent work on the randomization of interim inspections, giving two alternative game-theoretical solutions to the problem of determining optimal randomization strategies.

QUALITY OF MEASUREMENTS

Input and output transfer measurements have been well-defined over the years, with isotope dilution mass spectrometry (IDMS) as the method of choice for evaluating dissolver solutions and use of electrometric titration for product. These techniques provide the best precision and accuracy available. Present work is directed at improving the inspector verification measurements to provide better timeliness and at measuring or estimating the in-process inventory.

T. K. Li of Los Alamos reviewed his work on isotope dilution gamma-ray spectrometry (IDGS) as an in-plant method for the inspector to verify operator's IDMS measurements.[9] Samples are prepared as for IDMS but can be analyzed at the plant by using low-energy gamma rays. Data to date indicate that a precision of better than 1% relative standard deviation can be obtained. The work is being done in cooperation with the PNC Tokai reprocessing plant and the EURATOM Transuranic Institute in Karlsruhe.

The IDGS method relies on using resin beads for separating uranium and plutonium from fission products, as is done for IDMS. The resin bead technique can be time consuming and requires a well-trained analyst.

B. Smith of Los Alamos reviewed on-going work to simplify the separation using high-pressure liquid chromatography. Good separations have been obtained, and the method has been scaled up to obtain larger samples for IDGS using thorium as a stand in for plutonium. Alternatively, the plutonium can be measured spectrophotometrically with a precision of approximately of 2%.

S.-T. Hsue of Los Alamos described work on intrinsic X-ray and gamma densitometry.[10] The method is based on measuring intensities of X-rays and gamma rays generated in the sample and which bracket the K-absorption edge for plutonium. Thus, an external X-ray or gamma-ray source is not required, simplifying equipment requirements. Work is being performed in cooperation with the Transuranic Institute at Karlsruhe. Preliminary data indicate a precision of 1-3% can be obtained. The method is applicable for in-process samples as well as for the final product.

One of the major problems in applying NRTA is determining the amount of plutonium in the difficult-to-measure portion of the in-process inventory such as solvent extraction contactors. A. Beyerlein of Clemson University reviewed results of a cooperative study between the KfK reprocessing plant, GNS of Hanover, Los Alamos and Clemson on using theoretical models to estimate the inventory of pulsed columns.[11] Experimental data obtained at KfK were evaluated by using codes developed at Clemson. The analysis showed that simplified theoretical codes needing only input flow rates and concentrations could estimate the amount of uranium in columns to better than 10%. This accuracy is sufficient for NRTA.

DESIGN VERIFICATION

Verification of facility design will be important for NRTA as well as for conventional accounting. M. Ehinger, Oak Ridge National Laboratory (ORNL), reviewed work being performed jointly by ORNL, Los Alamos and the IAEA to use process monitoring data to verify facility design.[12] All future large reprocessing plants will have sophisticated computer-controlled process monitoring systems to rapidly evaluate and control the process. Some of this information may be of use in verifying certain aspects of facility design during the plant commissioning phase. The approach relies on correlating such parameters as flows, tank levels and the status of valves, pumps and air lifts to determine, for example, if key measurement points can be bypassed.

The technique relies on rapid analysis of large quantities of data from the process monitoring system. This analysis can be performed best by using sophisticated intelligent systems. J. Prommel and J. Howell of Los Alamos reviewed work being done on artificial intelligence systems such as Wisdom & Sense and neural networks and how they might be applied to analyze process monitoring data.

AUTHENTICATION OF INSTRUMENTS

It may not always be possible or practical for the inspectorate to install and operate its own instruments to measure all the data required for NRTA. In such cases, the inspectorate will have to rely on data obtained from operator-owned or supplied instruments or from instruments jointly used by the operator and the inspectorate. The information must be authenticated. Authentication has been defined by the IAEA as "the process to assure that genuine information is obtained for safeguards purposes using equipment for which the IAEA lacks complete control or knowledge." [13]

J. Halbig of Los Alamos described work performed jointly by the IAEA, Canada and Los Alamos in developing an authenticated system for joint IAEA and operator use for a CANDU reactor. The authentication technology is applicable to other types of instrumentation. The data acquisition electronics and the data analysis and storage computer are tamper protected by Agency seals. The system has two different types of detectors monitoring the spent fuel movements in the area of interest, namely, at the fuel handling machine. Each detector type has inherent "fingerprints" characteristic of the specific detector. These fingerprints change if the operating conditions change, including discontinuation and then reconnection. Because the detectors work on different physical principles and are sensitive to different ranges of the gamma-ray spectrum, it is difficult to fool both at the same time. The detector enclosures are under surveillance and are in a high radiation area, making it unlikely that shielding would be added to block the radiation signal.

Software limitations on allowed commands protect the sealed data-acquisition electronics from invalid operation that could occur if unauthorized commands are sent down the unsealed cable. This list of allowed commands can only be changed by inserting a hardware electronic key into the electronic chassis. The Agency controls the key.

Data sent from the electronics to the data analysis and storage computer have an "authentication" byte added to each transmission. Both the electronics and the computer have the authentication key. If the data do not pass this authentication test, the data are still stored but flagged for later resolution.

H. Menlove reviewed the development of an authenticated system for joint operator and IAEA use at the PFPF mixed oxide fuel fabrication plant at Tokai. The plutonium canister assay system (PCAS) relies on redundant equipment, visible cables and tamper-indicating features.

The Agency participated in acceptance tests and observed the installation, sealing key components at that time. A number of tamper-indicating features were built into the system. These features provide confidence that the detector, electronics and data-acquisition computer hardware have not been compromised. Software diagnostics test the incoming data stream for interruption or tampering with the signal from the detector to the data-acquisition electronics. The cables from the detector to the data-acquisition electronics cabinet are unbroken and visible. PCAS is under the surveillance of containment/surveillance (C/S) cameras, providing additional assurance that the cables have not been altered. The Agency kept control of the data analysis software and hardware by using IAEA-owned computers and IAEA-written software to analyze data collected by PCAS. Because the operator might have to perform maintenance on the system while inspectors are not there, provisions are made for reauthentication after such an activity. To check on sample tampering and to reestablish authentication, the technique of remeasuring items previously measured by PCAS is used. A random sampling of these items is remeasured in PCAS after the instrument is checked using neutron sources totally under Agency control and with inspectors present.

TABLE 1
NRTA Workshop Presentation
E. A. Hakkila, Los Alamos National Laboratory and R. Weh, GNS, Co-Chairmen

Tuesday, September 24	
Opening Remarks	*E. A. Hakkila, R. Weh*
Practical Performance of NRTA	*R. Weh, chairman*
The U.K.'s Reprocessing Plant Safeguards Program	T. Jones, Dounreay
NRTA Development Status at the Tokai Reprocessing Plant	E. Omari, PNC
Operating Experience with NRTA at WAK	J. Lausch, Germany
IAEA Application of an NRTA System at PFPF	
IAEA Application of an NRTA System at TRP	
Part 1. Procedural Implementation	S. Johnson, IAEA
Part 2. Results and Problems	D. Sellinschegg, IAEA
An Alternative View of a Reprocessing Plant	T. Jones, Dounreay
The Adjusted Running Book Inventory Approach	G. Hough, U.S.A.
NRTA Simulation Model Development	Y. Kawada, JNFS
Wednesday, September 25	
Quality of Measurements	*E. A. Hakkila, chairman*
GS Measurement of Reprocessing Plant Input Solutions	T.K. Li, LANL
Studies on Rapid Chemical Separation of U and Pu from Dissolver Solutions	B. Smith, LANL
Pulsed Column Inventory Estimation	A. Byerlein, Clemson
The Poor Man's Densitometer	S.T. Hsue, LANL
Statistics	*M. J. Canty, chairman*
Decision Theoretical Foundation of Optimization Criteria for NRTA	R. Avenhaus, Germany
The Independent Transformation in NRTA	R. Avenhaus, Germany
Automating Large-Scale LEMUF Calculations	R. R. Picard, LANL
Memo and Prosa as Software Tools in International Safeguards	R. Siefert, KFK
Experience in Establishing Detailed Measurement Models for Real NRTA Balance Data	R. Siefert, KFK
Inspection Games over Time	M. Canty, Julich
Thursday, September 26	
Design Verification	*M. Ehinger, chairman*
Use of Process Monitoring for Design Verification	M. Ehinger, ORNL
Use of Intelligent Systems for Evaluation of Process Monitoring Information	J. Prommel, LANL
	J. Howell, LANL
Authentication of Instruments	*R. Augustson, chairman*
Authentication of Remote Instrumentation	J. Halbig, LANL
Authentication of Instruments at PFPF	H. Menlove, LANL
Other Topics	
Some comments on EURATOM application of safeguards at UP-3	J. Regnier, COGEMA
Further Comments on ARBI	G. Hough, U.S.A.

There is an interesting interaction between the surveillance function of the automated containment surveillance (ACS) and the radiation monitoring feature of the PCAS. The ACS will see the movement of canisters into and out of the storage area but cannot determine if they contain plutonium. Neutron detectors in the PCAS will sense the movement of plutonium within the area but have limited capability to interpret the movement. Together they give a complete picture and, in addition, provide a kind of mutual authentication for each other. Canister movements show up in both systems, and if they do not, this is cause for action. Both systems would have to be compromised to carry out an undeclared and undetected canister shipment or receipt.

OTHER TOPICS

J. Regnier of COGEMA described the cumulative flux technique as it is applied by EURATOM at the La Hague UP-3 plant. All input transfers of dissolver solution and the output of PuO_2 are measured. In addition, plutonium is measured in those tanks where measurements can be obtained; all remaining in-process inventory is estimated from process data. Samples obtained by automatic samplers are authenticated for EURATOM to provide continuity of knowledge. A routine inspection effort involved three to five inspectors each week.

REFERENCES

1. Weh R., Hakkila E.A., Canty M.J. "The FRG-US Workshop on Near-Real-Time Accounting for Reprocessing Plants," *JNMM* XVI:12-16 (1987).
2. "The Second US/FRG Workshop on Near-Real-Time Accounting for Reprocessing Plants," *JNMM* XVII:3-5 (1988).
3. The Tokai Advanced Safeguards Techniques Experiment, TASTEX.
4. Hough, G., Johnson, E.R., Tingey, F.H., White, M.J. "Results of a Study on the Running Book Inventory Approach to International Safeguards," *Proceedings of 31st Annual Meeting of INMM, July 1990* Northbrook: INMM, 1990, p. 85-99.
5. Avenhaus, R. "Decision Theoretical Justification of Optimization Criteria for Near-Real-Time Accountancy Procedures," *JNMM* XX:26-33 (1992).
6. Picard, R. "Automating Large Scale LEMUF Calculations," to be published in the *JNMM*.
7. Bicking, U., Golly, W., Seifert, R. "MEMO – A PC Program to Establish Measurement Models for NRTA Evaluation Procedures," to be published in the *JNMM*.
8. Golly, W., Seifert, R., Lausch, J., Schmidt, D. "Experience in Establishing Detailed Measurement Models for Real NRTA Balance Data," to be published in the *JNMM*.
9. Li T.K., Kuno Y., Sato S., Akiyama T., Nakatsuaka J. "Determination of Plutonium Concentration and Isotopic Compositions by Isotope Dilution Gamma Ray Spectroscopy on Resin Beads," *Proceedings of 31st Annual Meeting of INMM, July 1990* Northbrook: INMM, 1990, p. 390.
10. Hsue S.-T., Cromboom O. "Intrinsic Densitometry Techniques for High-Burnup Plutonium Solutions," *Proceedings of 31st Annual Meeting of INMM, July 1990* Northbrook: INMM, 1990, pp. 397-401.
11. Beyerlein A.L., Geldard J.F., Weh R., Eiben K., Dander T., Hakkila E.A. "Experimental Validation of Pulsed Column Inventory Estimators," Fourth International Conference on Facility Operations/Safeguards Interface, Albuquerque, N.M., Sept. 29-Oct. 4, 1991 (to be published in proceedings).
12. Ehinger M.H., Zack N.R., Hakkila E.A., Franssen F."Use of Process Monitoring for Verifying Facility Design for Large-Scale Reprocessing Plants," Los Alamos National Laboratory/Oak Ridge National Laboratory report LA-12149-MS, ORNL/TM 11856, ISPO 331 (June 1991).
13. "On the Topic of Authentication," IAEA Consultants Meeting, March 4-8, 1991.

M. J. Canty, born in 1943 in Winnipeg, Canada, studied at the University of Manitoba and received his Ph.D. in nuclear physics there in 1969. He is presently a research scientist at the Technology Assessment Group, Jülich Research Centre in Germany, specializing in systems analysis for verification regimes.

E. A. Hakkila received a Ph.D. in analytical chemistry from The Ohio State Unvierstiy in 1957. He participated in research and development in X-ray spectroscopy, analytical chemistry of actinides, and electron and ion microprobe analysis at Los Alamos National Laboratory until 1976, when he joined the Nuclear Safeguards Program. He now serves as program coordinator for International Safeguards.

R. R. Picard joined the Los Alamos National Laboratory in 1981 after earning his B.A. in mathematics from Carleton College and a Ph.D. in applied statistics from the University of Minnesota. He has since worked on a variety of safeguards problems with the Safeguards Systems Group and on arms control problems with the Statistics Group.

R. Weh received his degree in chemical engineering from the Technical University of Munich, Germany. Subsequently, he spent more than seven years at the Institute of Radiochemistry in Garching/Munich. In 1979, he joined the Deutsche Gesellschaft für Wiederaufarbeitung von Kernbrennstoffen mbH (DWK) in Hanover, Germany. Due to the changes resulting from the abandoning of the Wackersdorf Reprocessing Plant project, he moved to the Gesellschaft für Nuklear-Service mbH (GNS) in 1990. He is currently head of Quality Management and Safeguards.

Non-destructive Assay Techniques and Associated Measurement Uncertainties

S.-T. Hsue
T. E. Sampson
Los Alamos National Laboratory
Los Alamos, New Mexico U.S.A.

ABSTRACT

To calculate the inventory differences for a facility or process, we should have random error and bias estimates for all the measurement systems in addition to the measurement results on each sample. For non-destructive assay (NDA) instruments, the assignment of these measurement errors is quite complex. This paper discusses the random and bias estimates of two NDA systems, one measuring homogeneous samples and the other measuring heterogeneous waste samples. Actual measurement data are used to illustrate the error estimates. The entire measurement system/material category combination must be examined to accurately assess measurement uncertainty for each measured item. Such an assessment might start with an error matrix for each instrument/material category combination as shown in this paper, in which many sources of error are considered. Only then can the random error and bias for measurements from the system be assigned.

I. INTRODUCTION

It is important, for calculating the inventory differences for a facility or process, that all the measurement systems provide random error and bias estimates in addition to the measurement results on each sample. For non-destructive assay (NDA) instruments, the assignment of measurement error is complex and requires careful study and close cooperation from everyone involved — NDA developers, materials control and accountability (MC&A) personnel and statisticians. This paper discusses several typical NDA systems and examines the various contributions to the overall measurement uncertainty to illustrate the methods of uncertainty assignment.[1]

II. MODELS

A. Physical Models

A physical model of a measurement is necessary to relate the response of the measuring instrument to the measured quantity of interest. The instrument developer attempts to use the physical principles of the measurement to find a fairly simple mathematical expression relating instrument response to the measured item's properties of interest.

When the measurement principles are fairly simple and understood, the measured property often can be expressed by a simple relationship with the measured response. One example is the assay method using transmission-corrected passive gamma rays practiced in instruments such as the segmented gamma-ray scanner (SGS) and the solution assay instrument. In both of these methods, the isotope mass M is directly proportional to the measured count rate (CR) of a gamma ray from the isotope of interest if appropriate physics-based corrections are performed. This relation can be expressed as

$$M \sim \mathrm{CF(rate\ loss)} \bullet \mathrm{CF(atten)} \bullet \mathrm{CR} \qquad (1)$$

where CF(rate loss) and CF(atten) are correction factors for rate-related counting losses and the attenuation of the measured gamma ray within the measured item. The proper specification of these correction factors makes the difference between a good physical model and a poor one and between a good NDA measurement and a poor one. All the understanding and "physics" of the physical model are wrapped up in the details of the attenuation correction.

Another example of a physical model is the one used in the K-edge densitometer. In this system, one measures the photon transmission above and below the K-edge of an element. The concentration of the measured element is given by

$$\rho = \ln R/(\Delta\mu \bullet d) \qquad (2)$$

where ρ is the element concentration, R is the measured transmission ratio, $\Delta\mu$ is the difference in the element's mass attenuation coefficient at the K-edge and d is the path length of the transmission beam across the sample cell. The measured response $\ln R$ is proportional to the concentration.

B. Empirical Models

Sometimes the instrument response cannot be simply related to the measured quantity. This arises when the correction factors are not known, not understood or too complex. In these cases, the instrument response is usually not proportional to the measured quantity of interest. The calibration curve is nonlinear, and we say that we have an empirical calibration. The instrument is calibrated by fitting functions to data from calibration standards. These functions sometimes incorporate knowledge of the physical processes involved in the measurement but often are fairly arbitrary functions with tractable mathematical properties.

Representative standards assume a greater importance for instruments based on empirical models than for those instruments based on understood physical models.

III. MEASUREMENT UNCERTAINTIES

A. Error Models

One of the advantages of a physical model is using it to derive an error model. From the error model it is hoped that the uncertainty for all measurements on all items can be predicted from the instrument response and any auxiliary measurements associated with the instrument. Statisticians often use simple additive or proportional error models. While these models are usually understood to be imperfect, they are often the only available models that are mathematically tractable. Even in instruments with understood physical models, the correction factors are often complex and cannot be easily modeled to predict errors. We are not aware of a single instance in which a complex NDA instrument has been completely modeled to predict meaningful and accurate measurement uncertainties. Simple additive or proportional error models can be written as

$$\text{additive} \qquad x = \mu + \beta + \varepsilon \qquad (3)$$

$$\text{proportional} \qquad x = \mu(1 + \beta + \varepsilon) \qquad (4)$$

where x is the measured value, μ is the unknown parameter representing the true value of the measured item, β is an unknown constant deviation of the measured value from the true value (bias) and ε is a random variable with an expected value of zero (random). More complete error models include additional terms for the multiple sources of both random and systematic errors that are usually present in NDA measurements and might also include combinations of additive and proportional models. The biggest complication usually arises because the error components, β and ε, are not constant values for all measured items, but instead, are complex functions of several parameters. These complex functions are often either not known or require extensive effort to characterize.

B. Influencing Factors

Many factors influence the bias and the random error — some of them apply to many NDA measurement systems and some are specific to each system. Many error components can be evaluated by statistical means (type A errors). There are also error components that are not easily treated statistically and have to be evaluated by other means (type B errors). The latter are usually specific to the system and have to be evaluated individually.

The discussion below considers some of the factors that influence NDA measurements.

1. Counting statistics. A unique feature of most radiation-based NDA instruments is the ability to propagate the random errors arising from counting statistics to predict the repeatability or precision of each measurement. The measurement precision component from counting statistics is usually a complex function of many parameters [special nuclear material (SNM) mass, counting time, sample characteristics] often unique to the individual item; it is only practical to obtain the uncertainty component of the measurement precision directly from the measurement data on each item (we use the terms precision and random error interchangeably). The part of the total measurement error from counting statistics is almost always available from each measurement. It is easily checked in selected cases with repeated measurements to give the user confidence that the error propagation is correct. It will almost always give a more valid estimate of this variability component for any individual item than will historical data from a single measurement control sample. The error propagation capability of NDA methods that uses radiation detection is often overlooked by statisticians trying to predict the total measurement error for all measurements on all samples. It is misleading to make repeated observations on a single item and infer that this variability is characteristic of all samples.

2. Measurement Geometry. The sensitivity of NDA measurements to geometry depends on the instrument and technique. Sample position reproducibility is often important but is usually not an important factor in a well-designed, carefully operated instrument.

3. Sample Container Size and Composition. The details of the measurement technique determine the influence of this factor. Newer gamma-ray techniques are less sensitive to container size; container composition is usually known or can be compensated for.

4. Matrix Composition. The effect of the sample matrix on a measurement technique is a major factor in determining whether representative standards are needed for calibration. Matrix is not a major factor for gamma-ray techniques with transmission corrections or for plutonium isotopic measurements using intrinsic relative-efficiency methods.

5. Sample Heterogeneity. Heterogeneity (matrix or SNM) in samples is one of the biggest sources of measurement uncertainty. Gamma-ray methods are generally affected most. Variability arises because representative standards cannot be produced. Biases arising from these effects are somewhat analogous to the so-called sampling errors that arise in analytical chemistry measurements.

6. Impurities. Impurities are not a problem for gamma-ray techniques unless the impurities are radioactive. However, impurities are much more important to the neutron-based assay instruments.

7. Sample Density. High sample density arising from either the SNM content or the matrix can sometimes compromise passive gamma-ray techniques.

8. Isotopic Composition of Sample. For some measurement methods, the isotopic composition is needed to correctly calculate the measurement result. Gamma-ray-based methods usually quantify a single isotope and need isotopic information to convert the measured result to total element mass.

9. Calibration. Calibration requires an understanding of the measurement physics of the assay system and careful preparation of the standards. Standards used in calibration have to satisfy the requirements of the measurement principles but need not always be identical in chemical composition or matrix form to the unknowns. Calibration data can be analyzed by statistical methods to determine the contribution to the bias and the random error.

The factors above (except 9) depend on the individual sample and vary with each measurement. Other factors influence the system's environment and therefore its variability, affecting all measurements similarly. These factors continue below.

10. Background Radiation Variations. Variation in background radiation can be a problem for any NDA instrument, especially if the variability occurs during a measurement. This source of uncertainty can be mitigated by good instrument design, proper instrument siting and administrative controls. The administrative controls usually relate to movement and storage of radioactive materials in proximity to the measurement system. Low-level measurements will be most affected.

11. Operator. Clear, accurate procedures and well-trained, conscientious operators are required for NDA measurements. Although an indifferent operator may have less effect on NDA measurements than on some other measurement techniques, a conscientious operator is a valuable component of an NDA system.

12. Temperature. NDA instrumentation generally will not operate well in temperature extremes or in environments where the temperature varies widely. Temperature problems are usually solved by proper instrument design and siting and/or air conditioning where appropriate.

13. Humidity. Excessive humidity can cause high-voltage breakdown and increased electrical noise. Neutron measurement systems are susceptible to humidity because high-voltage breakdown can mimic coincidence events. Most neutron systems are designed with desiccants to alleviate this problem. Static electricity from a dry environment can also cause problems. Proper siting can help.

14. Quality of Electrical Power. Electrical power quality can affect all measurements. Adverse effects are often mitigated by isolation transformers, line filters and uninterruptible power supplies.

15. Detector Deterioration. Data quality from high-resolution germanium detectors used in many gamma-ray measurements may degrade with time. System recalibration may be needed in the short term; detector replacement is usually required in the long term.

IV. ERROR COMPONENTS FOR A SYSTEM MEASURING HOMOGENEOUS SAMPLES

This section discusses the error components of a gamma-ray-based system measuring homogeneous solution samples. We consider the K-edge densitometer system designed to assay uranium solutions. The relation between the measured response ($\ln R$) and the concentration ρ has been given in Eq. 2.

A detailed discussion of the system and the error estimates can be found in the report by Ottmar and Eberle.[2] Table I presents a summary of errors for this technique. In this table, repeatability refers to the ability of an instrument to repeat a measurement under essentially the same measurement conditions — same operator, time and environment. Repeatability is a measure of an instrument's intrinsic variability; the operator places the sample in the system and measures the sample n times in a short period without removing the sample. Reproducibility refers to the ability of an instrument to reproduce a measurement over time; the intrinsic instrument variability and the variability because of instrument drift, sample positioning and measurement environment are included. The operator measures the sample over an extended period of time, removing the sample in between measurements. Most measurement control programs chart reproducibility. Under the best conditions reproducibility will be the same as the repeatability. Usually reproducibility will show greater variability than repeatability because it encompasses more sources of variability.

For unknown samples, the random error will also include additional variability from parameters characteristic of the individual sample — cell length, matrix and the isotopic variation. The effects of these will have to be evaluated by other means.

Table I
Estimated Error for K-Edge Densitometer

Error Source	*Type of Error*	*Magnitude of Error (%)*	*Single-Sample Repeatability*	*Single-Sample Reproducibility*	*Different Samples*
Counting Statistics	A	0.15	Random	Random	Random
Cell Length	B	0.01-0.1	Bias	Bias	Random
Postitioning of Cell	B	<0.1	Bias	Random	Random and bias
Sample Matrix	B	<0.2	Bias	Bias	Random and bias
Uranium Isotopic Composition	B	0.013	Bias	Bias	Random
Sample Temperature	B	0.05	Bias	Random	Random
Calibration	A	0.1	Bias	Bias	Bias
Nonlinearity	A	<0.2	Bias	Bias	Bias

For uniform samples, calibration is the main contributor to the bias of an unknown sample measurement. Under ideal situations, this bias can be as small as 0.1%.

The type of error, A or B, refers to the evaluation method discussed in Section III.B. Note that error components may appear as a bias in one type of measurement yet be considered a random error when unknowns are assayed.

In this example the major contributing factor to the random error for the repeatability measurement of a single sample is counting statistics. Therefore, repeatability offers the ideal measurement situation for the instrument developer to check the validity of the error propagation and discover software coding errors. Every system should be checked for repeatability over a significant concentration range. Figure 1 shows the precision or random error from counting statistics of a densitometer for a counting time of 1,000 s and a sample thickness of 2 cm. This type of curve is typical of most NDA counting systems. Notice that the precision is a function of the concentration or the SNM content. The precision curve has a minimum, and in this case it occurs at 275 g/L where the precision is 0.38%.

The precision of an assay system is not a well-defined number. Sometimes the precision at the minimum (or optimum sample concentration) is used; in this case the precision is 0.38% for the system. If this precision is used, the precision will be underestimated for all the samples assayed. Sometimes the precision over a concentration range is used; in this case the precision for the system is better than 1% from 52 to 500 g/L. In neither case can we use this system precision for the arbitrary sample; the precision may be better or worse than the system precision depending on how the system precision is defined and on the concentration of the unknown sample because of the SNM dependence. The system precision is useful in comparing the merit of the assay system but is not useful for calculating the inventory difference variance for a facility or process.

V. ERROR COMPONENTS FOR A SYSTEM MEASURING HETEROGENEOUS SAMPLES

A. General Considerations for the Segmented Gamma Scanner

Errors are generally larger for NDA systems assaying heterogeneous samples than they are for systems measuring homogeneous samples. In this section we discuss the error components of a gamma-ray-based system measuring heterogeneous waste samples. The system considered is an SGS system designed to assay low-density scrap and waste. The relation between the measured count rate CR and the isotopic mass M has been expressed in Eq. 1.

The SGS realistically illustrates the type of data, measurement control and calibration information that might be available for assigning uncertainties to individual measurements.

Table II
Bias and Random Error Components of an SGS System Measuring Heterogeneous Scrap and Waste Samples

Error Source	*Type of Error*	*Magnitude of Error (%)*	*Single-Sample Repeatability*	*Single-Sample Reproducibility*	*Different Samples*
Counting Statistics	A	0.5-2	Random	Random	Random
Container Size	B	0-5	Bias	Bias	Random
Postitioning of Sample	B	0-5	Bias	Random	Random
Sample Matrix	B	0-2	Bias	Bias	Random and bias
Matrix Heterogeneity	B	0-10	Bias	Bias	Random and bias
SNM Heterogeneity (lumps)	B	0-30	Bias	Bias	Random and bias
Calibration	A	0.2-1	Bias	Bias	Bias

First, we must understand some of the principal features of the SGS.[3] This gamma-ray-based device uses an external radioactive source to measure the gamma-ray attenuation of the item allowing calculation of a correction for self-absorption of the assay gamma rays within the sample. Biases increase as the item becomes more and more lumpy and heterogeneous, typical of the general category of materials called scrap and waste. The transmission of the gamma rays from the external radioactive source corrects for matrix attenuation effects but often does not properly correct for self-absorption in agglomerates or large particles of SNM. We attempt to improve the measurement accuracy for "lumpy" samples by enhanced data analysis algorithms. We will call this new analysis the lump-corrected SGS (LCSGS).[4]

Typical error contributions for the SGS measurements are summarized in Table II.

In Table II, the errors from the counting statistics and calibration are greater than errors for the K-edge densitometer. We will discuss the typical error contribution from calibration and discuss information that can be obtained from the measurement control data.

B. Calibration and Measurement Control
With this background as common knowledge, we now consider some realistic numbers for a typical SGS and LCSGS system.

1. Standards. Appropriate standards for an SGS are cans of PuO_2 mixed uniformly with diatomaceous earth. The mass of ^{239}Pu in the standard can be characterized with an uncertainty of 0.1% relative, or less. The principal uncertainty components arise from the plutonium concentration in PuO_2 and from the weighing. The mass spectroscopy error on ^{239}Pu is negligible. For the set of standards considered in this exercise, assessing measurements from three laboratories leads to the assignment of a relative uncertainty of 0.07% for the ^{239}Pu mass in each standard.[5]

2. Calibration. A physical model appropriate for an SGS was given earlier. This model uses a single calibration constant giving a straight line through the origin for the plot of corrected count rate (CCR) vs. SNM mass. An ideal way to determine the calibration constant for such a system is to plot the CCR per gram of SNM vs. grams SNM for each standard. The values should be the same for all standards. Figure 2 illustrates this type of analysis.

In Figure 2, each point represents the average of 4 to 18 runs with relative standard deviations (RSD) for a single measurement ranging from 2.3% (10 g) to 0.6% (250 g). The error bars represent the standard deviation of the mean for each average. A weighted average of the data points gives a calibration constant of 14.732 ± 0.019 (0.13%) for the corrected count rate/g of ^{239}Pu. The error is the standard deviation of the

Table III
SGS Assay of Homogeneous Samples

Sample ID	*Reference (g Pu)*	*LCSGS Assay (g Pu)*	*SGS/Reference Ratio*
STDASH-1	20.99	20.91	0.996
STDASH-2	20.91	21.06	1.005
ASH685	33.14	32.98	0.995
ASHHVA-27	51.30	52.03	1.014
ASHHVA-5	164.95	164.94	1.000
ASHHVA-6	6.70	6.72	1.004
		Average	1.002
		RSD	0.007

Table IV
SGS and LCDSGS Assay of Heterogeneous Samples

Sample ID	*^{239}Pu (g)*	*Reference SGS (g)*	*LCSGS (g)*	*Lump Corr (%)*	*Ratio (SGS/Ref)*	*Ratio (LCSGS/Ref)*
XBLP120	104.98	90.7	92.97	2.44	0.864	0.886
XBLP267	118.28	116.7	122.47	4.71	0.987	1.035
XBLPS300	186.35	163.9	170.20	3.70	0.88	0.913
XBLP270	93.05	89.7	92.20	2.71	0.964	0.991
XBLP121	146.03	128.6	133.77	3.86	0.881	0.916
XBLP278	85.51	74.0	76.20	2.89	0.865	0.891
XBLP301	231.26	186.1	209.93	11.35	0.805	0.908
RFMSE1	229.13	218.5	224.63	2.73	0.954	0.980
RFMSE2	349.65	326.3	351.53	7.18	0.933	1.005
RFMSE3	52.13	48.2	49.87	3.35	0.925	0.957
RFMSE4	383.69	358.6	389.03	7.82	0.935	1.014
RFMSE5	132.50	112.1	121.33	7.61	0.846	0.916
ARF876595	246.93	244.2	251.50	2.90	0.989	1.019
ARF876642	207.29	197.5	206.17	4.21	0.953	0.995
				Average	0.913	0.959
				RSD	0.056	0.052

mean. The bias of the calibration (the difference between true values of the standards minus the observed values based on the calibration curve) ranges from -0.50% to 0.47% for the five standards with an average bias of -0.07%; none of the bias is significantly different from zero considering the sigma of the bias. Note that the uncertainty assigned to the calibration constant is nearly a factor of 2 greater than the uncertainty of the calibration standards. Uncertainty in the characterization of the standards plays an insignificant role in this example.

3. *Measurement Control.* After the above calibration was performed, daily measurement control (MC) was started using the 48-g calibration standard.[6] Data for about two months are shown in Figure 3.

Several items of information are necessary to interpret these MC data. First, the accepted ^{239}Pu content of the MC source is 48.13 g, its calibration value. The average of the above MC bias (MCB) data gives a mean assay of 48.27 ± 0.29 g, 0.29% higher than the accepted value. The standard deviation of the MCB data is 1% whereas the precision from only counting statistics is 0.6%.

$$\text{variance(MCB)} = \text{variance(counting statistics)} + \text{variance(other factors)}$$

Table V
LCSGS Assay of SSC Samples

Sample ID	*Reference (g Pu)*	*LCSGS Assay (g Pu)*	*SGS/Reference Ratio*
MPX1825	134.26	102.84	0.766
MPX1843	216.00	218.88	1.013
MPX1907	222.81	165.14	0.741
MPX1945	63.70	52.84	0.830
MPX1986	124.00	109.90	0.886
MPX2190	166.00	155.32	0.936
MPX2240	136.00	133.78	0.984
MPX2286	294.00	109.98	0.374
		Average	0.816
		RSD	0.284

The other factors, in this case, are those discussed in items 10 through 15 in Section III.B. The standard deviation because of the other factors, in this example, is 0.8%. This 0.8% standard deviation from other factors should be included as a random error component and combined with the uncertainty in the sample-dependent counting statistics for each unknown. The random error for measuring unknown samples should be even greater than this. Table II lists other possible factors, in addition to the sample positioning, contributing to the random error. The following discussion shows that one of these factors, the matrix and SNM heterogeneity, is the major contributor to the random error and bias of assaying heterogeneous samples. Improving the counting statistics or calibration does little to improve the overall error.

C. Examples

1. Uniform, Homogeneous Incinerator Ash. After completing the calibration presented above, the SGS was used to assay a set of ash samples summarized in Table III.[7] Two of these samples, STDASH-1 and -2, are standards prepared 15 years ago for the SGS. The reference values were determined by chemical preparation and analysis. Recently the reference values were verified by calorimetry and gamma isotopic determination. The others are ash samples from Hanford, and the reference values were also determined by calorimetry and gamma isotopic measurements.

For this type of uniform, homogeneous sample, the SGS assay has very little observable bias. The RSD is consistent with the expected variation from the counting statistics.

2. Molten Salt Extraction (MSE) Salt. A pure plutonium button is formed in the MSE process of purifying plutonium. Some residual plutonium, however, remains in the salt and must be assayed for accountability purposes. The plutonium is mostly present in lumps embedded in the salts that are broken into pieces and put into a container for assay and disposal.

After the SGS measurements were completed, reference values, shown in Table IV, for these MSE salt samples were established by pulverizing the sample, blending it and chemically analyzing several representative samples. The chemical analysis from different samples agreed to within 1% to 2%; this is the uncertainty assigned to the reference values.

We observe that the bias for the traditional SGS is 8.7% whereas the bias of the LCSGS is 4.1%. Both of these are substantially larger than the average bias because of the calibration alone (-0.7%). The heterogeneity of the sample is the major contributing factor to the bias of the assay. The RSD is also substantially larger than that from the counting statistics alone.

3. Sand, Slag and Crucible (SSC). After the salt is removed, the crucible and slag remaining form the SSC samples. They also contain plutonium and are even more heterogeneous than the MSE samples because the plutonium is mostly on the surface of the crucible. Table V summarizes the results.

The average bias for these samples is ~18% including MPX2286. The major bias is from the MPX2286 sample — if it is excluded, both the bias and the RSD are reduced to 12%. This indicates that the bias may have a threshold effect and therefore may be mass dependent. The examples above present an actual measurement sequence from calibration through the measurement of unknown samples illustrating the magnitude of the contributions from different error components. For these examples, the random error because of counting statistics is ~0.5%; the bias because of calibration is ~0.3% or less. We find that the average bias of SGS for homogeneous samples (ash samples) is also relatively small (0.2%). However, the bias of SGS for MSE salts is 4.5%; for SSC samples, the bias is as large as 18%. The bias arising from heterogeneity is much larger than that from the calibration alone; for the SSC samples, the averaged bias from heterogeneity is 10 times that from the calibration. The heterogeneity of the samples also affects the random errors of these samples in that the sample-to-sample variations in the bias are substantially larger than those from the counting statistics alone.

The "true" values of these samples were established by studies requiring several man years of effort. Only by such studies can one determine the bias for assays of many classes of heterogeneous materials.

VI. CONCLUSION

This paper illustrates that providing a random error and bias in addition to the measurement results for a sample is not a simple or easy exercise. A single random error and the bias for an assay system are useful as a merit of the system in a comparative sense but not useful in calculating the inventory differences; both the random error and bias can depend on other parameters such as sample mass and sample type, especially for heterogeneous samples.

The assignment of measurement error requires close cooperation from many people — NDA developers, MC&A personnel and statisticians. One must look at the entire measurement system/material category combination to accurately assess measurement uncertainty for each measured item. Such an assessment might start with an error matrix for each instrument/material category combination as shown in this paper, in which many sources of error are considered. Only then can one assign the random error and bias for measurements from the system.

ACKNOWLEDGEMENT

We thank A. Goldman for calculating the bias of the calibration data in the SGS measurement.

REFERENCES

1. Guardini S., Guzzi G., Mousty F., Cuypers M. "Performance Evaluation of Non-Destructive Assay Techniques and Characterization of Standards for NDA in Safeguards," *ESARDA Bulletin* Dec. 17 1989, pp. 5-20.

2. Ottmar H., Eberle H. "The Hybrid K-edge/K-XRF Densitometer: Principles-Design-Performance," *Kernforschungszentrum Karlsruhe Report KfK 4590* (February 1991).

3. Martin E.R., Jones D.F., Parker J.L. "Gamma-Ray Measurements with the Segmented Gamma Scan," *Los Alamos National Laboratory Report LA-7059-M* (December 1977).

4. Sprinkle J.K. Jr., Hsue S.-T. "Recent Advances in Segmented Gamma Scanner Analysis," In *Proc. Third International Conference on Facility Operations—Safeguards Interface* La Grange Park, Ill.: American Nuclear Society, 1988, ANS Order No. 700132, pp. 188-193.

5. Bruckner L.A. "A Measurement Control Program To Meet Desired Levels of Precision and Accuracy," *JNMM* XIX(No. 1):29-34 (1990-1991).

6. Hsue S.-T., Miller M.C., Longmire V.L., Long S.M. "Design and Fabrication of SGS Plutonium Standards," presented at the 4th International Conference on Facility Operations—Safeguards Interface, Albuquerque, N. M., Sept. 29-Oct. 4, 1991, Los Alamos National Laboratory document LA-UR-91-2646 .

7. Sprinkle J.K. Jr., Bosler G.E., Hsue S.-T., Kellogg M.P., Miller M.C., Simmonds S.M., Smith A.R. "Nondestructive Assay of Plutonium-Bearing Scrap and Waste," *American Nuclear Society Proc. of the International Topical Meeting on Safety Margins in Criticality Safety, Nov. 26-30, 1989*, San Francisco, pp. 153-157.

S.-T. Hsue received his M.S. and Ph.D. from Indiana University in low energy nuclear physics. He also received an M.S. in nuclear engineer from University of Michigan. He has worked at Los Alamos National Laboratory in the Safeguards Assay group for 15 years. His interest is in applying the gamma-ray technique in measuring plutonium and uranium in various forms. The last few years he has been working on the assay of plutonium solution by means of passive technique and also by hybrid densitometry.

T.E. Sampson received his B.S. in physics from Case Institute of Technology and his M.S. and Ph.D. in nuclear science from the University of Michigan. He has worked in the safeguards program at Los Alamos for 22 years in the area of experimental measurements and the development of assay techniques and systems for the measurement of special nuclear materials. Among the many assay methods and instruments he has worked with are: uranium solution assay, plutonium isotopic compositions measurements using gamma-ray spectometry techniques, segmented gamma-ray scanner development, and neutron dieaway measurements of waste.

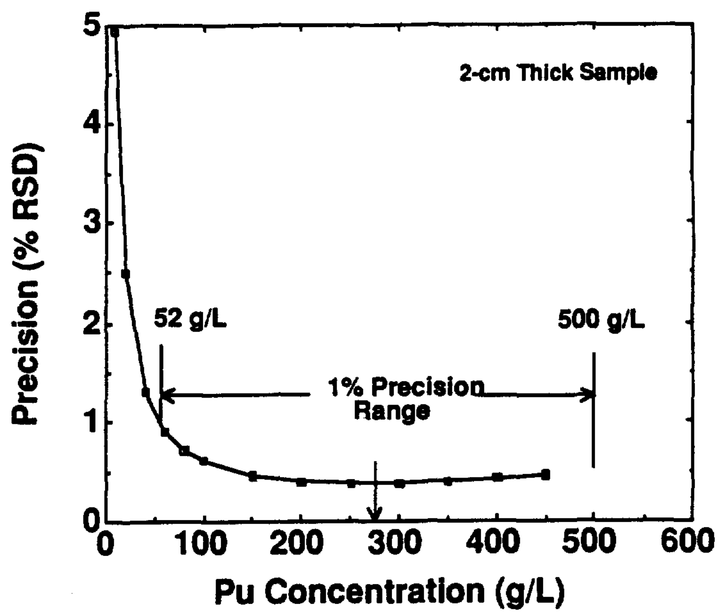


Fig. 1. Precision of densitometer for a 2-cm sample cell.

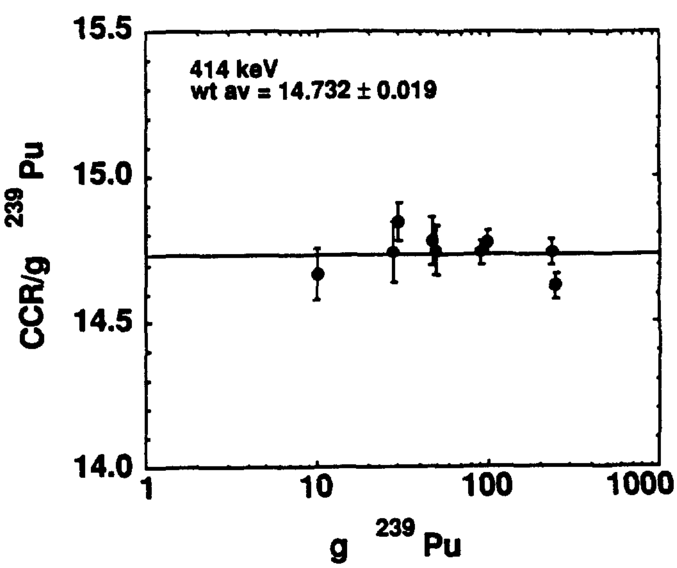


Fig. 2. SGS Calibration Data and Analysis

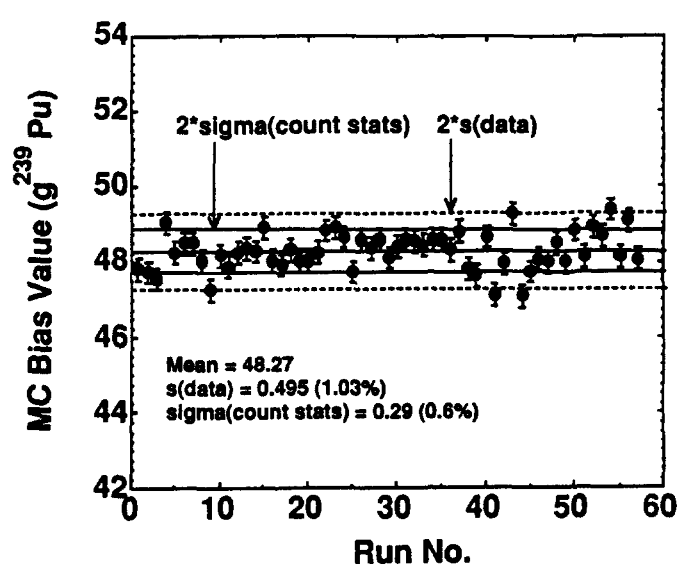


Fig. 3. Measurement Control Bias Data for an SGS.

Decision Theoretical Justification of Optimization Criteria for Near-Real-Time Accountancy Procedures

Rudolf Avenhaus
Universität der Bundeswehr München
Munich, Germany

ABSTRACT

In the beginning of nuclear material safeguards, emphasis was placed on safe detection of diversion of nuclear material. Later, the aspect of timely detection became equally important. Since there is a trade-off between these two objectives, the question of an appropriate compromise was raised.

In this paper, a decision theoretical framework is presented in which the objectives of the two "players," inspector and inspectee, are expressed in terms of general utility functions. Within this framework, optimal safeguards strategies are defined, and furthermore, conditions are formulated under which the optimization criteria corresponding to the objectives mentioned above can be justified.

1. INTRODUCTION

From the very beginning, according to the Model Agreement,[1] the objective of nuclear material safeguards was "the timely detection of the diversion of significant amounts of nuclear material." Nevertheless, in the early years of safeguards systems analyses, the emphasis was placed on devising procedures which guarantee a high probability of detecting any diversion of nuclear material, at a given level of the false alarm probability. Later on, more weight was put on the timely detection of diversion; *near-real-time accountancy* became the trademark of all efforts undertaken in this direction.

The reason for this historical development is quite obvious: In the case of statistical problems independent of time, it is standard practice to use the above-mentioned criteria. Beyond this, there exists the Neyman-Pearson lemma (see, for example, reference 2) which provides a tool for the determination of the optimal test procedure for a well-defined decision problem.

More than that, there are two basic problems that characterize the difficulties with which time-dependent statistical analyses, as well as near-real-time accountancy, have to struggle. First, there is no natural statistical criterion for timeliness. In fact, several criteria have been used during the last years. Second, there is no equivalent to the Neyman-Pearson lemma for sequential decision procedures.

Whatever criterion one chooses for the timeliness objective, there is a fundamental tradeoff between safe and timely detection of nuclear material. This was proven for the first time in 1980[3] for one material balance area and a sequence of inventory periods: If one considers a fixed reference time, then it is best for the safeguards authority — referred to as the inspector — to ignore intermediate inventories and to perform the material balance test only at the end of the reference time. This leads obviously to the longest detection time possible if one assumes pessimistically that any diversion takes place at the beginning of the reference time.

The compromise between the two objectives, safe detection and timely detection (i.e., the criterion which combines both aspects), can only be found with the help of a decision theoretical model in which the interests of both players — inspector and inspectee — are represented with the help of appropriate utility functions. For practical applications, however, this poses a major problem, since in concrete cases the values of the payoff parameters which characterize the utility functions can hardly be estimated quantitatively.

Therefore, and this is the purpose of this paper, it is important to know which assumptions, about the utility functions of the two players' criteria for the construction of decision procedures, can be developed which will depend only on the structure but not on the values of the payoff parameters. In particular, it is investigated which assumptions allow one to arrive at one of the criteria for timeliness which are used for the solution of practical statistical problems occurring, for example, in process or quality control.

At this point, one may ask why one does not apply this experience to near-real-time accountancy. The answer is that in the former case one deals with technique or inanimate nature, whereas here one deals with persons who may behave antagonistically, i.e., persons who may act strategically if they intend to divert material. Therefore, game theoretical instead of purely statistical models have to be used.

The problems sketched here have been analyzed recently[4] in an abstract mathematical way, without any reference to near-real-time accountancy. Here, the models used and the results obtained are summarized in a semiquantitative way, and their relevance to near-real-time accountancy is discussed.

In the following, first the general sequential game theoretical model and the inspector leadership principle are presented. Furthermore, a solution concept is used which is particularly useful for the application under consideration. Thereafter, two special cases of utility functions are considered, which lead to well-known results: If the payoff parameters are independent of time, i.e., of the stages of the sequential game with a finite time horizon, then one arrives again at the probability of detection and false alarm criteria. If the payoff parameters are exponentially discounted with time, i.e., stage number of the infinite time horizon game, then one arrives at average run length criteria which are frequently used in statistics (see reference 5). In the final discussion, the basic issues raised here are taken up once more in the light of the results obtained.

2. GAME THEORETICAL MODEL

Let us consider a sequential inspection game Γ_1 with the inspector *(I)* as player 1 and the inspectee (0) as player 2, whose extensive form is given in Figure 1, and which is played as follows:

1) At stage 1, the inspectee chooses an action μ_1 not observable to the inspector. An observation x_1 is made by a chance move according to the probability density function $f_1(\bullet|\mu_1)$. The observation x_1 becomes common knowledge to both players.
2) The inspector chooses either $\bar{A}$ (no alarm), in which case the game continues to stage 2, or A (alarm), in which case the game terminates with payoffs $(I_1(\mu_1), 0_1(\mu_1))$ to the two players.
3) Inductively: For every $t = 1,...,n$, after the inspectee chose actions $(\mu_1,...,\mu_{t-1})$ and observations $(x_1,...,x_{t-1})$ were made, the inspectee chooses an action μ_t with complete knowledge of $(\mu_1,x_1,...,\mu_{t-1},x_{t-1})$. Thereafter, an observation x_t is made by a chance move according to the conditional probability density function $f_t(\bullet| \mu_1, x_1,\ldots, \mu_{t-1}, x_{t-1}, \mu_t)$. With observations $(x_1,...,x_t)$, the inspector chooses either $\bar{A}$, in which case the game continues to stage $t+1$ if $t<n$ or terminates with payoffs $(\tilde{I}_n(\mu_1,..., \mu_t), \tilde{0}_n(\mu_1,..., \mu_t))$ if $t = n$, or A, in which case the game terminates with payoffs $(I_t(\mu_1,..., \mu_t), 0_t(\mu_1,..., \mu_t))$ to the two players.

In the following, we will make special assumptions which are called the *Inspector Leadership Principle*.

1) Before the start of the game, the inspector chooses and announces a test procedure which determines for which ranges of observations of relevant random variables an alarm (A) is raised or not $(\bar{A})$ at stages $1, \ldots, n$. Formally a test procedure δ for the inspector is defined by a collection $\delta = (\delta_1, \ldots, \delta_n)$ where each δ_t, $t = 1, \ldots, n$, assigns each set of observations either A or $\bar{A}$ at stage t.
2) Knowing the test procedure $\delta = (\delta_1, \ldots, \delta_n)$, the inspectee decides whether he will behave illegally (H_1) or legally (H_0). If he decides to behave illegally, he will choose an illegal vector $\mu = (\mu_1, \ldots, \mu_n)$, where μ_t is the size of the illegal action at stage $t = 1, \ldots, n$. For convenience, we put $\mu = (0, \ldots, 0)$ in the case of legal behavior. Thereafter, the game really starts and ends either after the ith stage if there is an alarm, or finally and definitely after n stages. Neither player has any possibility to adjust his decisions in the course of the game.

If an alarm is raised for the first time at stage t, then the game ends either with the payoffs

$$-a_t(\mu_1,..., \mu_t) = I_t(\mu_1,..., \mu_t)$$
$$-b_t(\mu_1,..., \mu_t) = 0_t(\mu_1,..., \mu_t)$$

to the inspector and the inspectee, respectively, in case of illegal behavior, or with the payoffs

$$-e_t = I_t(0,...,0), \quad -f_t = 0_t(0,...,0)$$

to the inspector and the inspectee, respectively, in case of legal behavior. If no alarm is raised at stage t, then the next stage $t+1$ will be reached. At the latest, after n stages the game ends with a terminal decision of the inspector. When no alarm is raised at stage n, the inspector and the inspectee receive the payoffs

$$-c(\mu_1,..., \mu_n) = \tilde{I}_n(\mu_1,..., \mu_n)$$
$$-d(\mu_1,..., \mu_n) = \tilde{0}_n(\mu_1,..., \mu_n)$$

respectively, in case of illegal behavior, and the payoffs (0,0) in case of legal behavior.

With the inspector leadership principle described so far, the sequential inspection game Γ_1 in the first section can be transformed into a simpler game whose extensive form is sketched in Figure 2; we call it the *sequential inspector leadership game*, denoted by Γ_2.

A strategy for the inspector in the game Γ_2 is defined to be $\gamma = (\gamma_1, \gamma_2)$ where γ_1 assigns to every δ either H_0 or H_1, and γ_2 to every δ an illegal vector $(\mu_1,..., \mu_n)$. Given a strategy pair (δ, γ), the expected payoffs for the inspector and the inspectee, denoted by $Eg_1(\delta, \gamma)$ and $Eg_2(\delta, \gamma)$, respectively, are defined in the usual manner. Also, the conditional payoff for the inspectee given that the inspector selects δ and the inspectee selects H_1 can be defined. It is denoted by $Eg_2(\gamma|\delta, H_1)$.

We can now define a subgame perfect equilibrium point of the sequential inspector leadership game Γ_2.

Definition 1

A strategy pair (δ^*, γ^*) is a *subgame perfect equilibrium point* of the game Γ_2 if and only if

1) $Eg_1(\delta^*, \gamma^*) \geq Eg_1(\delta, \gamma^*)$ for all δ
2) $Eg_2(\delta, \gamma^*) \geq Eg_2(\delta, \gamma)$ for all δ and all γ
3) $Eg_2(\gamma^* | \delta, H_1) \geq Eg_2(\gamma | \delta, H_1)$ for all δ and all γ. □

At this point, one should justify the relevance of the inspector leadership principle and of the subgame perfect equilibrium concept. The leadership principle, due to Stackelberg,[6] was used in inspection games the first time by Maschler,[7] who did not take into account, however, error probabilities. It has been shown for non-sequential inspection games that in case the inspector announces his strategy, then the optimal strategy of the inspector is legal behavior.[8] Therefore, this principle is used also for sequential inspection games, and we expect a similar result. Now, even if the inspectee's optimal strategy is legal action, by some mistake ("trembling hand," see reference 9), he could decide for illegal action. Then a subgame perfect equilibrium strategy of the inspector guarantees that also in this unreasonable case he makes the best of the situation.

Let us now return to our game Γ_2. The expected payoffs to the two players are given as follows:

$$Eg_1(\delta,\gamma) = \begin{cases} -\sum_{t=1}^{n} a_t(1-\beta_t)\prod_{s=1}^{t-1}\beta_s - c\prod_{t=1}^{n}\beta_t & H_1 \\ & \text{for } \gamma_1(\delta) = \\ -\sum_{t=1}^{n} e_t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s) & H_0 \end{cases}$$

$$Eg_2\delta,\gamma) = \begin{cases} -\sum_{t=1}^{n} b_t(1-\beta_t)\prod_{s=1}^{t-1}\beta_s + d\prod_{t=1}^{n}\beta_t & H_1 \\ & \text{for } \gamma_1(\delta) = \\ -\sum_{t=1}^{n} f_t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s) & H_0, \end{cases}$$

where $a_t = a_t(\mu_1,\dots,\mu_n)$, $b_t = b_t(\mu_1,\dots,\mu_n)$, $\beta_t = \beta_t(\delta, \mu_1,\dots,\mu_t)$ is the probability that in the case of illegal behavior of the inspectee no alarm is raised at stage t (given no alarm was raised before) and $\alpha_t = \alpha_t(\delta)$ is the probability that in the case of legal behavior of the inspectee an alarm (false alarm) is raised (given no alarm was raised before). It should be mentioned that α and β correspond to the error first and second kind probabilities generally used in decision theory.

With these payoffs, one now can characterize a subgame perfect equilibrium point of the sequential inspector leadership game Γ_2.

Proposition 2

A pure strategy combination (δ^*,γ^*), $\delta^* = (\delta_1^*,\dots,\delta_n^*)$, $\gamma^* = (\gamma_1^*, \gamma_2^*)$ of the sequential inspector leadership game Γ_2 is a subgame perfect equilibrium point of Γ_2, if and only if the following conditions are satisfied:

1) For every δ, $\gamma_2^*(\delta) = (\mu_1^*,\dots,\mu_n^*)$ is a solution of

$$\max_{(\mu_1,\dots,\mu_n)} [-\sum_{t=1}^{n} b_t(1-\beta_t)\prod_{s=1}^{t-1}\beta_s + d\prod_{t=1}^{n}\beta_t].$$

We denote this maximum value by $M(\delta)$.

2) For every δ, $\gamma_1^*(\delta)$ is equal to

$$\begin{matrix} H_0 & & < & \\ & \text{if } M(\delta) & & -\sum_{t=1}^{n} f_t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s). \\ H_1 & & > & \end{matrix}$$

3) δ^* is a solution of $\sup_\delta I(\delta)$, i.e.,

$$\delta^* = \arg\sup_\delta I(\delta),$$

where $I(\delta)$ is given by

$$I(\delta) = \begin{cases} -\sum_{t=1}^{n} e_t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s) & H_0 \\ & \text{for } \gamma_1^*(\delta) = \\ -\sum_{t=1}^{n} a_t(1-\beta_t)\prod_{s=1}^{t-1}\beta_s - c\prod_{t=1}^{n}\beta_t & H_1, \end{cases}$$

where $a_t = a_t(\mu_1^*,\dots,\mu_n^*)$ and $\beta_t = \beta_t(\delta, \mu_1^*,\dots,\mu_n^*)$ for $t = 1,\dots, n$. □

It should be mentioned that in Proposition 2, $\gamma_1^*(\delta)$ is not determined for the case

$$M(\delta) = -\sum_{t} f_t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s).$$

In the following two sections, two special forms of the payoff parameters are considered where just this case becomes the important one.

3. FINITE TIME HORIZON, CONSTANT PAYOFF PARAMETERS

In this section we consider the very special situation that the payoff parameters for the inspector and for the inspectee are independent of the stage number, and furthermore, that they are independent of the illegal vector $(\mu_1,\dots,\mu_n)$.

We assume that there exist positive constants a, b, c, d, e and f such that

$$\begin{aligned} a &= a_t(\mu_1,\dots,\mu_t), & b &= b_t(\mu_1,\dots,\mu_t) \\ c &= c(\mu_1,\dots,\mu_n), & d &= d(\mu_1,\dots,\mu_n) \\ e &= e_t, & f &= f_t \end{aligned}$$

for every $t = 1,..., n$ and $\mu = (\mu_1,..., \mu_n)$, with $e < a < c$ and $f < b$.

Under these assumptions, the expected payoffs for the inspector and for the inspectee in the game Γ_2 are given as follows:

$$Eg_1(\delta,\gamma) = \begin{cases} -a(1-\beta(\delta,\mu)) - c\beta(\delta,\mu) & \\ & \text{for } \gamma_1(\delta) = \\ -e\alpha(\delta) & \end{cases} \begin{matrix} H_1 \\ \\ H_0 \end{matrix}$$

$$Eg_2\delta,\gamma) = \begin{cases} -b(1-\beta(\delta,\mu)) + d\beta(\delta,\mu) & \\ & \text{for } \gamma_1(\delta) = \\ -f\alpha(\delta) & \end{cases} \begin{matrix} H_1 \\ \\ H_0 \end{matrix}$$

where $\mu = (\mu_1,..., \mu_n)$, and where $\beta(\delta,\mu) = \prod_{t=1}^{n} \beta_t(\delta_t, \mu_1,..., \mu_t)$ and $\alpha(\delta) = 1 - \prod_{t=1}^{n} \alpha_t(\delta)$ are the overall non-detection and false alarm probabilities.

With these expected payoffs, we can reduce the sequential inspector leadership game Γ_2 to the non-sequential inspector leadership game Γ_3, the extensive form of which is given in Figure 3.

A subgame perfect equilibrium point of this game can be characterized as follows.

Proposition 3

A pure strategy combination (δ^*,γ^*), $\delta^*=(\delta_1^*,...,\delta_n^*)$, $\gamma^*=(\gamma_1^*, \gamma_2^*)$ of the non-sequential inspector leadership game Γ_3 is a subgame perfect equilibrium point of Γ_3, if and only if the following conditions are satisfied:

1) The false alarm probability

$$\alpha^* = \alpha(\delta^*) = 1 - \prod_{t=1}^{n} (1 - \alpha_t(\delta^*))$$

of δ^* is a solution of the equation

$$-b + (b + d)\,\beta(\alpha) + f\alpha = 0,$$

where $\beta(\alpha)$ is given by

$$\beta(\alpha) = \min_{\delta \in \Delta_\alpha} \max_{\mu} \beta(\delta, \mu),$$

and where Δ_α is given by

$$\Delta_\alpha = \{\delta = (\delta_1,..., \delta_n) \mid \alpha(\delta) = \alpha\}.$$

2) $\delta^*=(\delta_1^*,..., \delta_n^*)$ is a solution of the optimization problem

$$\min_{\delta \in \Delta_\alpha} \max_{\mu} \beta(\delta, \mu).$$

3) For every δ, $\gamma_1^*(\delta)$ is given as

$$\gamma_1^*(\delta) = \begin{cases} H_0 & \\ & \text{if } -b + (b+d)\beta(\delta) + f\alpha(\delta) \begin{matrix} \leq \\ \\ > \end{matrix} 0, \\ H_1 & \end{cases}$$

where $\beta(\delta)$ is given by

$$\beta(\delta) = \max_{\mu} \beta(\delta, \mu).$$

4) For every δ, $\gamma_2^*(\delta)$ is a solution of

$$\max_{\mu} \beta(\delta, \mu). \qquad \square$$

This proposition shows, first of all, that the inspectee behaves legally in equilibrium even though a best illegal strategy is determined, and even though his payoff in equilibrium is the same for legal and for illegal behavior.

Furthermore, this proposition shows that in the case that both players' payoff parameters are independent of the stage where the game terminates, it suffices to optimize the probability of no detection for a given value of the false alarm probability α which is determined with the help of a structurally simple equation.

This is important for several reasons: First, it is in line with standard statistical practice to proceed this way, and it permits the determination of optimal test procedures with the help of the Neyman-Pearson lemma.[2]

One subtle point should be mentioned here: The application of the Neyman-Pearson lemma requires a fixed alternative hypothesis which leads to the optimization problem

$$\beta(\alpha) = \max_{\mu} \min_{\delta \in \Delta_\alpha} \beta(\delta, \mu)$$

instead of the one given in Proposition 3. If, however, there exists a saddlepoint, then this way we can obtain an equilibrium point. With this procedure, a series of practical problems have been solved.[10]

In particular, it was shown what had been mentioned already in the introduction: If one considers a series of inventory periods $[t_0,t_1]...[t_{n-1},t_n]$ and defines the corresponding material balance test statistics $Z_i = I_{i-1} + D_i - I_i$ where I_i is the real inventory at I_i and D_i the net flow during $[t_{i-1}, t_i]$, $i = 0,..., n$, then the best test for H_0: $E_0(Z_i) = 0$ for $i = 1,..., n$ against H_1: $E_1(Z_i) = \mu_i$ for $i = 1,..., n$ with $\Sigma_i \mu_i$ fixed is characterized by the test statistic $Z = I_0 + \Sigma_i D_i - I_n$ which means that all intermediate inventories are ignored, and the decision between H_0 and H_1 is taken only at the end of the reference time $[t_0,t_n]$.

Second, for a given value of the false alarm probability α, the payoff parameters need not be known for the determination of the optimal decision procedure. In fact, in general it is impossible to estimate even ranges of these parameters. Proposition 3 shows that only if one wants to determine the optimal value of α, then one needs to know the two ratios b/f and d/f of the inspectee's payoff parameters.

4. INFINITE TIME HORIZON, DISCOUNTED PAYOFF PARAMETERS

Let us consider the sequential inspector leadership game of the second section with infinitely many stages, and let us assume that the payoffs to both players at each stage depend on the stage number as follows.

There exist positive constants ν_1, ν_2, λ_1 and λ_2 such that the payoffs to both players are given by

$$a_t(\mu_1,\ldots,\mu_t) = a\exp(\nu_1 t)$$

$$b_t(\mu_1,\ldots,\mu_t) = b\exp(-\nu_2 t)$$

$$e_t = e\exp(-\lambda_1 t),\ f_t = f\exp(-\lambda_2 t)$$

for every $t = 1,2,\ldots$ and every $\mu = (\mu_1, \mu_2, \ldots)$, where $0 < e < a$ and $f < b$.

These assumptions mean that the losses e_t and f_t, caused by false alarm, are exponentially decreasing with respect to t. An earlier false alarm imposes more damages. Secondly, the two players have opposite time preferences with respect to the detection of illegal behavior. The inspector prefers earlier detection, while the inspectee prefers later detection.

The sequential inspector leadership game with infinitely many stages is denoted by Γ_4. In what follows, we use the same notations as before whenever no confusion arises. For a strategy pair (δ, γ), we can define the false alarm probability at stage t, denoted by $\alpha_t(\delta)$, and the no detection probability at stage t, denoted by $\beta_t(\delta, \mu)$.

The expected payoffs to the inspector and the inspectee in the game Γ_4 are

$$Eg_1(\delta,\gamma) = \begin{cases} -a\sum_{t=1}^{n}\exp(\nu_1 t)(1-\beta_t)\prod_{s=1}^{t-1}\beta_s & \\ & \text{for } \gamma_1(\delta) = \\ -e\sum_{t=1}^{n}\exp(-\lambda_1 t)\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s) & \end{cases} \begin{matrix} H_1 \\ \\ H_0, \end{matrix}$$

$$Eg_2(\delta,\gamma) = \begin{cases} -b\sum_{t=1}^{n}\exp(-\nu_2 t)(1-\beta_t)\prod_{s=1}^{t-1}\beta_s & \\ & \text{for } \gamma_1(\delta) = \\ -f\sum_{t=1}^{n}\exp(-\lambda_2 t)\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s) & \end{cases} \begin{matrix} H_1 \\ \\ H_0. \end{matrix}$$

Now we assume

$$(\nu_1, \nu_2, \lambda_1, \lambda_2) << (1, 1, 1, 1)$$

and apply a Taylor series expansion to the exponential functions,

$$\exp(\nu_1 t) \approx 1 + \nu_1 t,\ \exp(-\lambda_1 t) \approx 1 - \lambda_1 t,\ \text{etc.}$$

Furthermore, we introduce the expected or *average run lengths* L_1 and L_0 defined by

$$L_1(\delta,\mu) = \sum_{t=1}^{\infty} t(1-\beta_t)\prod_{s=1}^{t-1}\beta_s$$

$$L_0(\delta) = \sum_{t=1}^{\infty} t\alpha_t\prod_{s=1}^{t-1}(1-\alpha_s).$$

Then the expected payoffs to the two players in the game Γ_4 are given by

$$Eg_1(\delta,\gamma) = \begin{cases} -a(1+\nu_1 L_1(\delta,\mu)) & \\ & \text{for } \gamma_1(\delta) = \\ -e(1-\lambda_1 L_0(\delta)) & \end{cases} \begin{matrix} H_1 \\ \\ H_0, \end{matrix}$$

$$Eg_2(\delta,\gamma) = \begin{cases} -b(1-\nu_2 L_1(\delta,\mu)) & \\ & \text{for } \gamma_1(\delta) = \\ -f(1-\lambda_2 L_0(\delta)) & \end{cases} \begin{matrix} H_1 \\ \\ H_0, \end{matrix}$$

With these expected payoffs, a subgame perfect equilibrium point of the game Γ_4 can be characterized as follows.

Proposition 4

A pure strategy combination (δ^*, γ^*) of the sequential inspector leadership game Γ_4 with infinite time horizon is a subgame perfect equilibrium point of Γ_4, if and only if the following conditions are satisfied:

1) The average run length $L_0(\delta^*)$ under H_0 is the solution L_0^* of the equation

$$-b(1 - \nu_2 L_1(L_0)) + f(1 - \lambda_2 L_0) = 0$$

where $L_1(L_0)$ is defined by

$$L_1(L_0) = \min_{\delta\in\Delta_{L_0}} \max_{\mu} L_1(\delta, \mu),$$

and where ΔL_0 is the set of all test procedures δ with fixed average run length L_0 under H_0.

2) The test procedure δ^* of the inspector is a solution of the minimax problem

$$\min_{\delta\in\Delta_{L_0^*}} \max_{\mu} L_1(\delta, \mu).$$

3) For every $\delta \in \Delta$, the inspectee behaves according to

$$\gamma_1^*(\delta) = \begin{cases} H_0 & \\ & \text{if } -b(1-\nu_2 L_1(L_0)) + f(1-\lambda_2 L_0(\delta)) \\ H_1 & \end{cases} \begin{matrix} \le \\ 0. \\ > \end{matrix}$$

4) For every $\delta \in \Delta$, the illegal strategy γ_2^* of the inspectee

is a solution of the maximization problem

$$L_1(\delta) = \max_{\mu} L_1(\delta, \mu) \qquad \square$$

There are many similarities between this proposition and the previous one, Proposition 3. First, again the inspectee behaves legally in equilibrium even though a best illegal strategy is determined. Second, there is now a new statistical criterion, the average run length, which takes the role that had been taken before by the error probability. Again, for a given value of the average run length L_0 under H_0, the payoff parameters need not be known for the determination of the optimal decision procedure.

There are also differences between the results provided by Propositions 3 and 4. Whereas in the case of Proposition 3 the equation determining the optimal value of α under reasonable conditions

$$\beta(\bullet) \text{ convex}, \quad \beta(0) = 1, \quad \beta(1) = 0$$

always has a solution, this is not necessarily so in the case of Proposition 4. In general, $L_1(L_0)$ is a monotonically increasing function of L_0, starting with $L_1 = 1$ for $L_0 = 1$. Since the function

$$f(L_0) = \frac{1}{\nu_2}\left(1 - \frac{f}{b}(1 - \lambda_2 L_0)\right)$$

is also linearly increasing in L_0, starting with

$$f = \frac{1}{\nu_2}\left(1 - \frac{f}{b}(1 - \lambda_2)\right) \text{ for } L_0 = 1,$$

there is only a solution, if $L_0(L_1)$ is stronger than linearly increasing in L_0, and if furthermore

$$\frac{1}{\nu_2}\left(1 - \frac{f}{b}(1 - \lambda_2)\right) > 1 \text{ or } \frac{1 - \nu_2}{1 - \lambda_2} > \frac{f}{b},$$

which because of $f < b$ implies $\lambda_2 < \nu_2$.

For the practical application, Proposition 4 provides a commonly used statistical criterion as well. However, as already mentioned in the Introduction, there is no equivalent to the Neyman-Pearson lemma, which provides a tool to construct an optimal decision procedure for a well-defined sequential problem. In addition, it is not as intuitive as in the non-sequential case to define a reasonable set of illegal strategies: Whereas in the former case one considers all strategies which lead to a total (finite) diversion, this is not reasonable in the sequential case with infinite time horizon.

5. DISCUSSION

In the Introduction, we raised the question in which way the best compromise between the two criteria — safe and timely detection of the diversion of nuclear material — can be found. We argued that the answer to this question can only be given with the help of appropriate utility functions for both players: inspector and inspectee.

For two special cases we arrived at familiar conclusions: If the payoff parameters are independent of time, then the criteria for constructing best decision procedures are the well-known error first and second kind probabilities. If they are exponentially discounted with time, then the criteria turn out to be the average run lengths. One also may formulate these results another way: We showed under which assumptions on the utility functions these well-known statistical criteria are the appropriate ones.

From a theoretical point of view, there is no problem with the above-mentioned compromise. For well-defined utility functions of the players, Proposition 2 provides the criteria with the help of which the best decision procedures have to be constructed.

The situation becomes difficult if one wants an answer for a practical case where it is not possible to formulate the utility functions quantitatively, and both cases, covered by Propositions 3 and 4, are not considered to be satisfying. In the following, just an idea is presented.

Let us consider again a *finite* time horizon sequential game with exponentially discounted payoffs. For simplicity, we use only the expected payoff of the inspectee, since that of the inspector can be treated the same way. With

$$b_t = \exp(-\nu_2 t) \approx 1 - \nu_2 t, \quad f_t = f\exp(-\lambda_2 t) \approx 1 - \lambda_2 t$$

and

$$\beta(\delta, \mu) = \prod_{t=1}^{n} \beta_t, \quad \alpha(\delta) = \prod_{t=1}^{n} \alpha_t$$

we get the expected payoffs.

$$Eg_2(\delta, \gamma) = \begin{cases} -b + (b+d)\beta(\delta, \mu) + b\nu_2 \sum_{t=1}^{n} t(1 - \beta_t) \prod_{s=1}^{t-1} \beta_s & \\ & \text{for } \gamma_1(\delta) = \\ -f(\alpha(\delta) - \lambda_2 \sum_{t=1}^{n} t(1 - \beta_t) \prod_{s=1}^{t-1} \beta_s & \end{cases} \begin{array}{c} H_1 \\ \\ H_0 \end{array}$$

Because of the finite time horizon, the sums are not the average run lengths. If, however, we approximate these sums by L_1 and L_0, then we get

$$Eg_2(\delta, \gamma) = \begin{cases} -b + (b+d)\left(\beta(\delta, \mu) + \frac{b\nu_2}{b+d} L_1(\delta, \mu)\right) & \\ & \text{for } \gamma_1(\delta) = \\ -f(\alpha(\delta) - \lambda_2 L_0(\delta)) & \end{cases} \begin{array}{c} H_1 \\ \\ H_0. \end{array}$$

We see that the expected payoff of the inspectee is now a linear combination of error probabilities and average run lengths. In fact, such a linear combination has already been proposed by Beedgen[11] without further justification. Nevertheless, even if the approximations can be justified, there remains the problem of estimating the weighting factors $bv_2 / (b + d)$ and λ_2: The plain truth "there is no free lunch" also holds in near real time material accountancy.

ACKNOWLEDGMENT

This work was supported by the German Ministry of Research and Technology under Contract No. KWA 79-4.

REFERENCES

1. International Atomic Energy Agency "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153, Vienna 1971.
2. Lehmann E.L. *Testing Statistical Hypotheses* New York: John Wiley, 1957.
3. Avenhaus R., Jaech J "On Subdividing Material Balances in Time and/or Space," *JNMM.* 4(3):24-33 (1981).
4. Avenhaus R., Okada A. "Statistical Criteria for Sequential Inspection Games," *IASFOR-Report No. S-9008* Universität der Bundeswehr München, November 1990.
5. Wetherill G.B. *Sampling Inspection and Quality Control*, 2nd ed., London and New York: Chapman and Hall, 1982.
6. Stackelberg H.v. *Marktform und Gleichgewicht* Berlin: Springer, 1934.
7. Maschler, M. "A Price Leadership Method for Solving the Inspector's Non-Constant-Sum Game," *Nav.Res.Log.Quart.* 13:11-33 (1966).
8. Avenhaus R., Okada A. "Inspector Leadership Games with Incomplete Information," *ZIF Discussion Paper No. 17* Bielefeld, FRG, July 1988.
9. Selten R. *Models of Strategic Rationality* Kluwer Academic Publishers, 1988, pp. 1-31.
10. Avenhaus R. *Safeguards Systems Analysis - With Application to Nuclear Material Safeguards and Other Inspection Problems* New York and London: Plenum, 1986.
11. Beedgen R. "Statistical Considerations Concerning Multiple Materials Balance Models," *Report No. LA-9645-MS* Los Alamos National Laboratory, August 1983.

Rudolf Avenhaus is professor of Statistics and Operations Research at the German Armed Forces University in Munich. Prior to his academic appointment in 1980, he was research assistant at the Mathematics and Physics Institutes of the Universities of Karlsruhe and Geneva, and research scholar at the Nuclear Research Centre Karlsruhe. From 1973 to 1975 and again in 1982, he worked at the International Institute for Applied Systems Analysis (IIASA) Laxenburg, near Vienna. He is the author of numerous papers in physics, statistics, game theory and its application to nuclear problems, especially nuclear material safeguards. He is the author of the books Material Accountability *(Wiley 1977) and* Safeguards Systems Analysis *(Plenum 1986), and co-author of the books* Mathematical and Statistical Methods in Nuclear Safeguards *(Harwood 1982) and* Quantitative Assessment in Arms Control *(Plenum 1984).*

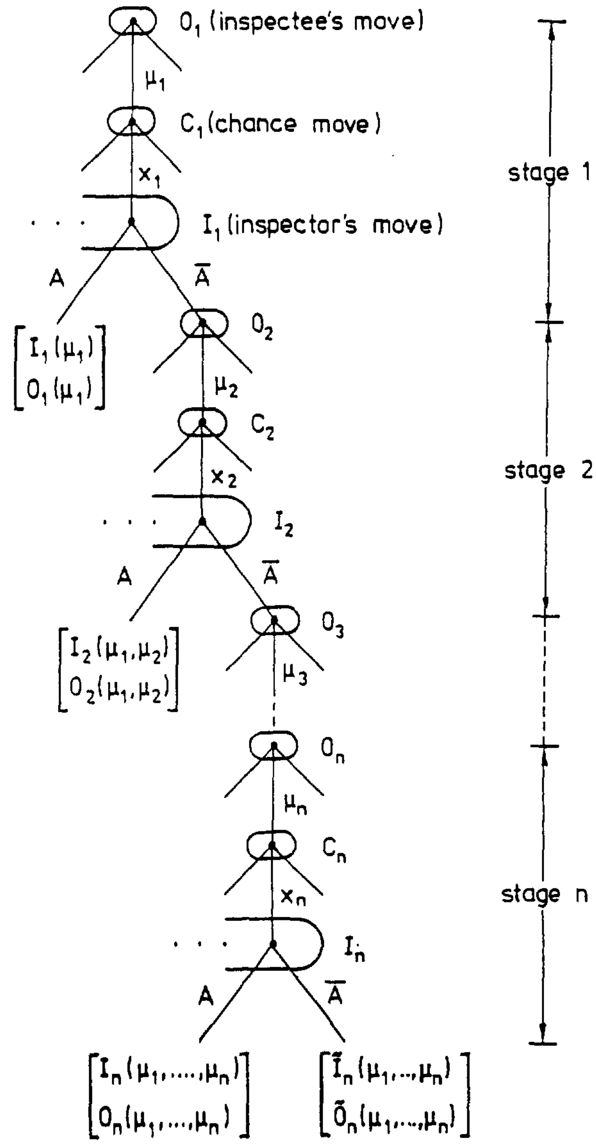


Figure 1: Extensive form of the sequential inspection game Γ_1.

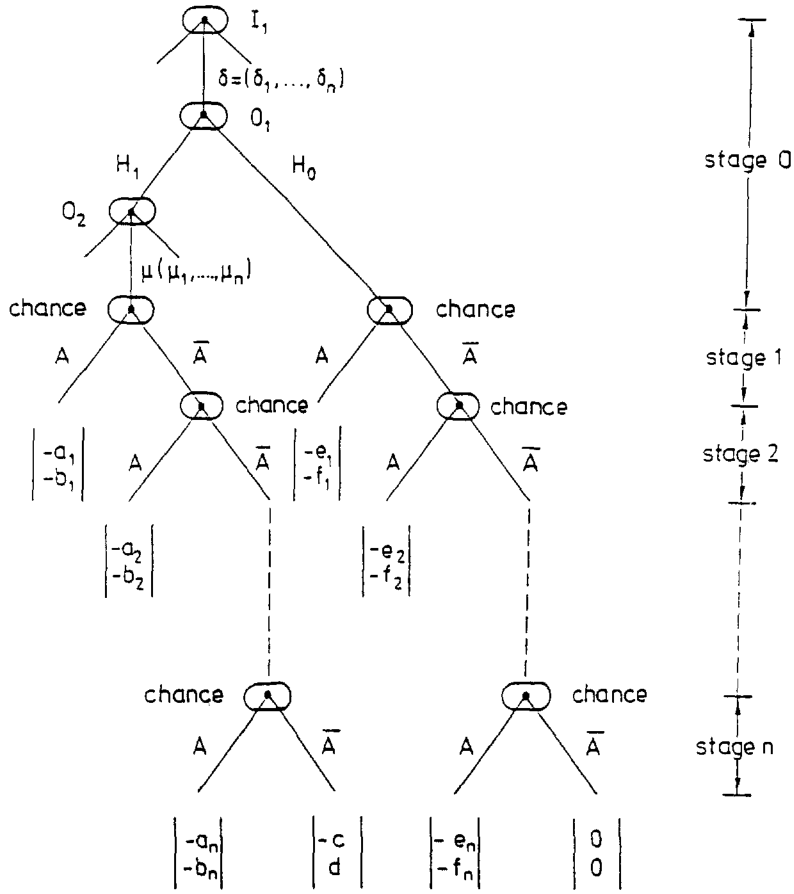


Figure 2: Extensive form of the sequential inspector-leadership game Γ_2.

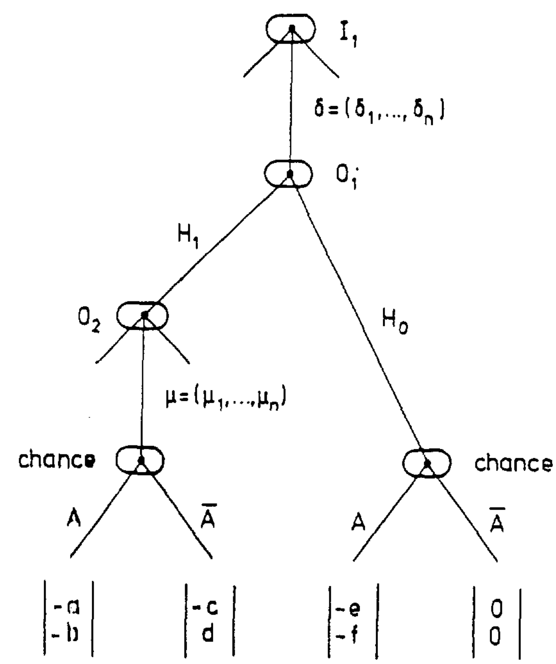


Figure 3: Extensive form of the nonsequential inspector-leadership game Γ_3.

In-Tank Density Determination Revisited

Frank E. Jones
Consultant
Potomac, Maryland U.S.A.

ABSTRACT

This paper presents the results for two sets of tank calibration runs which again established the feasibility of in-tank determination of the density of nuclear process solutions in the field with a precision competitive with that claimed for laboratory determinations of the density of samples taken from a tank. Density was inferred from the differential pressure measured between two bubbler probes immersed in fluid at different heights in the tank. The first set of runs in water provided a calibration factor with a relative standard error of 0.0093%, which was used to infer the density of 2% nitric acid solutions in the same tank. The relative standard errors for four nitric acid solution runs were 0.011%, 0.012%, 0.099, and 0.0073%.

INTRODUCTION

In an earlier paper,[1] results were presented for an investigation of the feasibility of in-tank determination of the density of nuclear process solutions in the field with a precision competitive with the precision claimed for laboratory determinations of the density of samples taken from a tank. In-tank determinations were made by inferring the density from the differential pressure measured between two probes immersed in fluid at different levels in the tank. The differential pressure was measured using a null-operated quartz bourdon type electromanometer. The work provided a calibration factor, with a precision (estimate of the relative standard deviation of the mean) of 2.2 parts in 10,000 (0.022%), which could be used to infer density from differential pressure measurements in the particular accountability tank. The technique eliminates one error in the laboratory determination of density and minimizes another.

The relationship between the differential pressure, DP, between two points separated vertically by a distance h and the density of the fluid in between is

$$DP = \rho(gh) \tag{1}$$

where ρ is the density of the fluid and g is the local acceleration due to gravity. The ratio of DP to ρ is a measure of the product (gh). Therefore, a series of measurements of DP in a liquid of known density, water, provides a determination of (gh) with an estimate of precision from the multiple measurements. The (gh) so determined then becomes a calibration factor relating ρ to DP in a rearrangement of Eq. 1:

$$\rho = DP/(gh) \tag{2}$$

The determination of (gh) can be made in the course of volume calibration of a tank with little or no additional effort, or an experimental determination can be made in preparation for a volume calibration.

The density of water to be used in the determination of (gh) can be calculated by using the equation in reference 2:

$$\rho_{as} = 998.47654 + 0.279971t - (2.14356 \times 10^{-2})t^2 + (4.37094 \times 10^{-4})t^3 - (5.44028 \times 10^{-6})t^4 + (2.72562 \times 10^{-8})t^5$$

where ρ_{as} is the density of air-saturated water at a pressure of one atmosphere in the temperature range 15 to 60 °C, in kg m^{-3}, and t is temperature of the water in °C.

In the present work, the approximate accuracy and precision of this method of determining the density of a solution in a tank have been determined in a tank containing water or a 2% nitric acid solution.

EXPERIMENTAL SECTION

An in-tank density determination experiment was performed at the Savannah River Site during the volume calibration of a tank. A null-operated quartz bourdon type differential pressure electromanometer was connected across two vertically separated bubbler tubes in the liquid. The probes were stainless steel tubes of 0.019-meter (m) inside diameter, with a vertical separation of nominally 0.254 m. A flow of air of 8 mL s^{-1} was maintained through each of the probes, communicating the differential pressure to the electromanometer. The temperature of the liquid in the tank was measured by using a device used in the operation of the tank.

With the tips of both probes immersed in water and with air flowing through them, a series of measurements of differential pressure, DP, and temperature was made for each of four runs. The data for the four runs are listed in Tables 1 through 4. The tables list the temperature of the water, in °C; the DP across the probes, in pascals (Pa); the density of water calculated by using Eq. 3 and the temperature of the water, in kg m^{-3}; and values of (gh) calculated, in $m^2 s^{-2}$, as the ratio of DP to ρ, corrected to (gh) at a reference temperature of 20 °C, $(gh)_{20}$; the estimate of standard deviation, SD; the standard error, SE, which is SD divided by the square root of the number of determinations of $(gh)_{20}$, n; and the relative standard error, which is SE divided by the mean $(gh)_{20}$.

Values of $(gh)_{20}$ were calculated by using the equation

$$(gh)_{20} = (gh)_t[1 + \alpha(20 - t)] \qquad (4)$$

where $(gh)_t$ is the value of (gh) at the measured temperature t and α is the coefficient of linear expansion of the probe material, 15.9×10^{-6} $(°C)^{-1}$ for stainless steel in this case.

An analysis of variance, ANOVA, was made of the data for the four runs in water to test the hypothesis that all the determinations of (gh) are random samples from the same population. The value of F for the ANOVA was 0.33094, which is sufficiently small that the hypothesis can be accepted.

Since all the determinations can be considered to be random samples from the same population, they were all used to determine an overall mean value of $(gh)_{20}$ and corresponding values of SD, SE and relative SE. The overall mean $(gh)_{20}$ is 2.4696 $m^2 s^{-2}$, the SD is 0.0028 $m^2 s^{-2}$, the SE (for $n = 151$) is 0.00023 $m^2 s^{-2}$ and the relative SE is 9.3×10^{-5} or 0.0093%.

Neither g nor h needs to be known separately. Rather, the product (gh) is determined from measured DP and calculated density of water. However, the value of the effective separation of the bubbler probe tips can be determined from (gh) if the acceleration of gravity at the location at which the measurements are made is known. At the location of the tank, the value of g is known to be 9.79547 m s^{-2}. The value of h is then 0.2521 m, which is near the design value 0.254 m.

In the use of the system to determine the densities of other liquids, nitric acid solutions in the present case, the overall mean $(gh)_{20}$ would be used. Since $(gh)_{20}$ corresponds to a temperature of 20 °C, a correction for the expansion or contraction of the probes will be made when the system is used at other temperatures. An equation of the form of Eq. 4 with $(gh)_{20}$ and $(gh)_t$, and 20 and t, interchanged would be used to make the correction.

In the same tank, the probes were immersed in nominal 2% nitric acid solutions. Thus, the value of $(gh)_{20}$ determined with water could be used to determine the density of the acid solutions by using an equation of the form of Eq. 2. Four runs were made with acid solutions in the tank. The data for the four runs are listed in Tables 5 through 8. The tables list the temperature of the solution, in °C; the DP across the probes, in Pa; (gh) at the temperature of the solution, in $m^2 s^{-2}$; the density of the solution at its temperature, in kg m^{-3}; and the density of the solution at the reference temperature, 20 °C, in kg m^{-3}. Also included in each table is the mean density at the reference temperature ρ_{20}, the SD, the SE and the relative SE.

The density at the reference temperature, ρ_{20}, was calculated by using the equation:

$$\rho_{20} = \rho_t[1 + \beta(20 - t)] \qquad (5)$$

where $\beta = -0.262$ kg m^{-3} $(°C)^{-1}$ is the change in density with temperature in the temperature range 20 to 25 °C. This value of β was calculated from values of ρ_t listed in the International Critical Tables.[3]

RESULTS

The data for the water runs used to determine $(gh)_{20}$ resulted in an overall mean $(gh)_{20}$, for 151 determinations, of 2.4696 $m^2 s^{-2}$. The SD was 0.0028 $m^2 s^{-2}$, the SE was 0.00023 $m^2 s^{-2}$ and the relative SE was 9.3×10^{-5} or 0.0093%.

The data for the four runs in nominal 2% nitric acid solutions resulted in a mean ρ_{20} for each of the four separate runs. For Run No. 1, the mean ρ_{20} for 30 determinations was 1009.81 kg m^{-3}; for Run No. 2, the mean ρ_{20} for 28 determinations was 1009.91 kg m^{-3}; for Run No. 3, the mean ρ_{20} for 27 determinations was 1010.27 kg m^{-3}; and for Run No. 4, for 26 determinations it was 1010.26 kg m^{-3}. The corresponding values of the relative SE were 0.011%, 0.012%, 0.0099% and 0.0073%, respectively.

CONCLUSIONS

The in-tank determination of solution density obtained by using bubbler probes and a precise and accurate differential pressure measuring system has again been shown to be very precise, with a relative SE for the determination of the density for 2% nitric acid solutions in the vicinity of 0.01%. The data were gathered during tank volume calibrations. The density determining system was thus not optimized, particularly in terms of the number of determinations made and the treatment of the data. Perhaps better precision might be attained for an optimized system; however, a primary limiting factor is the capability of the differential pressure measuring system.

REFERENCES

1. Jones F.E., Schoonover R.M., Houser J.F. "In-Tank Measurement of Solution Density," *J. Res. Nat. Bur. Stand. (U.S.)* 85:219-221 (1980).
2. Jones F.E. "Density of Water for Tank Volume Calibration," *JNMM* 18:26-27 (1990).
3. *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* New York: McGraw-Hill Book Co., 1928, Vol. 3, p. 58.

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 volume calibration at the Savannah River Site, as well as many other tank volume calibrations. He also performed definitive in-tank determinations of solution density. He served as deputy office chief in the NBS Nuclear Safeguards Progam, has authored more than 70 technical papers, has authored one book and has three others in progress, 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 is a consultant to the writing group for American National Standard ANSI N15.19, "Volume Calibration Techniques for Nuclear Material Control."

Table 1
Data for Run No. 1 in Water

Temp. °C	DP Pa	ρ, H_2O kg m^{-3}	$(gh)_{20}$ m^2s^{-2}
19.4	2467.6	998.3362	2.4717
19.7	2468.3	998.2763	2.4726
19.6	2465.9	998.2964	2.4701
19.7	2469.4	998.2763	2.4737
19.7	2461.4	998.2763	2.4657
19.7	2465.2	998.2763	2.4695
19.7	2465.9	998.2763	2.4702
19.7	2468.0	998.2763	2.4723
19.7	2469.7	998.2763	2.4740
19.7	2464.2	998.2763	2.4685
19.7	2468.3	998.2763	2.4726
19.7	2469.0	998.2763	2.4733
19.7	2465.2	998.2763	2.4695
19.7	2467.6	998.2763	2.4719
19.7	2466.2	998.2763	2.4705
19.7	2466.9	998.7263	2.4712
19.7	2467.3	998.2763	2.4716
19.7	2466.9	998.2763	2.4712
19.7	2463.2	998.2763	2.4675
19.7	2462.8	998.2763	2.4671
19.7	2466.2	998.2763	2.4705
19.7	2464.5	998.2763	2.4688
19.7	2464.9	998.2763	2.4692
19.7	2462.5	998.2763	2.4668
19.7	2460.4	998.2763	2.4646
19.7	2459.7	998.2763	2.4639
19.7	2464.9	998.2763	2.4692
19.7	2464.5	998.2763	2.4688
19.7	2466.6	998.2763	2.4709
19.7	2462.8	998.2763	2.4671
19.7	2464.9	998.2763	2.4692
19.7	2465.2	998.2763	2.4695
19.7	2464.5	998.2763	2.4688
19.7	2465.2	998.2763	2.4695
19.7	2464.2	998.2763	2.4685
19.7	2463.8	998.2763	2.4681

$\overline{(gh)}_{20}$ = 2.4697 m^2s^{-2}
SD = 0.0024 m^2s^{-2}
SE = 0.00040 m^2s^{-2}
Relative SE = 0.016%

Table 2
Data for Run No. 2 in Water

Temp. °C	DP Pa	ρ, H_2O kg m^{-3}	$(gh)_{20}$ m^2s^{-2}
19.6	2469.7	998.2964	2.4739
19.8	2469.0	998.2560	2.4733
19.8	2464.5	998.2560	2.4688
19.8	2466.6	998.2560	2.4709
19.8	2465.2	998.2560	2.4695
19.8	2471.4	998.2560	2.4757
19.8	2468.7	998.2560	2.4730
19.8	2469.0	998.2560	2.4733
19.8	2466.9	998.2560	2.4703
19.8	2467.6	998.2560	2.4719
19.9	2465.9	998.2357	2.4703
19.8	2470.7	998.2560	2.4750
19.8	2465.9	998.2560	2.4702
19.9	2468.7	998.2357	2.4731
19.9	2466.9	998.2357	2.4713
19.9	2467.3	998.2357	2.4717
19.9	2465.9	998.2357	2.4703
20.0	2467.3	998.2152	2.4717
20.1	2466.6	998.1947	2.4711
20.1	2463.5	998.1947	2.4680
20.2	2462.5	998.1740	2.4670
20.2	2466.6	998.1740	2.4711
20.2	2462.5	998.1740	2.4670
20.2	2462.5	998.1740	2.4670
20.2	2463.5	998.1740	2.4680
20.2	2462.8	998.1740	2.4673
20.3	2463.8	998.1531	2.4684
20.3	2463.8	998.1531	2.4684
20.3	2459.4	998.1531	2.4640
20.3	2458.7	998.1531	2.4632
20.3	2460.7	998.1531	2.4653
20.3	2459.4	998.1531	2.4640
20.3	2462.5	998.1531	2.4671
20.4	2460.7	998.1322	2.4653
20.4	2465.9	998.1322	2.4705
20.4	2463.5	998.1322	2.4681
20.4	2463.8	998.1322	2.4684
20.4	2465.9	998.1322	2.4705
20.4	2460.7	998.1322	2.4653
20.4	2464.2	998.1322	2.4688

$\overline{(gh)}_{20}$ = 2.4694 m^2s^{-2}
SD = 0.0031 m^2s^{-2}
SE = 0.00048 m^2s^{-2}
Relative SE = 0.020%

Table 3
Data for Run No. 3 in Water

Temp. °C	DP Pa	ρ, H_2O kg m^{-3}	$(gh)_{20}$ $m^2 s^{-2}$
20.1	2465.6	998.1947	2.4701
20.4	2467.6	998.1322	2.4722
20.5	2468.0	998.1111	2.4727
20.5	2460.4	998.1111	2.4651
20.4	2469.4	998:1322	2.4740
20.5	2465.6	998.1111	2.4703
20.5	2469.4	998.1111	2.4741
20.4	2468.7	998.1322	2.4733
20.4	2467.3	998.1322	2.4719
20.4	2469.0	998.1322	2.4736
20.4	2466.6	998.1322	2.4712
20.4	2467.3	998.1322	2.4719
20.4	2468.3	998.1322	2.4729
20.4	2466.9	998.1322	2.4715
20.4	2468.7	998.1322	2.4733
20.4	2467.6	998.1322	2.4722
20.4	2468.0	998.1322	2.4726
20.4	2462.5	998.1322	2.4761
20.4	2462.8	998.1322	2.4674
20.4	2466.3	998.1322	2.4709
20.4	2465.2	998.1322	2.4698
20.4	2466.9	998.1322	2.4715
20.4	2466.9	998.1322	2.4715
20.4	2468.0	998.1322	2.4726
20.4	2466.6	998.1322	2.4712
20.4	2468.3	998.1322	2.4729
20.4	2464.2	998.1322	2.4688
20.4	2464.2	998.1322	2.4688
20.4	2465.2	998.1322	2.4698
20.4	2461.1	998.1322	2.4657
20.4	2458.3	998.1322	2.4629
20.4	2461.4	998.1322	2.4660
20.4	2461.8	998.1322	2.4664
20.3	2462.1	998.1531	2.4667
20.3	2460.7	998.1531	2.4653
20.3	2463.2	998.1531	2.4678
20.3	2463.8	998.1531	2.4684
20.3	2464.9	998.1531	2.4695
20.3	2461.4	998.1531	2.4660
20.3	2461.8	998.1531	2.4664
20.3	2463.5	998.1531	2.4681
20.3	2461.4	998.1531	2.4660
20.4	2459.0	998.1322	2.4636
20.3	2466.9	998.1531	2.4715
20.4	2467.3	998.1322	2.4719

$\overline{(gh)_{20}}$ = 2.4699 $m^2 s^{-2}$
SD = 0.0032 $m^2 s^{-2}$
SE = 0.00047 $m^2 s^{-2}$
Relative SE = 0.019%

Table 4
Data for Run No. 4 in Water

Temp. °C	DP Pa	ρ, H_2O kg m^{-3}	$(gh)_{20}$ $m^2 s^{-2}$
20.7	2461.8	998.0686	2.4666
20.6	2463.5	998.0899	2.4682
20.6	2466.9	998.0899	2.4716
20.6	2464.9	998.0899	2.4696
20.4	2466.6	998.1322	2.4712
20.8	2467.3	998.0472	2.4721
20.8	2466.9	998.0472	2.4717
20.8	2465.6	998.0472	2.4704
20.9	2463.8	998.0257	2.4684
20.8	2463.5	998.0472	2.4683
20.8	2466.9	998.0472	2.4717
20.8	2465.2	998.0472	2.4700
20.8	2466.6	998.0472	2.4714
20.9	2465.9	998.0257	2.4708
20.9	2460.1	998.0257	2.4650
20.9	2461.4	998.0257	2.4663
20.9	2465.9	998.0257	2.4708
20.9	2461.4	998.0257	2.4663
20.9	2463.8	998.0257	2.4687
20.9	2461.4	998.0257	2.4663
20.9	2463.8	998.0257	2.4687
21.0	2461.1	998.0040	2.4660
21.0	2460.7	998.0040	2.4656
21.0	2464.2	998.0040	2.4691
21.0	2464.5	998.0040	2.4694
21.0	2465.2	998.0040	2.4701
21.0	2461.8	998.0040	2.4667
21.0	2464.5	998.0040	2.4694

$\overline{(gh)_{20}}$ = 2.4691 $m^2 s^{-2}$
SD = 0.0021 $m^2 s^{-2}$
SE = 0.00039 $m^2 s^{-2}$
Relative SE = 0.016%

Table 5
Data for Run No. 1 in Acid Solution

Temp. °C	DP Pa	$(gh)_t$ $m^2 s^{-2}$	ρ_t kg m^{-3}	ρ_{20} kg m^{-3}
22.24	2491.4	2.4697	1008.8	1009.4
22.43	2492.8	2.4697	1009.4	1010.0
22.45	2493.8	2.4697	1009.8	1010.4
22.47	2494.9	2.4697	1010.2	1010.9
22.49	2493.8	2.4697	1009.8	1010.5
22.55	2495.2	2.4697	1010.3	1011.0
22.56	2494.9	2.4697	1010.2	1010.9
22.56	2493.5	2.4697	1009.6	1010.3
22.56	2491.4	2.4697	1008.8	1009.5
22.56	2492.8	2.4697	1009.4	1010.1
22.54	2493.1	2.4697	1009.5	1010.2
20.74	2494.5	2.4696	1010.1	1010.3
20.77	2491.8	2.4696	1009.0	1009.2
20.77	2493.5	2.4696	1009.7	1009.9
20.75	2490.7	2.4696	1008.5	1008.7
20.75	2493.8	2.4696	1009.8	1010.0
20.68	2492.1	2.4696	1009.1	1009.3
20.68	2491.8	2.4696	1009.0	1009.2
20.67	2494.5	2.4696	1010.1	1010.3
20.66	2492.1	2.4696	1009.1	1009.2
20.64	2493.5	2.4696	1009.7	1009.8
20.62	2492.5	2.4696	1009.3	1009.4
20.61	2494.5	2.4696	1010.1	1010.2
20.56	2492.8	2.4696	1009.4	1009.5
20.55	2492.1	2.4696	1009.1	1009.2
20.54	2492.8	2.4696	1009.4	1009.5
20.53	2491.4	2.4696	1008.8	1008.9
20.51	2493.5	2.4696	1009.7	1009.8
20.50	2491.4	2.4696	1008.8	1008.9
20.49	2493.8	2.4696	1009.8	1009.9

$\overline{\rho_{20}}$ = 1009.81 kg m^{-3}
SD = 0.62 kg m^{-3}
SE = 0.11 kg m^{-3}
Relative SE = 0.011%

Table 6
Data for Run No. 2 in Acid Solution

Temp. °C	DP Pa	$(gh)_t$ $m^2 s^{-2}$	ρ_t kg m^{-3}	ρ_{20} kg m^{-3}
20.34	2495.9	2.4696	1010.6	1010.7
20.34	2495.9	2.4696	1010.6	1010.7
20.34	2496.2	2.4696	1010.9	1011.0
20.34	2496.6	2.4696	1010.9	1011.0
20.34	2496.2	2.4696	1010.8	1010.9
20.35	2494.5	2.4696	1010.1	1010.2
20.37	2494.9	2.4696	1010.2	1010.3
20.36	2495.9	2.4696	1010.6	1010.7
20.37	2496.9	2.4696	1011.1	1011.2
20.36	2492.8	2.4696	1009.4	1009.5
20.37	2492.8	2.4696	1009.4	1009.5
20.38	2493.5	2.4696	1009.7	1009.8
20.40	2491.1	2.4696	1008.7	1008.8
20.41	2492.8	2.4696	1009.4	1009.5
20.41	2492.5	2.4696	1009.2	1009.3
20.42	2492.8	2.4696	1009.4	1009.5
20.43	2492.8	2.4696	1009.4	1009.5
20.44	2492.5	2.4696	1009.2	1009.3
20.44	2492.8	2.4696	1009.4	1009.5
20.44	2492.8	2.4696	1009.4	1009.5
20.44	2494.2	2.4696	1009.9	1010.0
20.44	2493.5	2.4696	1009.7	1009.8
20.44	2491.4	2.4696	1008.8	1008.9
20.45	2493.1	2.4696	1009.5	1009.6
20.45	2492.8	2.4696	1009.4	1009.5
20.47	2494.2	2.4696	1009.9	1010.0
20.47	2493.1	2.4696	1009.5	1009.6
20.47	2493.8	2.4696	1009.8	1009.9

$\overline{\rho_{20}}$ = 1009.91 kg m^{-3}
SD = 0.65 kg m^{-3}
SE = 0.12 kg m^{-3}
Relative SE = 0.012%

Table 7
Data for Run No. 3 in Acid Solution

Temp. °C	DP Pa	$(gh)_t$ $m^2 s^{-2}$	ρ_t kg m^{-3}	ρ_{20} kg m^{-3}
20.66	2497.3	2.4696	1011.2	1011.4
20.66	2493.8	2.4696	1009.8	1010.0
20.59	2494.9	2.4696	1010.2	1010.4
20.58	2494.5	2.4696	1010.1	1010.2
20.56	2495.6	2.4696	1010.5	1010.7
20.55	2496.6	2.4696	1010.9	1011.0
20.53	2495.9	2.4696	1010.6	1010.7
20.52	2495.6	2.4696	1010.5	1010.7
20.51	2496.2	2.4696	1010.8	1010.9
20.52	2493.5	2.4696	1009.6	1009.7
20.54	2496.6	2.4696	1010.9	1011.0
20.53	2495.9	2.4696	1010.6	1010.7
20.53	2493.8	2.4696	1009.8	1009.9
20.53	2496.6	2.4696	1010.9	1011.0
20.52	2493.1	2.4696	1009.5	1009.6
20.53	2493.1	2.4696	1009.5	1009.6
20.53	2493.5	2.4696	1009.6	1009.7
20.54	2493.1	2.4696	1009.5	1009.6
20.56	2493.8	2.4696	1009.8	2009.9
20.58	2493.8	2.4696	1009.8	1010.0
20.62	2493.5	2.4696	1009.7	1009.9
20.63	2494.9	2.4696	1010.2	1010.4
20.65	2493.8	2.4696	1009.8	1010.0
20.66	2494.2	2.4696	1010.0	1010.2
20.67	2493.8	2.4696	1009.8	1010.0
20.69	2493.8	2.4696	1009.8	1010.0
20.75	2494.2	2.4696	1010.0	1010.2

$\overline{\rho_{20}}$ = 1010.27 kg m^{-3}
SD = 0.52 kg m^{-3}
SE = 0.10 kg m^{-3}
Relative SE = 0.0099%

Table 8
Data for Run No. 4 in Acid Solution

Temp. °C	DP Pa	$(gh)_t$ $m^2 s^{-2}$	ρ_t kg m^{-3}	ρ_{20} kg m^{-3}
21.19	2495.2	2.4696	1010.4	1010.7
21.16	2496.2	2.4696	1010.8	1011.2
21.16	2495.2	2.4696	1010.4	1010.7
21.11	2495.2	2.4696	1010.4	1010.6
21.10	2495.6	2.4696	1010.5	1010.8
21.25	2495.2	2.4696	1010.4	1010.7
21.29	2494.5	2.4697	1010.0	1010.5
21.35	2494.9	2.4697	1010.2	1010.6
21.33	2494.5	2.4697	1010.1	1010.5
21.33	2493.8	2.4697	1009.8	1010.2
21.35	2493.5	2.4697	1009.6	1010.0
21.37	2494.2	2.4697	1009.9	1010.3
21.70	2492.8	2.4697	1009.4	1009.9
21.72	2492.8	2.4697	1009.4	1009.9
21.72	2492.8	2.4697	1009.4	1009.9
21.74	2493.1	2.4697	1009.5	1010.0
21.75	2493.8	2.4697	1009.8	1010.3
21.76	2493.1	2.4697	1009.5	1010.0
21.72	2493.1	2.4697	1009.5	1010.0
21.70	2493.1	2.4697	1009.5	1010.0
21.74	2493.5	2.4697	1009.6	1010.1
21.77	2493.1	2.4697	1009.5	1010.0
21.77	2492.1	2.4697	1009.1	1009.6
21.77	2493.1	2.4697	1009.5	1010.0
21.75	2493.1	2.4697	1009.5	1010.0
21.73	2493.8	2.4697	1009.8	1010.3

$\overline{\rho_{20}}$ = 1010.26 kg m^{-3}
SD = 0.37 kg m^{-3}
SE = 0.073 kg m^{-3}
Relative SE = 0.0073%

New Pump-Out System for Drum Compactors

Hazardous and other liquids squeezed out during compaction of materials within a drum can safely be removed by a new pump-out system from S&G Enterprises.

Commonly compacted materials include filters, cleaning rags, bottles, cans, absorbent papers and so forth. In some cases, up to one-third of a drum's volume may be filled with liquid.

The system automatically removes such liquids, increasing the drum's storage capacity and reducing ultimate disposal costs.

In operation, as the hydraulic ram shaft descends for compaction, liquids squeezed out of the material flow upward, onto the compaction head.

Removal ports in the compaction head collect the liquids, which are then pumped out of the drum through the hydraulic shaft for disposal or treatment. The compactor can be used with the pump-out system turned on or off.

The pump-out system is available on all Ram Flat (R) compactors as an option. Ram Flat models are designed to compact materials within an 85 gallon drum or smaller.

For details about the Ram Flat pump-out system, write for Bulletin RFPO 791, Lorin Griffith, S&G Enterprises, 5626 N. 91st St., Milwaukee, WI 53225, phone (800) 233-3721.

DES Encryption Available for Vindicator Monitor and Control Systems

Vindicator Corp. has announced the availability of the company's new DES-Net family of transponders and gateways which provide data encryption in accordance with the Data Encryption Standard (DES) as defined by the National Institute of Standards and Technology. Like the high performance UHS-Net series, the DES-Net series will provide alarm annunciation for eight sensors and control four relays per transponder. Up to 250 transponders can be linked on a single network in order to monitor thousands of alarms. All the standard features of UHS-Net are available in the DES-Net series such as redundant communications, distributed polling, automatic sensor self-test and high reliability.

Each device uses DES in the cipher feedback mode and is consistent with Federal Information Processing Standards (FIPS) 46-1 and 81. When combined with Vindicator Monitor and Control Unit and appropriate sensors, the entire electronic security system can meet the Class A line security requirements.

For information write Vindicator, 3001 Bee Cave Rd., City of Rollingwood, Austin, TX 78746, phone (512) 328-8080.

Local Area Networks for Nuclear Spectroscopy

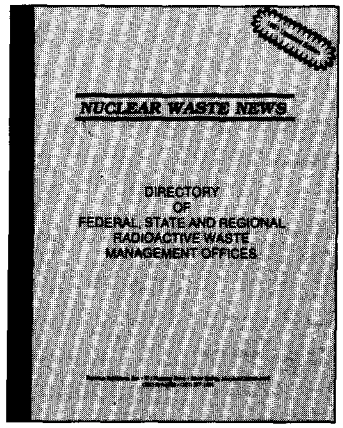
Local Area Network (LAN) capability is a part of MAESTRO for Windows 3 (Version 2) Multichannel Analyzer software from EG&G Ortec. When MAESTRO V2 is installed along with the optional MCB Gateway software in a standard NetBIOS environment (such as Novell or DEC Pathworks Ethernet), spectra can be seamlessly stored from workstations onto a secure central disk or file server.

Applications include the integration of medium to large laboratory installations to provide integrated data archiving, and add autonomous "intelligent nodes" to existing VAX installations. Its remote-control-with-live-display feature provides an excellent solution to remote measurements such as for primary coolant, waste container, stack and post-accident monitoring.

Remote control and live spectral display over the network allows a workstation to simultaneously control up to 20 local and remote detector systems. Restricted file access, password protection and user log-in records are readily available.

Installation with existing LANS and DEC VAX systems is easily achieved.

Call the HOTLINE, (800) 251-9750, or the local EG&G Ortec representative for a data sheet and more information.



Directory of Radioactive Waste Offices Published

Business Publishers, Inc., publishers of *Nuclear Waste News*, is now offering a reference book, "The Directory of Federal, State and Regional Radioactive Waste Offices."

The Directory includes more than 600 names, addresses and phone numbers of radioactive waste officials at all government levels.

Included are the Department of Energy, Nuclear Regulatory Commission, Environmental Protection Agency, Department of Transportation, regional low-level radioactive waste boards and state administrations.

The Directory is $28.95 and can be purchased by contacting Kathleen Harrow at (301) 587-5103 or writing to Nuclear Waste Directory c/o Business Publishers, 951 Pershing Dr., Silver Spring, MD 20910.

March 1 – 5, 1992
Waste Management '92, Tuscon, Ariz. *Sponsor:* University of Arizona, U.S. DOE, American Nuclear Society, ASME. *Contact:* Technical Program Chair Morton E. Wacks, College of Engineering and Mines, Bldg. 20, University of Arizona, Tuscon, AR 85721, phone (602) 621-6160.

March 2 – 6, 1992
Pathway Analysis and Risk Assessment for Environmental Compliance and Dose Reconstruction — The Second Course. *Sponsor:* Radiological Assessments Corp. *Contact:* CAPS Ltd., 1715 North Wells, #34, Chicago, IL 60614, phone (312) 988-7667.

March 9 – 13, 1992
Gamma Spectroscopy *Sponsor:* Oak Ridge Associated Universities Professional Training Programs. *Contact:* Registrar, Professional Training Programs, ORAU, P.O. Box 117, Oak Ridge, TN 37831-0117, phone (615) 576-3576.

March 15 - 18, 1992
Safeguards and Security: Threats, Consequences and Performance Workshop. *Sponsor:* INMM. *Contact:* Laura Rainey, INMM headquarters, phone (708) 480-9573.

March 22 – 25, 1992
Fuel Cycle Conference 92, OMNI Charleston, Charleston, S.C. *Sponsor:* U.S. Council for Energy Awareness *Contact:* Conference Office, U.S. Council for Energy Awareness, 1776 I St., N.W., Suite 400, Washington, D.C. 20006-3708, phone (202) 293-0770.

April 8 – 10, 1992
Japan Atomic Industrial Forum 25th Annual Conference, Yokohama, Japan. *Sponsor:* Japan Atomic Industrial Forum. *Contact:* Department of Planning and International Affairs, Japan Atomic Industrial Forum Inc., 1-1-13 Shimbashi, Minato-ku, Tokyo 105, Japan, phone 03-3508-2411.

April 12 - 16, 1992
International High Level Radioactive Waste Management Conference, Mirage Hotel, Las Vegas, Nev. *Sponsor:* American Nuclear Society, American Society of Civil Engineers *Contact:* George L. De Feis, Secretariat, phone (212) 705-7290.

May 11 – 14, 1992
1992 Incineration Conference (11th Annual), Hyatt Regency Hotel, Albuquerque Hotel, Albuquerque, N.M. *Sponsor:* University of California, Irvine, Cosponsored by the U.S. DOE, U.S. EPA, ASME, AICHE, AWMA, ANS, CRWI, HPS in cooperation with IAEA. *Contact:* C. Baker, analyst, University of California, EH&S, Irvine, CA 92717, phone (714) 856-7066.

June 7 – 12, 1992
1992 ANS Annual Meeting, Boston Marriott, Boston. *Sponsor:* American Nuclear Society. *Contact:* General Chair Andrew J. Kadak, Yankee Atomic Electric Co., 580 Main St., Boston, MA 01740-1398, phone (508) 779-6711.

July 19 – 22, 1992
INMM's 33rd Annual Meeting, Orlando, Fla. *Sponsor:* Institute of Nuclear Materials Management. *Contact:* Barbara Scott, INMM headquarters, phone (708) 480-9573.

September 13 – 18, 1992
PATRAM '92, the 10th International Symposium on the Packaging and Transportation of Radioactive Materials, Pacific Convention Plaza, Yokohama, Japan *Sponsor:* PATRAM '92 Organizing Committee, Science and Technology Agency, Ministry of Transport, International Atomic Energy Agency, U.S. Department of Energy. *Contact:* Nuclear Safety Technology Center, 5-1-3 Hakusan, Bunkyo-kui, Tokyo 112, Japan, phone 81-03-3814-7480.

ADVERTISER INDEX

Clark Joins Johnson

James Clark

As of Nov. 15, 1991, James Clark joined E.R. Johnson Associates, Inc. (JAI), Oakton, Va., as vice president in charge of JAI's participation as a subcontractor to TRW in the Department of Energy's Office of Civilian Radioactive Waste Management and Operations Contract. Before joining JAI Clark was senior vice president of Nuclear Fuel Services Inc. of Rockville, Md. and Erwin, Tenn. Clark served Nuclear Fuel Services in various capacities from 1966 until joining JAI.

The Institute of Nuclear Materials Management Organizational Chart appearing on the back of this sheet and the list of volunteer leaders and staff below include corrections and amendments to the list and chart beginning on page six of this issue of the *Journal of Nuclear Materials Management.* Use this reference guide to identify areas in which you would like to participate, and then contact the appropriate INMM volunteer or headquarters staff person.

Executive Committee

Officers

Chairman — Darryl Smith, Los Alamos National Laboratory, (505) 667-6394

Vice Chairman — Dennis Mangan, Sandia National Laboratories, (505) 845-8710

Secretary — Vincent J. DeVito, Consultant, (614) 947-5213

Treasurer — Robert U. Curl, EG&G Idaho Inc., (208) 526-2823

Members-at-Large

Obie Amacker, Pacific Northwest Laboratory, (509) 376-2819

Patricia Baird, Martin Marietta Energy Systems Inc., (615) 574-5343

Joseph Indusi, Brookhaven National Laboratory, (516) 282-2975

John Lemming, EG&G Mound Applied Technologies, (513) 865-3689

Elizabeth Ten Eyck, U.S. Nuclear Regulatory Commission, (301) 492-3344

Committee Chairs

Annual Meeting Arrangements — Deanna Osowski, Westinghouse Hanford Co., (509) 376-4312

Exhibits — Open

Technical Program — Charles E. Pietri, U.S. Department of Energy, (708) 972-2449

Registration — Gary J. Carnival, EG&G Rocky Flats Inc., (303) 966-2403

Local Arrangements — Deanna Osowski, Westinghouse Hanford Co., (509) 376-4312

Bylaws & Constitution — Roy Cardwell, Consultant, (615) 986-7347

Fellows — Glenn Hammond, 21st Century Industries, Inc., (301) 253-3372

Awards — Yvonne Ferris, EG&G Rocky Flats Inc., (303) 966-4867

Communications — Laura Thomas, U.S. Department of Energy, (505) 845-4713

Journal Technical Editor — William Higinbotham, Brookhaven National Laboratory, (516) 282-2908

Government/Industry Liaison — John Matter, Sandia National Laboratories, (505) 845-8103

Long-Range Planning — Jim Tape, Los Alamos National Laboratory, (505) 667-6394

Membership — Charlie Vaughan, General Electric Co., (919) 675-5656

Professional Recognition — Paul Ebel, BE, Inc., (803)259-2346

Standards

N-14 — John W. Arendt, Oak Ridge Associated Universities, (615) 483-6622

N-15 — Sharon Jacobsen, Martin Marietta Energy Systems Inc., (615) 574-8707

Technical Divisions

Physical Protection — James D. Williams, Sandia National Laboratories, (505) 845-8766

Materials Control & Accounting — Rich Strittmatter, Los Alamos National Laboratory, (505) 667-7903

Transportation — Open

Waste Management — E. R. Johnson, E. R. Johnson Associates Inc., (703) 359-9355

Arms Control/Verification — Open

International Safeguards/Nuclear Non-Proliferation— Cecil Sonnier, Sandia National Laboratories, (505) 844-2124

Chapters

Central — Walter Strohm, EG&G Mound Applied Technologies, (513) 865-3462

Pacific Northwest — Brian Smith, Pacific Northwest Laboratory, (303) 966-6646

Southeast — Fran Davis, Westinghouse Savannah River Co., (803) 725-5009

Japan — Mitsuho Hirata, Japan Atomic Energy, (03) 593-2551

Vienna — Tom Shea, International Atomic Energy Agency, (011) 43-1-236000

Headquarters

Executive Director — Barbara Scott

Administrative Director — Laura Rainey

Accounting Services — Gloria Buzanis

INMM Journal Managing Editor — Greg Schultz

INMM Journal Associate Editors — Mary Dulabaum, James Rayball

INMM Headquarters
60 Revere Drive, Suite 500
Northbrook, Illinois 60062 USA
Tel: (708) 480-9573
Fax: (708) 480-9282

Institute of Nuclear Materials Management

Organization