IN THIS ISSUE

17th Annual Meeting, Institute of Nuclear Materials Management, Inc., Washington Plaza Hotel, Seattle, Wash., June 22-24, 1976.

INMM

NUCLEAR MATERIALS MANAGEMENT

VOL. V, NO. I

SPRING 1976

JOURNAL OF THE INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

NUCLEAR MATERIALS MANAGEMENT is published four times a year, three regular issues and a proceedings of the annual meeting of the Institute of Nuclear Materials Management, Inc. Official headquarters of INMM: Mr. V. J. DeVito, INMM Secretary, Goodyear Atomic Corp., P.O. Box 628, Piketon OH 45661.

Subscription rates: annual (domestic), $25; annual (foreign), $35; single copy of regular issues published in spring, summer and winter (domestic), $7; single copy of regular issue (foreign), $9; single copy of fall proceedings (domestic), $15; and single copy of proceedings (foreign), $25. Mail subscription requests to NUCLEAR MATERIALS MANAGEMENT, Journal of INMM, Seaton Hall, Kansas State University, Manhattan, KS 66506. Make checks payable to INMM, Inc.

Inquiries about distribution and delivery of **NUCLEAR MATERIALS MANAGEMENT** and requests for changes of address should be directed to the above address in Manhattan, Kan. Allow six weeks for a change of address to be implemented. Phone number of the I.N.M.M. Publications and Editorial Office: Area Code 913-532-5837.

Inquiries regarding INMM membership should be directed to Mr. V. J. DeVito, INMM Secretary, Goodyear Atomic Corp., P.O. Box 628, Piketon OH 45661.

Third-class postage paid at Manhattan, Kansas 66506.

Dr. Higinbotham

EDITORIAL

MATERIAL CONTROL

By W.A. Higinbotham

Back in 1968, safeguards measures were described under three headings: materials accountability, physical security, and surveillance. At that time there was little concern about attack by terrorists and most attention was paid to materials accounting as the method to detect diversion by those who might have access to the materials. Techniques for measuring dirty scrap and wastes were very poor or non-existent. As a consequence of this, emphasis was placed on development of non-destructive assay methods.

As it developed policies and requirements for safeguards at licensee facilities, the AEC Regulatory directorate expanded on the accounting and surveillance elements of safeguards. By-difference measurements and normal-operating-losses were replaced by measurements of all material flows and calculations of MUF and LEMUF. Recognizing that accounting, at least as practical then and now, can only detect diversion after-the-fact, Regulatory developed requirements for surveillance: admittance to material areas only to authorized personnel; assigned responsibility for custodianship; no transfers or operations on materials except as directed by responsible authorities; and establishment of a line organization responsible for materials accounting that is separate from line organizations responsible for production and finance.

As these requirements became part of the regulations in the Code of the Federal Register, the distinction between the accounting and the surveillance elements became blurred and mixed together under the heading, Material Control and Accounting (MC & A).

Even in those early days it was recognized that commercial shipments were very vulnerable to theft and hijacking. More recently, public concern has swung from internal diversion to external attack. The attention of the Government agencies has followed the public concerns, so that what is most discussed today is protection of plants and shipments against well armed robbers.

Actually, the threats have always been from external force, sneak thiefs, insiders, and various combinations thereof. Since no one can assign probabilities to the threats, safeguards systems should be designed to prevent all of them with a high degree of reliability. In order to do this, we need to make optimum use of the three system elements: accounting, material control, and physical protection. Furthermore, there are the activities relating to safety and radiation protection and prudent industrial good practice, all of which should contribute to better protection of the nuclear materials.

In my opinion, properly designed safeguards systems for facilities and for shipments can be made to be very effective and very credible. This does require that all of the available safeguards techniques and methods be intelligently applied and coordinated with each other.

This brings me to appeal to the members of INMM, to look at this issue of the Journal, to note that the papers do not begin to be balanced in terms of the fields outlined above or in terms of what safeguards measures are needed for prompt detection and prevention and those needed by NRC or the IAEA to provide public assurance, after-the-fact, that the systems are indeed well designed and diligently carried out.

We need your help to correct this imbalance.

FUTURE PLANS COMMITTEE REPORT

A common item found in all professional societies is a periodic publication. The Institute has progressed from a newsletter to the present professional Journal. Our Journal compares favorably with those of many societies. A review of the content of other journals gives a clue as to what we might include to expand our journal. Among these are book reviews and a reader information service that could include information on such things as Federal Register notices of interest, Regulatory Guides published and possibly comments thereon, industry news, and personnel news. **Tom Gerdis** has included some of these items. The most recent issue had a book review and several notes of industry and personnel news. More of this type item along with more technical reports is needed.

Many societies publish reports and monographs other than their periodic journals. The Institute did one such report. There must be others. We took on transportation. How about NRC ratcheting, effectiveness of safeguards system implementation, or how effective are safeguard systems. Technical monographs different from N-15 standards or Regulatory Guides should be considered.

Expansion of the Journal and undertaking additional publications cannot be done with the present publication arrangement. These additional efforts will require time to dig for information, to beat the bushes for topics and articles whether for the Journal or for monographs. Tom cannot afford that time under the present part-time situation. It is recommended that the Executive Committee consider an expanded publication effort, even to the extent of a full-time paid staff. This would undoubtedly cost more and may require raising the dues. It may well be worth it.

A second item found common to today's professional societies is the annual meetings. The Institute has been most successful in this regard. The committee has little to offer that has not already been discussed. The annual meeting is in good hands. So far as other meetings, such as regional or topical, these too have been discussed. There does not appear to be an overwhelming demand for these as yet. Again this effort has been considered and is in good hands. No recommendation is offered except perhaps a caution that such meetings should be considered only if there is an obvious demand and need for them.

In this same general area is the question of chapters, especially foreign chapters. We should consider carefully why we need or want foreign chapters. Who would benefit? Who would support them? More members? Perhaps, but to what purpose? Surely we are motivated by something more than "bigger is better." In discussing some other professional societies, the problem voiced by some of their members was, "It's too big—I don't feel a part of it and wonder why I belong."

The Institute is not at a point yet where we are going to be accused of being too big. We do need to make an effort to make the members feel that they are a part of the Institute. Perhaps this can be the purpose of regional and foreign chapters.

Another major area of effort in many societies is the education program. The Institute has successfully sponsored two rounds of safeguards schools at Argonne. There have been mixed reports on these schools as to their usefulness and effectiveness in safeguards training. They have made a profit for the Institute but is that our purpose? Is it not our purpose to promote nuclear materials management as a profession? To provide professional level information and training to the members and others who need or want it? Many societies have educational programs which are structured and operated so as to qualify for granting Continuing Education Units (CEU) for the successful completion of courses given. The CEU is a means of measurement of standardized recognition of individual participation in noncredit continuing education as evidence of the maintenance or improvement of professional growth. This seems to be an appropriate goal for the purpose. The units may be awarded by any organization, including professional societies, willing and able to sponsor and establish an ongoing educational program meeting the administrative and educational criteria. These criteria include responsible sponsorship, capable program direction, qualified instruction, performance requirements with means of measuring satisfactory compliance, and continuing program evaluation. It would seem appropriate for the Institute to undertake such a program possibly oriented toward Nuclear Materials Manager Certification.

It is recommended that the Institute Education Committee be expanded, reconstituted or otherwise modified to include representatives from the academic world who can guide the education program toward an ultimate goal of attaining Continuing Education Unit status. This probably should include hiring a consultant rather than depending on volunteers. Attached with this report is a publication of the National University Extension Association, "The Continuing Education Unit, Criteria and Guidelines," prepared by the National Task Force on the Continuing Education Unit. This report can provide the detailed criteria and guidelines for the Institute's education program.

There are two other major areas of effort in which the Institute can enhance its image and serve its members. These are the Nuclear Materials Manager Certification Program and the INMM N-15 Standards Committee work. No recommendations are made in these areas. They are in good hands.

Other areas noted in other societies that will be mentioned in passing are insurance programs, society jewelry and emblems, travel programs, and employment services. It is recommended that the Institute not become involved in such as these at this time.

In summary it is concluded that the Institute has been doing something right. We have grown and progressed. We are not as large as some professional societies but there are those who believe we are more effective and useful than some of the bigger ones. The suggestions and recommendations of this report are intended to stimulate growth in quality—growth in numbers will follow.

THE INMM CHAIRMAN SPEAKS

Mr. Soucy

SEATTLE IN A TIME OF CRISIS

By Armand R. Soucy, Chairman
Institute of Nuclear Materials Management, Inc.

Of course, although the Institute's Annual Technical Meeting is the highlight of our yearly activities, it is only one of many areas in which the Institute is involved. As present members are well aware, INMM supports educational programs in the area of nuclear materials management, we develop standards in all areas of nuclear materials control, and we are in the process of expanding our certification program for nuclear materials managers. Additionally, we communicate with Regulatory officials on the problems of the regulations of nuclear materials, and we perform special studies on specific problems on safeguards. One major new current activity is our attempt to expand our participation in the area of public affairs.

Of critical importance in the performance of these tasks is the fact that we are a professional organization, and that we view the issues on safeguards from both a negative and a positive viewpoint.

As we meet in Seattle, therefore, in a time of crisis on the safeguards issue, it is well to remember our present and past accomplishments as an organization. We should also use this occasion to increase our determination to expand our contributions as an organization to the field of nuclear materials management. Never before has the Institute of Nuclear Materials Management had the financial stability, had more members, or been involved in so many activities. We are therefore in an excellent position to meet the present challenge and to proceed with the resolution of the complex issues of nuclear materials management.

Possibly the only secure statement that can be made on the safeguards issue as we meet for our 17th Annual Meeting is that the nuclear industry faces a crisis on the safeguards issue. Those of you who have been members of the Institute for several years can probably remember instances when it was difficult to arouse attention on the safeguards subject.

Unfortunately, one of the principal reasons why safeguards is a major problem for the nuclear industry today is that it was given only a secondary priority by the nuclear industry in past years.

Because of this past lack of awareness by the nuclear industry, of the potential problems which could develop from the safeguards issue, it now appears that the industry will have to pay dearly before the issues are resolved. These payments by the nuclear industry are not limited only to the actual cost of safeguarding nuclear materials but also to the delays in the reprocessing of depleted uranium and the recycling of plutonium.

The question which we should therefore ask ourselves as we meet in Seattle for the 17th Annual Meeting of the Institute of Nuclear Materials Management is **what can we, as a professional organization, do to resolve the** safeguards issue? It is my view that by supporting INMM we have taken an important step in contributing to the resolution of the safeguards issue. Secondly, after our New Orleans meeting last year, knowledgeable people in the industry recognize that if one wants to keep abreast of the developments in Nuclear Materials Management, he must attend the Institute's Annual Technical Meeting. By our attendance at the 17th Annual Meeting of the Institute, we have therefore taken another step in our individual efforts to resolve the safeguards problems.

Mr. Cardwell

DON'T MISS SEATTLE!

By Roy G. Cardwell
INMM Vice-Chairman

Having just returned from our Winter Executive Committee Meeting in Seattle, I am happy that we are about to go to press with our next Journal so that I can freshly relate to you some of the fine things that are happening in preparation for the most exciting Annual Meeting yet.

First, a big thank you should go to **Bill DeMerschman,** our Local Chairman, and to **Dick Parks.** Dick, who is with Seattle's Olympic Engineering Corporation, has kindly agreed to be Public Relations Chairman for the Annual Meeting and is already running well ahead in arrangements. As a big starter, the Executive Committee was greeted the morning of their second day with a full-blown press conference, including eight or ten reporters and a TV camera. The one-hour session starred DeMerschman, **Bob Keepin,** and **Fred Forscher,** and made the evening news broadcast. The press attending indicated more than a passing interest in the upcoming June meeting.

You will not be disappointed with Bill DeMerschman's selection of the Washington Plaza as our hotel. **Tom Hawley,** Manager of Sales, gave us an extensive tour, and I am pleased to report that we will have plenty of elbow room for the sessions and our other activities. The hotel is within short walking distance of downtown shopping and adjacent to the monorail train that will zoom you to the Space Needle in 40 seconds. We found service in the hotel to be excellent. Both Tom, and **Vicki Siegel,** the Convention Coordinator, are delightful people to work with.

Elsewhere in this issue, Program Chairman Bob Keepin will tell you about the excellent technical program to be expected, highlighted by keynoter Congressman **Mike McCormack.** Bob and I have given considerable thought to your various responses to the New Orleans questionnaire and have made a serious effort to provide more time for discussion as well as planned breaks. Because of this, running on schedule will be most important. If you are to be a Session Chairman, I admonish you to hold your speakers to their time limits.

And, of course, **we are all looking forward to our cruise across Puget Sound and dinner at Kiana Lodge. While we all enjoy steamed little-neck clams and clam nectar from their iron caldrons, we can watch them cook up fresh Neah Bay salmon over green adler coals in their massive barbecue pits.** For our added entertainment during the evening, we will "have music wherever we go" starting at our departure from the Seattle dock.

Don't miss Seattle! The hospitality of the folks up there is some of the greatest I have ever experienced. Bring the whole family for a vacation they will never forget!

Pre-registration packages will be mailed to you about May 1. Additional packages may be had by sending your requests to **Tom Gerdis,** our Editor.

Advertising Index

Mr. DeVito

INMM DUES NOW $20 PER ANNUM

By V.J. DeVito
Secretary of INMM

An executive meeting was held on February 25 and 26, 1976, in **Seattle, Washington,** at the Washington Plaza Hotel.

The financial statements reviewed by the Executive Committee showed that as of February 20, 1976, there was a cash balance of $9,998 in the checking account and $14,593 in the savings account.

The resignation of **Bill Gallagher,** Treasurer, was accepted and **Robert Curl** of Argonne-West was appointed as Treasurer for the balance of this fiscal year.

Jim Lee, Membership Chairman, reported that 57 new members had been processed to date this fiscal year. The INMM membership now totals 479.

The Executive Committee reviewed the hotels for the 18th annual meeting to be held in **Washington, D.C.,** the week of June 19, 1977. The Shoreham Hotel was selected. Albuquerque was approved as the site for the 20th annual meeting to be held in 1979. The site committee was asked to investigate **Gatlinburg** and **Chicago** for the 19th annual meeting in 1978.

The Executive Committee approved an increase in the single rate for annual proceedings, which will be $15 and $25 for domestic and foreign mailing, respectively. The Executive Committee also approved an increase in the annual dues, which will be $20 as of the fiscal year beginning July 1, 1976.

Manny Kanter reported that a total of 51 people attended the three INMM-sponsored safeguards courses in November. The next educational safeguards courses are contemplated for early fall of this year and tentatively are Chemical Assay, Advanced Statistics and Advanced Fundamentals of Nuclear Materials Control.

Tom Bowie reported on an INMM topical meeting held in Columbus attended by low enriched uranium fabricators. The meeting was well attended and the Executive Committee will determine whether a position paper is to be prepared and issued.

Fred Forscher *reported on certification, indicating that* the draft "American National Standard Criteria for the Certification of Nuclear Marerials Managers" was out for approval.

The next Executive Committee meetings will be held in conjunction with the annual meeting in Seattle, Washington, the week of June 20, 1976.

Dr. Keepin

OUTSTANDING PROGRAM, SPEAKERS, PANELISTS SET FOR INMM 1976 MEETING IN SEATTLE

By Dr. G. Robert Keepin, Chairman
INMM Annual Meeting Technical Program Committee

The Institute's Seventeenth Annual Meeting will open in Seattle, Washington, on Tuesday, June 22, 1976, with a Plenary Session of prominent invited speakers from government and industry. As keynoter this bicentennial year, we hope to have U.S. Congressman **Mike McCormack** (D-Wash), a dynamic and knowledgeable champion of nuclear power, to present his strong convictions on the progress and promise of nuclear power, as well as some of the broad policy aspects of nuclear safeguards on both the national and international levels.

The roster of distinguished invited speakers at Seattle includes **Richard W. Roberts,** Assistant Administrator for Nuclear Energy, U.S. ERDA; **Kenneth R. Chapman,** Director, Office of Nuclear Material Safety and Safeguards, U.S. NRC; **Frank P. Baranowski,** Director, Division of Nuclear Fuel Cycle and Production, U.S. ERDA; **Harvey E. Lyon,** Director, Division of Safeguards and Security, U.S. ERDA; and **Gene Schubert,** President, Allied-General Nuclear Services.

The Institute Paper will be presented this year by **Norman Rasmussen,** Chairman of the Nuclear Engineering Department, Massachusetts Institute of Technology. Professor Rasmussen is a veteran INMM member and an accomplished safeguards researcher in his own right. He will present a review of the basic methodology used in the now-famous "Rasmussen Study" on Reactor Safety (WASH-1400); he will then examine how certain features of his proven probabilistic methodology might be used in the quantitative assessment of nuclear safeguards risks. Also, as a "veteran from the front lines" of the nuclear power debate and controversy, Norm Rasmussen should have some good first-hand advice on how to handle those increasingly frequent confrontations with nuclear critics, the news media, "documentary" film makers, etc.

Mr. **Dean Worthington,** Senior Vice President of Pacific Gas and Electric Co., has been invited to give us the utilities' perspective on today's raging nuclear power controversy, with particular reference to the California Nuclear Power Plants initiative. Obviously the result of the California initiative—win, lose or draw—will be fresh in everyone's mind at Seattle, and its significance will be a matter of vital interest to us all; Mr. Worthington is following developments closely in this major issue, and he has agreed to give us his interpretation of the significance and portent of the June 8 vote—what it may mean for the future of nuclear power in California, and what it could imply for the nation.

The final invited speaker in the Plenary Session on Tuesday afternoon is **William Lanouette** of **The National Observer,** winner of the Atomic Industrial Forum's distinguished "Forum Award" in 1974 "for excellence in informing the public about peaceful uses of nuclear energy." All who were at the New Orleans meeting last June will recall that Bill Lanouette was a highly articulate and objective participant in the INMM Panel, "Safeguards, the Press and the Public." Mr. Lanouette —whose extensive journalism experience includes coverage of some of the major safeguards developments of the past several years—will share with us a seasoned journalist's view of the pivotal issues of nuclear power—safety, safeguards, proliferation, etc., as well as his own impressions of our growing Institute—its activities, opportunities and professional responsibilities in the expanding field of nuclear materials management, safeguards and control.

Wednesday afternoon, June 23, will feature a panel discussion by prominent industry and government experts on the timely topic, "The 'Back End' of the Fuel Cycle." **A. Eugene Schubert,** President of Allied-General Nuclear Services, will be panel moderator, and panelists will include **Raymond L. Dickeman,** President, Exxon Nuclear; **Kenneth R. Chapman,** Director, Office of Nuclear Material Safety and Safeguards, U.S. NRC; **Frank P. Baranowski,** Director, Division of Nuclear Fuel Cycle and Production, U.S. ERDA; **Paul J. DeBievre** of the European Commission (EEC), Central Bureau for Nuclear Measurements; and **Paul M. Dragoumis,** former Director of the FEA Nuclear Affairs Office, now Executive Director of the Nuclear Energy Subcommittee of President Ford's Energy Resources Council. We are indeed fortunate to have this outstanding group of panelists to address such a vital and timely topic which is clearly a matter of very special concern in the nuclear industry today.

A large number of contributed papers will be presented this year covering the many areas of INMM interest as set forth in the Call for Papers for the 17th An-

nual Meeting. Also this year at Seattle we anticipate significantly increased foreign attendance and participation; this is attributable in part to the increasing emphasis in many countries on more stringent safeguards and security, nuclear export controls, and mounting concerns over nuclear weapons proliferation. Thus, this past year has seen increasingly frequent contacts and interactions between INMM people and our professional counterparts in other countries. At the IAEA International Symposium on Safeguarding Nuclear Materials, held in Vienna last October, some 30 delegates from several European and Asian countries indicated considerable interest in the objectives and scope of activities of the Institute of Nuclear Materials Management. INMM officers and members attending the Vienna Symposium met with the interested foreign delegates and discussed the program and activities of the INMM, the possibility of forming future regional or international chapters of the Institute, and a number of technical topics of mutual professional concern. It seems abundantly clear that this type of direct person-to-person interaction and valuable technical exchange between INMM members and our professional colleagues abroad will inevitably result in increased foreign participation and interest in Institute activities, not only this year at Seattle, but increasingly so in the years to come.

In planning the Seattle meeting, the INMM Program Committee has made every effort to take into account your comments and suggestions in response to the questionnaire we distributed in New Orleans. Accordingly, at Seattle more time has been allocated for discussion of all papers—both invited and contributed; also there will be scheduled coffee breaks for those very valuable "hallway confabs," and all meeting rooms will be amply sized (without those large mirrored centerposts!) for the anticipated large attendance in June.

For more convenient travel scheduling to and from Seattle, particularly for those returning from Seattle to the eastern U.S., the Annual Meeting this year will be Tuesday through Thursday, rather than Wednesday through Friday as in the past. Accordingly, the American National Standards Institute (ANSI) committee meetings have been scheduled for Monday and Friday, June 21 and 25.

Our local arrangements chairman, **Bill DeMerschman** is doing an excellent job for us all on accommodations, logistical arrangements, entertainment, and the ladies' program (or should I say "spouses' program!"). For example, the Potlatch Salmon Barbecue on Wednesday evening, June 23, promises to be a real bell(y)-ringer, complete with 1½-hour boat trip across Puget Sound to the Kiana Lodge in the "Garden of the Gods" on the beautiful Olympic peninsula. Our INMM headquarters will be the spacious new Washington Plaza Hotel, conveniently located near Seattle's best restaurants, shopping, sightseeing, and the monorail to the space needle and the Seattle World's Fairgrounds.

In summary . . . this great bicentennial year for our nation is clearly proving to be also a year of critical decisions concerning nuclear power for our nation—decisions. in which some of the pivotal issues center around the specific areas of expertise which the INMM uniquely embodies. The challenge to our profession—and our professional organization, the INMM—is clear: this country's full realization of the promise of nuclear power could depend, in large measure, on how effectively we are able to safeguard, manage and control the strategic nuclear materials that fuel the nuclear power industry. Clearly the stakes are high, and considering the import and urgency of the issues—and the Institute's key professional role in them—the upcoming 1976 Annual Meeting in Seattle has got to be one of the most significant meetings the INMM has ever convened. Mindful of this challenge, your Program Committee has worked hard to put together a top-flight technical program that reflects the Institute's unique role and high standards of professionalism in the field of nuclear safeguards and materials management; now all we need is YOU!

So . . . make your plans now to be with us in Seattle next June 22-24 and help make this, our 1976 bicentennial-year meeting, the best in the Institute's history!

Mr. Jaech

N15 REPORT

WRITE, REVIEW STANDARDS

By John L. Jaech, Chairman

On several occasions in the past, you as an individual member of the INMM have been invited to participate in the development of ANSI standards. From a numbers viewpoint, the degree of participation has been outstanding with the ratio of individuals on standards-writing subcommittees to the total INMM membership being very high. Thus, it would seem that almost everyone with the desire to participate has availed himself of the opportunity to do so in this capacity.

It is recognized, however, that there are individual members of INMM who, for some reason, cannot accept an appointment on a working subcommittee. If you fall in this category, you need not necessarily exclude yourself from standards work. In the Winter issue, I extended an invitation to you to participate in reviewing proposed standards up for balloting. You need not be an active member of a subcommittee to involve yourself in this review process. It is not necessary to be a member of a subcommittee in order to draft standards. If you see a need for a standard in a given area, and there is none under preparation, go ahead and write a draft. It will be forwarded to the appropriate subcommittee chairman for appropriate action, and I will assure you that it will not fall through the cracks. Or, if it is beyond your resources to draft a standard, you are still invited to suggest needed standards for someone else to write. Your suggestions can be forwarded to me personally.

On a broader scale, if your suggestion does not fall under the N15 scope, the Nuclear Technical Advisory Board of ANSI has a formal process for considering recommendations for standards and welcomes such recommendations from anyone. The recommended format for requesting approval of new projects proposals and changes or deletions of existing projects is the subject of an NTAB Topical Bulletin (NTAB 338-B8 Revision 1). If you wish a copy of this, I will be happy to send you one. The message is: No one in INMM is intentionally excluding you from participating in the development of ANSI standards; don't exclude yourself.

I would like to direct your attention to two items that appear elsewhere in this issue. One is a short article by **Lou Doher,** Chairman of INMM-8, on the subject of the replica mass standards program. This is a follow-on to the recently published ANSI standard N15.18, "Mass Calibration Techniques for Nuclear Material Control." Also, as a professional engaged in nuclear materials control, you should have a vital interest in the draft standard on certification developed by **Fred Forscher's** Subcommittee INMM-11. His column on this subject will update the progress on this important project.

Mr. Wilson

SAFEGUARDS REPORT

NUCLEAR MIRACLE MEN!

By Dennis W. Wilson, Chairman

At the direction of the Executive Committee, the Safeguards Committee has undertaken a most timely and interesting study of domestic safeguards for low-enriched uranium. This study is long overdue in view of the recent emphasis on safeguards for plutonium recycle—a future probability. Low-enriched uranium is currently the life-blood of the industry, and yet it has received the least amount of appropriate attention in the safeguards arena, which strangely tends to concentrate on numbers of bombs or horrifying descriptions of mass death from poisonous SNM for its publicity. With the obvious exception of physical protection requirements specified in 10CFR73, low-enriched uranium currently demands the same safeguards as strategic SNM under 10CFR70; and heretofore, little has been done to evaluate the appropriateness of these across-the-board requirements.

The study has as its basic objective "to develop domestic safeguards recommendations for low-enriched uranium." One of the tasks, of course, is to define low-enriched uranium, and the recommendations will be defined in terms of LEU's hazard to the health and safety of the public and the common defense and security of the nation. In order to evaluate these hazards, the Committee is studying three major areas: 1) radiological hazards, 2) direct use in weapons, and 3) indirect use in weapons through use as a "better" feed for various enriching schemes. At this point, it is the belief of the Committee's writing group that below some enrichment no such hazard exists.

Before the results are released, considerable internal INMM review is planned, then the results of the study will be made available to the NRC. Finally, the published report will be made available to all interested parties, including automatic distribution to all INMM members.

We believe that safeguards issues such as the one described appropriately lie within the purview of the INMM. We again invite interested members to participate in these kinds of activities. Your ideas are important and your input necessary if we are to continue professional, productive contributions to the nuclear effort. To paraphrase one of our more famous and independent members, we invite you to become Involved Nuclear Miracle Men!

NEW BOOK ON RADIATION PROTECTION

A Guide to Radiation Protection. By J. Craig-Robertson, lecturer at Dundee College of Technology.

The increasing use of radiation and radioactive materials in science, technology, and medicine has faced many people with the problem of handling these materials or at the very least with the problem of ensuring the safety of their radiation workers. Most of the literature on the subject of radiation protection is written for specialists and draws heavily on previous scientific knowledge. This book is intended to serve as a guide for the layman who is faced with the problem of dealing with radioactive materials in the course of his work. The required scientific and technical background is dealt with in a low key manner but with sufficient detail so that no important points are overlooked. It is intended as a guide to policemen, firemen, teachers and industrialists.

Contents: Biological Effects of Radiation. What is Radioactivity? Recognition and Classification of Radioactive Materials. Types of Radioactive Source. The Shielding of Radiation. The Decay Laws. Radiation Units. The Detection and Measurement of Radiation. Day to Day Control of Radiation, Including the Transport of Radioactive Materials. Forewarned is Forearmed: the Uses of Radioactive Materials in Industry: Classification of Radionuclides.

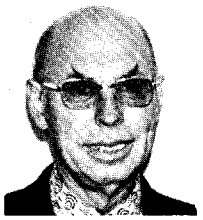
Publication Date: January 1976, **Pages:** 500 approx., **Price:** $24.50, **ISBN:** 0-470-18353-5, **Distribution Rights:** USA.

PSI—NEW COMPANY

Charleston, S.C.—A new company, Power Services, Inc., specializing in placements to the nuclear industry, has opened in Charleston, S.C. The firm is founded by **Dan Heagerty,** President (INMM member) and **John Peters,** Vice President, both graduate engineers and experienced in the nuclear field.

Power Services will concentrate on technical recruiting in the areas of engineering, design, project management, quality assurance, reactor operations, health physics, licensing and safeguards. Most recently Heagerty was Manager of Technical Services Systems for General Atomic's proposed fuel fabrication facility to be built in Youngsville, N.C. He was responsible for having the plant's design meet criticality safety, health physics, licensing and safeguards requirements. Peters, a qualified reactor operator, was Manager of Administration and Staff Engineer at Metropolitan Edison's Three Mile Island twin nuclear unit. His duties included personnel recruiting.

Both Heagerty and Peters have backgrounds in safeguards. Heagerty's background is in designing and testing NDA equipment, design of plant protection systems, and developing statistical procedures—all for fuel fabrication plants. Peters' background encompasses security plant protection systems and managing guard forces.



Mr. Lee

A LITTLE JUDICIOUS PRODDING

By James W. Lee
INMM Membership Chairman

It will come as a surprise to many members of the Institute to learn that the INMM Membership Committee consists of only three persons—**Ralph Jones, Vince DeVito** and your humble author, assisted by the money man, **Bob Curl,** treasurer of the Institute.

While all of us on the Committee work diligently to obtain new members, assisted to no small degree by a little judicious prodding from the dry wit of the Institute's energetic chairman, the real accomplishments of the Membership Committee are realized through the hard work and cooperation of many members and officers who constantly funnel prospects' names and suggestions to the Committee for action and follow-up.

With the new member count at 57 in February, just past the midpoint of the Institute's fiscal year, the Membership Committee welcomes, and eagerly encourages much more of this kind of communication and input.

Now, more than ever before, the nuclear industry urgently needs an active, participating and rapidly-growing INMM membership to deliver the message that the right things are being done about safeguards, about the control of nuclear materials, and to let the public know that there is in existence, a highly professional society whose members' activities are concentrated towards the safe and proper supervision of the nuclear fuel cycle.

The nuclear industry is replete with persons who not only need the benefit of INMM membership and participation, but, who additionally, can contribute greatly to the successful work of the Institute.

It is the job of the Institute's present members to locate these people and to help show them why they should join INMM by furnishing their names to the Membership Committee.

It always is difficult to single out individuals for special recognition for fear of slighting others who also contributed greatly to the progress of the Membership Committee. Because effort above and beyond the call of duty does merit recognition, I will, with advance apology to those who are slighted through inadvertent omission, single out the following:

Tom Bowie, past chairman, who, as an Executive Committee member has shown keen interest and made many helpful and pertinent suggestions;

John Jaech, another Executive Committee member who has kept an alert eye open for new prospects;

Jim Lovett, another past chairman, who, although located in beautiful, musical Vienna, miles from the Institute's home base, continues to contribute a strong drive towards establishing the Institute in the European Community;

Harley Toy, who may be a past chairman, but is presently a very active provider of prospects' names;

George Wuller, for his submission of numerous names of prospects;

Bob Keepin, who seldom lets a week pass without furnishing the name of a prospective member, as well as following up each referral with the usual intense effort he applies to all of his activities;

And, of course, **Manny Kanter,** who send us names in bunches!

Tom Gerdis, although last on this list, provided invaluable help by organizing and carrying out to a successful conclusion, several mass mailing campaigns on behalf of the Committee.

It would give me great pleasure to be able to publish a similar list of other contributing members in the next issue of the Journal. It will be easy to qualify for my next list. Just send me the names of two prospects. In fact, just to make it sporting, if you send only one prospect I will list your initials, but for two—you get the full treatment!

17 NEW MEMBERS

The following 17 individuals have been accepted for INMM membership as of March 16, 1976. To each, the INMM Executive Committee extends it congratulations.

New members not mentioned in this issue of the Journal will be listed in the summer 1976 (Volume V, No. 2) issue to be mailed about July 21, 1976.

Thierry E. Arnal, Commissariat a l'Energie Atomique, CEN Cadarache, BP n 1.13: ST. Paul-Ice-Durance, France.

Thomas M. Beetle, International Atomic Energy Agency, P.O. Box 645, A-1010 Wien, Austria.

Allen J. Budnick, 4330 Sheila Court, Decatur, IL 62526.

David A. Ditmars, National Bureau of Standards, Bldg. 221, Room A324, Washington, DC 20234.

Jay Bernard Durst, 2120 Bucknell Terrace, Silver Spring, MD 20902.

Ralph G. Gutmacher, 121 Cantas Place, San Ramon, CA 94583.

Keith O. Johnson, Exxon Nuclear Co., Inc., 2101 Horn Rapids Road, Richland, WA 99352.

Orval E. Jones, Director, Nuclear Security Systems, SANDIA Laboratories, P.O. Box 5800, Albuquerque, NM 87115.

John Frederick Lemming, Monsanto Research Corp., Mound Laboratory, P.O. Box 32, Miamisburg, OH 45342.

Kenneth D. Long, Nuclear Materials Accountability Specialist, Babcock & Wilcox Co., Lynchburg Research Center, P.O. Box 1260, Lynchburg, VA 24505.

Milad Rafla Matthias, P.O. Box 763, Oakville, Ont., Canada L6J5CI.

Tsuyoshi Mishima, 2021-C, 22nd Street, Los Alamos, NM 87544.

Joseph Ryden, Jr., Exxon Nuclear Co., Inc., 2101 Horn Rapids Road, Richland, WA 99352.

Otto E. Saalborn, Manager, Nuclear Division, Burns International Security Services, Inc., Briarcliff Manor, NY 10510.

Richard A. Schaus, RBU, General Electric Co., Postfach 110060, 6450 Hanau 11, West Germany.

Philip Ting, U.S. NRC, Office of Standards Development, Washington, DC 20555.

Robert A. Williams, Manager, Technical Control, Babcock & Wilcox Co., 609 North Warren Avenue, Apollo, PA 15613.

ABSTRACTING SERVICE

In 1976 INIS ATOMINDEX converts from a world-renowned bibliography to the world's only international nuclear science abstracting service.

ATOMINDEX fully incorporates into its data base the service heretofore provided by NUCLEAR SCIENCE ABSTRACTS—the U.S. Energy Research and Development Administration (ERDA) periodical which is being discontinued—including full coverage of all nuclear-related input generated by ERDA and other U.S. sources.

Produced since 1970 by International Nuclear Information System (INIS), an information dissemination project of International Atomic Energy Agency (IAEA), ATOMINDEX pinpoints information necessary to identify, locate, assess, and obtain all items recorded in the System.

DETECTOR 'FINDS CONCEALED EXPLOSIVES'

Ion Track Instruments, Inc., Waltham, Mass., announces the latest addition to their security product line of specialized equipment for the detection of concealed explosives from vapor emissions.

The ITI Model 70 Series introduces a new concept in explosives detection technology which achieves both an instantaneous "sniff" response to microscopic amounts of commercial and military explosives materials, as well as automatically rejecting any interference of decoy vapors present.

The detection technique utilizes a unique twin electron capture detector developed from the standard ITI Models 58 and 62 Portable Explosives Detectors which have proved successful in worldwide use over the past five years.

The Model 70 Series is available either in the basic portable configuration or with an optional "check-point" configuration adapter for fixed locations and unattended personnel screening applications.

The portable configuration features a neon-logarithmic visual display and audio alarm. Integral rechargeable batteries permit the operator to rapidly screen suspect items or areas without external power.

The check-point configuration adaption unit is designed for ease in integration with any personnel access control booth or check station. Included are provisions for remoting an alarm signal, as well as green/red safe and alarm lights display. Logic interfacing with integrated computer controlled security systems is also possible.

For further information please contact: Ion Track Instruments, Incorporated, 179 Bear Hill Road, Waltham, MA 02154, Telephone: (617) 890-4343, and TWX: 710-324-0752.

Dr. Forscher

CERTIFICATION REPORT

SEEK APPROVAL FOR ANSI STANDARD N15.28

By Dr. Frederick Forscher, Chairman
INMM Certification Committee

Special Nuclear Materials are by their nature of great economic and national security significance. Individuals who, by virtue of their positions in government and industry have immediate managerial responsibilities for the accountability and protection of nuclear materials, are in a position to make decisions affecting not only corporate profitability, but also national security, public safety, and environmental quality. Such individuals should be persons of professional standing, attested to by their peers, and recognized in society by an accredited "Certification."

Public recognition of this profession can be enhanced by the development of criteria and standards that define the qualification for, and that control the admission to this profession. The INMM has for years recognized the professional character of this activity and has, over the years "certified" over 70 nuclear materials managers on a more or less informal basis. In mid-1974, the INMM executive committee felt the need to put the certification program on a more formal and accreditable basis, and asked Dr. **Frederick Forscher,** the new chairman of the INMM Certification Committee, to proceed on this assignment. ANSI granted a charter for this standard-development effort, and the Nuclear Technical Advisory Board (now NSMB) approved the inclusion of this standard-development in the ongoing ETIP-program, administered by Battelle PNL.

The working group for this standard-development, designated as INMM-11, was recruited from all sectors of the nuclear community. Specifically, the chairman approached the following interests for recommendation of two knowledgeable and senior people: industry (AIF); regulatory agency (AEC, now NRC); safeguards and security (JCAE); and technical societies (INMM, ANS).

The question of security clearance for the "certified" nuclear materials manager was a main topic during the first few meetings of the working group. It was determined that the criteria for certification are not directly related to, or contingent on, an applicant's ability or inability to obtain government clearance or access authorization to nuclear materials. The latter determinations are strictly a matter of concern between the individual applicant and the government agency having jurisdiction in such matters.

This consideration is particularly important in view of the international applicability of the "Certification," and the general requirement that any such professional certification must be available to all qualified persons, independent of race, creed, sex or nationality. Acceptance criteria must be based on performance and demonstrated knowledge and understanding in the fields of material control and accounting, and material and plant protection.

The determination of a candidate's qualification for, and the issuance of, a "certificate" are the sole responsibility of the Certification Board for Nuclear Materials Managers. This board has not yet been established. Proposed Charter and Bylaws, not a part of ANSI Standard N15.28, are an appendix to the standard. A seven-member board, broadly representative of the nuclear community including perhaps the IAEA, is visualized. Request for nominations has gone out in August 1975 to 10 knowledgeable and respected individuals who appear to represent all sectors of the nuclear community.

It is anticipated that a board will be established by the end of 1976. There is no need to activate this board until a viable testing program has been developed that will be able to measure the knowledge and understanding of the applicants in the fields of (a) material control and accounting, and (b) materials and plant protection.

This testing program will be developed by the Educational Testing Service of Princeton, N.J., (ETS) with years of practical experience in the development of proficiency testing for industry and government. Technical and scientific guidance throughout all phases of the test development program will be provided by INMM-11 and additional experts, coordinated by the Pittsburgh, Pa. firm of Energy Management Consultants, Inc. of which Dr. Forscher is president. The test development program will take at least 18 months after the source of funding ($66,000) has been identified and agreed to.

The working group, and the INMM membership in general, is well aware of the commercial, political, and military implications of nuclear proliferation. It must be clear to all informed people that, irrespective of what safeguards system, domestically and worldwide, is finally agreed upon and implemented by the various national and international regulatory bodies, all depend, in the final analysis, on the competence, expertise, and motivation of the individuals in industry and government who are charged with its execution.

The speedy approval of ANSI Standard N15.28 and the expeditious development of the testing program will help immeasurably in the safe and beneficial application of nuclear power.

CITES WORK OF I.N.M.M.

Editor's Note: The following letter-to-the-editor of THE WALL STREET JOURNAL was written by Dr. Frederick Forscher, Pittsburgh, Pa., an INMM member. Dr. Forscher is Chairman of INMM 11, Certification Committee of the Institute.

To the Editor of
THE WALL STREET JOURNAL
50 Broad Street
New York, N.Y. 10004

Dear Sir:

This is to comment on your October 23 article about the risks of shipping plutonium. It is hard to tell whether your article intended to scare or encourage the public as well as the potential diverters. It is doing a poor job in either case, and is not very informative to boot.

Your subheadings reflect a certain bias, even paranoia, about the subject. For example "Anxiety at Power Station" has no justification either in context or in fact. There is no readily available or usable plutonium in any of the fuel that either comes or goes from a nuclear power station. A knowledgeable diverter would certainly not focus his attention on low-concentration, radioactive and toxic plutonium compounds: why not steal a ready made bomb? Also, instead of headlining that "New York Bans Shipments," it would be more typical of the U.S. to stress that in 1974 there were 372 shipments (4,600 lbs.) of plutonium without harm to anyone.

The restrictions on our freedom of choice and mobility that may accrue from the employment of small and specialized security forces, is insignificant in comparison to already accepted restrictions. For example, to travel on prescribed roads and to stop at a red traffic light is clearly a restriction of our freedom that we readily accept in lieu of utter chaos.

I think the public should become aware that there exists the **Institute of Nuclear Materials Management,** an organization of professionals with international membership, that has for the past sixteen years addressed itself successfully to the problem of measurement, control, and protection of all nuclear materials, including plutonium. Members of the institute, in government, academia, industry and labor, and in many countries around the world, provide the first and most effective line of defense against **any** potential saboteur or diverter.

In order to reach self-sufficiency in energy as soon as possible, this country must rely on electric power and on the solid fuels that generate it: coal and nuclear. There is no other near term solution. God knows we need better rules and better enforcement in the areas of coal and nuclear power. But, to this end your article is not conducive; rather it is counterproductive. Sincerely, **Frederick Forscher,** Ph.D.

SOLAR ENERGY SEMINAR

New York, N.Y. A two-day seminar in solar energy for heating, hot water and cooling has been announced by The Energy Bureau. The program will be offered in New York, Houston and Toronto.

Please note the following for your calendar: "Solar Energy For Heating, Hot Water and Cooling," offered by The Energy Bureau in New York May 3rd and 4th at The Roosevelt Hotel; in Houston May 24th and 25th at the Sheraton-Houston Hotel; in Toronto June 21st and 22nd at the Park Plaza Hotel.

This intensive two-day seminar is designed for architects, engineers, designers, builders, manufacturers and others in the commercial and residential heating and cooling field. The course is taught by **Harold Jaffe,** president of Solar Dynamics, a company specializing in design and specification of solar equipment, solar architecture and whole solar communities. The program will include an analysis of solar energy utilization, study and comparison of solar energy collectors, economics of solar energy for heating and cooling, and the legal and other considerations so often overlooked. It will include a specially designed manual with extensive workbook and reference materials.

For more information, contact **Robert W. Nash,** Executive Director, The Energy Bureau, 101 Park Avenue, New York, N.Y. 10017. Telephone: 212-889-0199.

NONDESTRUCTIVE ASSAY MEASUREMENT TRACEABILITY: THE BURDEN OF PROOF

D. M. Bishop
General Electric Company
San Jose, Calif.

1.0 INTRODUCTION AND SUMMARY

The desire for improved nuclear materials safeguards, including considerations of real time measurement and control capability, has been the driving force for many recent developments in the area of nuclear fuel cycle measurements. This emphasis has already effected operating requirements for the control of special nuclear materials in domestic fuel fabrication and reprocessing facilities. Typical effects have included:

a. Improved measurement capability

b. Increased utilization of available technology

c. Increasingly detailed and rigorous regulations

As a result of these and other incentives, nondestructive assay methods have emerged as a practical possible approach for satisfying numerous special nuclear materials measurement requirements. Particular advantage has been shown where materials to be measured are difficult to sample (e.g., heterogeneous), or where prompt measurements are required to satisfy process control, safety or safeguards considerations.

This paper reviews the underlying factors which contribute to successful nondestructive assay safeguards measurement applications and relates performance requirements, as defined for licensee facilities in recent Nuclear Regulatory Commission (NRC) regulations, with current capabilities. The need to complete the development cycle associated with currently available nondestructive assay technology to include mechanisms for establishing measurement traceability is discussed. The achievement of such traceability is identified as a cardinal prerequisite to the satisfaction of recently issued NRC measurement control regulations for all safeguards measurements.

Alternative solutions to the nondestructive assay traceability problem are reviewed and evaluated, including two primary approaches: (1) independently supplied standards, and (2) standards comparison programs. It is suggested that any cost effective allocation of near term NRC development resources should address the traceability aspects of nondestructive assay methods at the expense of developing or demonstrating additional measurement techniques or hardware. Without such efforts, the usefulness of available nondestructive assay technology, as a tool for satisfying current licensee safeguards regulatory requirements, is considered to be seriously restricted.

2.0 BACKGROUND

Nondestructive assay measurement methods represent a newly developed and emerging technology. In light of this relative youth as a measurement alternative, a question many nuclear facility managers are asking is: "Can nondestructive assay methods contribute to the solution of today's process control, safeguards and quality measurement needs?" The best response to such a question results from a detailed review of specific measurement applications, requirements and capabilities. Although such a detailed analysis exceeds the scope and capabilities of this paper, key components in such an evaluation are presented in the following discussion.

Recent experience in the safeguards area shows that irrespective of the evaluation criteria associated with any investigation of system performance or capability, one point remains universally true. In today's atmosphere of competition among alternative measurement methods, and close scrutiny by regulators and environmentalists, hard evidence must be available to support any claims of utility associated with a measurement system. Further, the recent shift in emphasis among the nuclear antagonists, from reactor safety to safeguards, has made it increasingly clear that even the future viability of the nuclear power industry may well rest on groundwork laid today in important areas such as nuclear materials control and assurance methods. As has been the case for some time in other sectors of the nuclear industry, the "burden of proof" is increasingly on the safeguards manager to demonstrate that each component of the total safeguards systems meets or exceeds customer, regulatory and social requirements. The public, the press and the antagonists must be provided with positive assurance.

This paper reviews the status of current nondestructive assay methodology, as potentially applied to nuclear materials control, in terms of this burden of proof requirement. Particular emphasis is given to reviewing the underlying basis for the current nondestructive assay approach in terms of regulatory requirements, and industry capabilities and experience in satisfying these requirements.

3.0 DISCUSSION

3.1 Overview

In order to optimize the performance and utilization of nondestructive assay methods on any current nuclear fuel cycle measurement application, numerous technical factors must be evaluated and controlled. Depending on the application, principal control criteria include–

a. Container geometry and composition

b. Packaging and sorting methods

c. Physical calibration standards

d. Instrument selection

e. Calibration, control and assurance methods

The hierarchical relationship of these variables to attainable performance has been previously discussed,[1] and is summarized in Figure 1. Each component of the total measurement system is interrelated and must be evaluated before nondestructive assay measurement systems can be successfully applied to the solution of today's safeguards measurement problems. However, once properly understood, and controlled, the goal of each measurement system must be quantitative and comparable test results. In today's vernacular, the product of such controls for safeguards measurements must result in traceability to the "national measurement system."* In the context of business and social commitments, and NRC regulations, such traceability is a cardinal prerequisite to the usefulness of safeguards measurement systems of all types. As such, traceability is an important and difficult step in satisfying the burden of proof requirement for nondestructive assay safeguards measurements.

Each potential control criteria identified above is a component of, and contributes to, measurement traceability. However, certain of these topics are currently better understood and controlled than others. For example, uniform methods for calibrating nondestructive assay systems have been developed under the auspicious of the American National Standards Institute (ANSI) by the Institute of Nuclear Materials Management (INMM) standards subcommittee on Calibration (INMM-8).[2] This and similar ANSI standards currently under development by the subcommittee on Nondestructive Assay (INMM-9)[3] represent important steps in attempts to close links in the traceability chain for nondestructive assay measurements. However, important as these efforts may be, it is still obvious to those close to practical nondestructive assay

*A term discussed in Section 4.0 (Requirements).

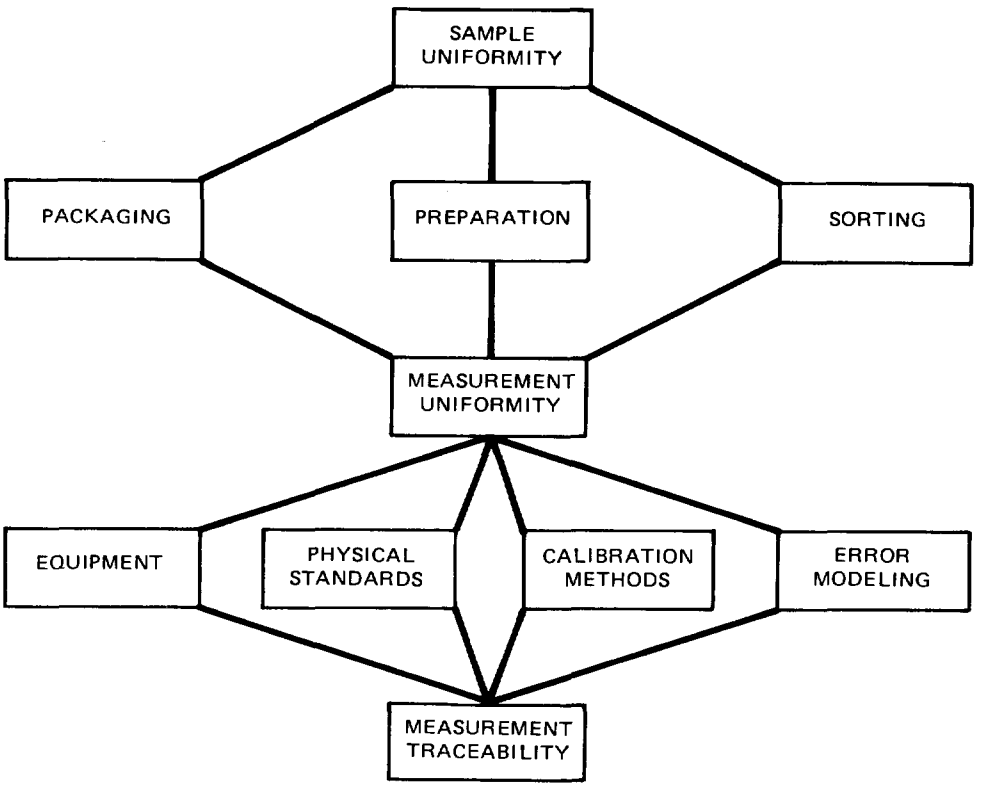


Figure 1. Summary Relationship Between Nondestructive Assay Measurement Traceability and Key Factors

applications that an even more basic prerequisite to achieving measurement traceability for nondestructive assay methods has yet to be adequately addressed. Methods to establish absolute bases, based on an unbroken chain of comparison to the national measurement system, are currently only indirectly available for nondestructive assay methods. Development efforts in this important area have lagged behind recent improvements in instrumentation technology. As a result, the use of current nondestructive assay technology, as a tool for solving safeguards measurement problems in the licensee sector, may be seriously restricted.

The current situation is summarized as follows:

Problem Statement

Available nondestructive assay instrumentation appears to offer adequate "precision" to satisfy many current licensee safeguards measurement applications. However, absolute bases for defining "accuracy" capabilities, in compliance with current licensee regulations, do not appear to be entirely adequate for nondestructive assay methods.

In a nutshell, it has been repeatedly and irrefutably demonstrated that today's nondestructive assay techniques can be adequately precise to satisfy many possible nuclear fuel cycle related measurement applications, if applied for this purpose. Hard evidence is available to provide such "proof." Further, current nondestructive assay methods are probably adequate to satisfy certain accuracy requirements. However, as of now this capability either "can't be proven" or is proven only in a circuitous manner. In the context of today's "burden of proof" requirements, evidence in the "accuracy" area is not always adequate to provide positive assurance of compliance with current requirements. To the extent this is true, the very credibility of the nondestructive assay approach would be vulnerable if the methods were generally applied to safeguards work.

The principal problem associated with quantifying nondestructive assay measurement "accuracy" lies in the area of certification of physical standards used to calibrate measurement systems. Without a firm basis for such standards, credible and complete "accuracy" statements (e.g., bias estimates and limits of systematic error) are not currently possible. The basic question is simply one of traceability. Specific requirements and needs in this area for licensee facilities are outlined in the following discussion and Section 4.0 (Requirements).

3.2 Current Status

The question of physical standards for nondestructive assay methods has been a popular topic of debate in recent years.[4,5,6] However, little if any real progress has been made toward resolving basic issues associated with the traceability of such methods. In the absence of alternative methods, practitioners of nondestructive assay methodology throughout the industry typically strive to fabricate standards that typify materials to be measured. However, objective criteria for evaluating representativeness have yet to be defined. Further, source materials for fabricating such standards are typically generated and certified internally, based on chemical analysis before fabrication into standard configurations In some cases source materials used for such standards may be submitted for independent analysis by a commercial laboratory. However, sampling frequencies and action criteria associated with resolving discrepancies are not defined on an industry basis. Following fabrication, detailed documents are written to describe and substantiate the assay value of working standards. Such documentation usually includes a description of fabrication methods, and internal certification methods. However, a basic component of the traceability process is nearly universally omitted. That is, certification verification by an outside source after the standards are fabricated. When such verification is accomplished at all, it is typically based on destructive analysis of samples from source materials subsequently fabricated into nondestructive assay standards. A less frequently used alternative is post-measurement destructive analysis (in-house) of the standard. However, in the preponderant number of cases no such verification is accomplished.

There is one overpowering reason for the omission of independent verification of nondestructive assay physical calibration standards used in the licensee sector. No methods have been established to define what measurement practices should be utilized to certify or verify such standards. Further, no guidance or capability is available for the initial or periodic verification of nondestructive assay working standards. Available materials and services associated with nuclear portions of the national measurement system relate only to chemical analytical standards. Little, if any, consideration is given in the current national measurement program to providing source materials or services needed to fabricate or certify nondestructive assay standards.

It is clear that industry certification programs for nondestructive assay methods do not currently exist. It is equally clear that current national and international chemical analytical standards are only partially applicable to nondestructive assay measurements. In this context it seems necessary to identify exactly what a nondestructive assay standard is, and how it differs from traditional analytical chemistry standards (see Section 3.3). Subsequent sections discuss specific requirements and identify potential methods of achieving nondestructive assay measurement traceability.

3.3 Description

Nondestructive assay measurements are typically based on the observation of an instrument response to some characteristic of the material being measured, and comparison to a known point or function derived from standards. The reliability of these measurements is predicated in part on how well the physical standards used to calibrate the instrument typify the materials being measured. Further, such standards must be directly relatable to the national measurement system before absolute bases for nondestructive assay measurements are available for licensee facilities.

Nondestructive assay methods offer one primary advantage over chemical analytical measurement techniques: lack of sample preparation. As a result of this capability many nondestructive assay applications deal with non-uniform materials which are difficult to abstract in the form of representative standards.

The first line of any standards program consists of working standards. Because of the diversity of nuclear industry product and measurement objectives, nondestructive assay working standards have remained the responsibility of the individual processing facility. Typical standards often include input, in-process, product, scrap and waste material types.

Examples of typical standards are shown in Figure 2, including product pellet and solid waste material types. The unique feature of such standards is that they do not provide the same luxury afforded chemical analytical standards in that chemical isolation of the nuclide of interest (e.g., from extraneous interferences) is not possible. In addition, geometric factors must be considered. As a result, nondestructive assay calibration standards must be representative of materials to be measured in both a physical and chemical sense.

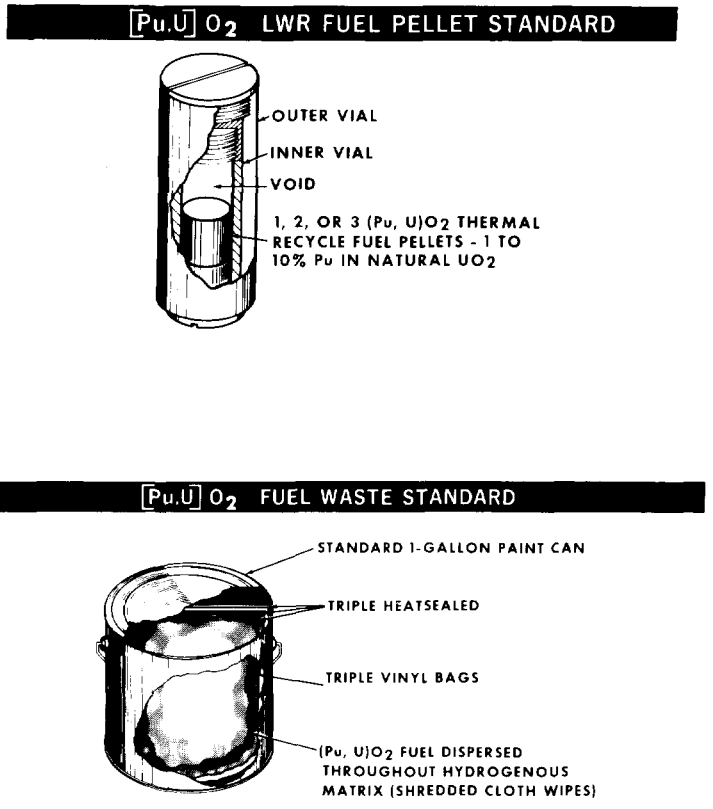


Figure 2. Typical Nondestructive Assay Physical Calibration Standards

The problem most practitioners of nondestructive assay technology currently face is that in order to supplement such working standards and provide positive proof of measurement system performance, an overview system is needed which can provide for the certification of working standards by an independent source above the licensee in the measurement hierarchy.

After initial certification, periodic recertification is also needed to assure continued satisfactory measurement system performance. These needs relate to the "reference standard" and "traceability" requirements discussed in Section 4.0 (Requirements).

4.0 REQUIREMENTS

Measurement requirements in a nuclear facility originate from numerous sources, including:

a. NRC safeguards

b. Internal process and quality control

c. Customer quality

d. Industrial and nuclear safety

e. Business and financial

f. Other license or regulatory

However, measurement related regulations issued by the Nuclear Regulatory Commission (NRC) currently represent by far the most specific and restrictive requirements for safeguards measurement in licensee facilities. For example, in October 1974 the NRC issued 10CFR70.58 (Fundamental Nuclear Material Control) regulations which required that all safeguards and accountability values on a special nuclear material (SNM) inventory in a licensee facility be based on measured values, in order to close a measured material balance. Additionally, in August 1975 the NRC issued 10CFR70.57 (Measurement Control) regulations which defined the need for detailed procedural and statistical controls for all SNM measurement methods. To excerpt pertinent portions of 10CFR70.57, Paragraph b(8), a measurement control program is required of each licensee to:

> ". . . generate current data on the performance of measuring processes, including, as appropriate, values for bias corrections and their uncertainties, random error variances, limits for systematic errors, and other parameters needed to establish the uncertainty of measurements pertaining to materials control and accounting. The program data shall reflect the current process and measurement conditions existing at the time the control measurements are made. Measurements which are not controlled by the program shall not be used for materials control or for accounting purposes. The program shall include:
>
> (1) The ongoing use of standards for calibration and control of all applicable measurement systems. Calibrations shall be repeated whenever any significant change occurs in a measurement system or when program data, generated by tests performed at a predetermined frequency, indicate a need for recalibration. Calibrations and tests shall be based upon reference standards.
>
> (2) A system of control measurements to provide current data for the determination of random error behavior on a predetermined schedule. The system shall include the replicate analysis of process samples, the replicate weight or volume measurement of bulk quantities of material, and the analysis of replicate process samples."

Several key points associated with this regulatory statement are best understood by reviewing specific terminology utilized in the regulation. Starting with the error terms, *Random Error* is defined in 10CFR70.57 as follows:

> "the chance variation encountered in all measurement work, characterized by the random occurrence of both positive and negative deviations from a mean value, the algebraic average of which approaches zero with a sufficiently large number of measurements."

In this context random error is analogous to precision, or reproducability, and imposses no real technical feasibility constraint on either nondestructive or other static measurement methods. Such requirements are typically satisfied by performing replicate analyses for each measurement method and material type during a material balance period.

However, methods for satisfying and demonstrating compliance with the NRC definition of systematic error, as applied to nondestructive assay methods, are considerably less definitive. *Systematic Error* is defined in 10CFR70.57 as follows:

> ". . . a constant unidirectional component of error that affects all members of a data set; its value can, in some instances, be estimated by the deviation of the mean of a measurement process from a reference value. A systematic error whose value has been determined in this manner is called a bias, whose effect can be corrected for."

Accepted, traceable, physical calibration standards for nondestructive assay methods become a necessity if bias correction and limits of systematic errors are to be meaningfully defined in compliance with 10CFR70.57 requirements. In the context of these requirements, 10CFR70.57 goes on to define the following terms:

Calibration as:

> ". . . the process of determining the numerical relationship between the observed output of a measurement system and the value, based upon reference standards, of the characteristics being measured."

Reference Standard as:

> ". . . a material, device or instrument whose assigned value is known relative to national standards or nationally accepted measurement systems."

and, **Traceability** as:

> ". . . the ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons."

Thus, before measurement bias and limits of systematic error can be defined for nondestructive assay methods, in compliance with future requirements, accepted methods for establishing measurement traceability must be established. The remaining sections of this paper discuss current and proposed future alternative solutions to the nondestructive assay measurement traceability problem.

5.0 TRACEABILITY

Alternative methods for establishing nondestructive assay measurement traceability fall into two general categories:

a. Independently Supplied Standards

b. Standards Comparison Programs

The relative merits of each alternative are summarized in the following discussion.

5.1 Independently Supplied Standards

In the case of independently supplied standards Glancy[6] has proposed three basic alternatives, which are summarized as follows:

a. Maximum Credible Extremes Standards

b. Destructive Post-Measurement Verification

c. Certified Representative Standards

5.1.1 Maximum Credible Extreme Standards

One potential solution to the problem of nondestructive assay traceability to the national measurement system is the development of national standards for use on a rotating basis within the nuclear industry. Because of the variety of applications and material types, such standards could not be representative of all materials subject to measurement. However, an acceptable alternative might be to use calibration standards which represent extremes in material composition and to assign the conservative error estimates associated with the use of such standards to measurement result.

Characteristics of the maximum credible extremes calibration standards approach are outlined in Figure 3. The advantage of this approach is that a minimum cost system of national standards might be feasible; but only if material categories, packaging and containerization can be standardized. Although material compositions differ from facility to facility, even within each generic material type, the credible extremes represented by the standards could conceivably be made wide enough to encompass an acceptable range.

The use of standards that are not representative of actual conditions, but represent the range of credible conditions, provides a number of advantages: (1) the calibration standards could be fabricated by an independent group (e.g., a nationally recognized laboratory) with the resources and qualifications to quantify the effect of significant physical characteristics of the material in each material category and nondestructive assay technique. For the task to be manageable, categorization of material, standardization of packaging and containerization, and the selection of a limited number of nondestructive assay techniques for each material category are essential; (2) the standards would be interchangeable, allowing comparisons of methods between facilities; (3) the cost of the standards could be shared by affected members of the nuclear industry; (4) independent instruments and techniques could be evaluated by comparing results.

The last point is probably the most significant. With the present lack of standards it is currently difficult to compare the performance of different instruments and methods. Comparisons of assay results on national standards which represent extreme test conditions would facilitate instrument development and evaluation, even if other approaches provide the primary basis for calibration.

The basic shortcoming of the maximum credible extremes calibration method is that no 95% confidence limits on the assay results can be established. However, the maximum credible model can be used to generate a conservative error estimate sufficient to assure that 95% confidence limits computed using other components are reliable.

5.1.2 Destructive Post-Measurement Verification

The maximum credible extremes standards method discussed above outlines a practical approach to obtaining a realistic, but conservative, estimate of the systematic errors for nondestructive assay methods. This approach is probably not practical for most safeguards applications. A realistic measure of the 95% confidence interval about a measurement datum is needed to make meaningful error estimates for nondestructive assay methods.

The common approach to estimating bias and constructing a 95% confidence interval around the bias-corrected result is by frequent measurement of standards. The mean result from the standard is used to compute the bias and the variance in the bias is used in constructing a 95% confidence level (the precision must also be included in constructing the confidence interval). However, since no standards that are independent of calibration currently exist for nondestructive assay methods, this traditional approach is not valid. The only value in repeatedly assaying the standards used in calibration is in evaluating measurement precision and standards integrity. As has been previously described, a measure of the degree to which the standards are representative of the unknown is needed. This can only be achieved through intercomparison of results with the national measurement system.

An ideal approach for establishing the traceability of nondestructive assay results to the national measurement system is through a series of comparative analyses. Because of the difficulty in fabricating national, highly representative, standards, the destructive analysis of nondestructive assay working standards appears to be a feasible solution to the traceability question. As part of this approach, unknown materials would first be assayed based on in-house working standards. Subsequent to measurement a select number of working standards, or measured samples, would be submitted to a nationally recognized laboratory for comparative analysis. This laboratory would periodically compare its results with the National Bureau of Standards. Comparison of test results would provide the basis for defining systematic errors based on an unbroken chain of comparisons to the national measurement system. Specifics of this method are outlined in Figure 4.

5.1.3 Certified Representative Standards

The final method for providing nondestructive assay traceability to the national measurement system is outlined in Figure 5 and is based on representative standards similar to the in-house working standards. However, in this case representative standards would be fabricated and certified by a nationally recognized laboratory. Representative standards sufficient for proper calibration are generally only practical if the material to be assayed is uniform or the nondestructive assay technique is not severely affected by the material variability. The use of an outside independent organization for fabrication and certification is essential to provide proof of traceability, i.e., a credible calibration and error analysis.

5.2 Standards Comparison Programs

Traceability alternatives in the area of standards comparison programs center around two basic approaches:

a. Horizontal Comparison

b. Vertical Comparison

The relative merits of each alternative are summarized in the following discussion.

5.2.1 Horizontal Comparison

In the absence of more definitive and comprehensive alternatives, the horizontal comparison approach has historically provided much of the current basis for verifying nondestructive assay calibration standards. Because source material are generally not available to fabricate such standards, and no independent laboratory exists with the capability of either destructive or nondestructively analyzing such standards, a common approach has been to informally exchange samples among colleagues in national laboratories, contractors and other licensees. However, because of the diversity of applications associated with such a facility, such exchange programs seldom involve samples that are representative of unknown materials. Further, such programs do little more than provide added credibility to in-house verification data because the comparison is usually qualitative. When the results of such a comparison are positive (e.g., good agreement) a sense of confidence is provided. When results differ, definite action is difficult and unless an obvious error can be identified, the results are often discounted. As a result, the horizontal comparison method can be considered to contribute to nondestructive assay measurement traceability, but it lacks a tie to the national measurement system based on an unbroken chain of comparison.

5.2.2 Vertical Comparison Method

The most obvious and in many respects useful approach to achieving nondestructive assay measurement traceability is the vertical calibration standard comparison methods. Its basis would be a hierarchical relationship, similar to that used for nuclear chemical analytical standards, where independent facilities at a recognized national level would be chartered with the responsibility of supplying support services in the area of nondestructive assay calibration standards. A prime function of such a service would be the development of source materials to fabricate necessary standard, coupled with the ability to provide initial and periodic certification of licensee nondestructive assay working standards.

BASIS:	Standards nationally fabricated and certified to include credible material forms and composition.
USE:	Standards are nationally applicable for calibration error analysis, instrument performance evaluation. Most applicable to low SNM content material of variable material composition.
REQUIREMENTS:	1. Contents accurately measured by technique traceable to standard reference material. 2. Number of standards sufficient to cover all operating ranges. 3. Composition of standards inclusive of all material forms. 4. Standard containerization and packaging. 5. Standard categorization and NDA technique selection.
ADVANTAGES:	1. Standards fabricated by an independent nationally recognized group. 2. Standards are interchangeable, facilitating comparisons. 3. Cost is born by all members of the industry on a use basis. 4. Universal nature of standards allows flexibility of NDA technique if material form changes.
ERROR MODEL:	Calibration error estimates credible bounds due to material variability.

Figure 3. Maximum Credible Extremes Approach[6]

PRINCIPLE:	NDA results compared with assay on same material by independent nationally recognized certification laboratory.
USE:	Generally applicable for all NDA methods, and all material forms, most applicable to high SNM content material of variable material composition.
REQUIREMENTS:	Existence of a nationally recognized laboratory with the capability to verify the contents of containers of SNM, preferably with the ability to return the SNM contents either in the original form or purified.
ADVANTAGES:	Intercomparison of all techniques possible, provides *proven* consistency of measurement.
ERROR MODEL:	Comparative results provide reliable estimate of bias and systematic error (variance in the bias).

Figure 4. Destructive Post-Measurement Verification[6]

PRINCIPLE:	Standards are fabricated and certified by a nationally recognized laboratory to be representative of the unknowns. An extensive data base is used to identify a representative standard.
USE:	Applicable primarily to material of high SNM content that is uniform and highly characterized, such as product material.
REQUIREMENTS:	Existence of a nationally recognized laboratory with capability to fabricate representative standards.
	Existence of an extensive body of data, continually updated, to identify representative standards.
	A cooperative arrangement between the National Standards Laboratory and each facility which may require the use of in-house material and equipment.
ADVANTAGE:	Representative standards.
ERROR MODEL:	Synthetic parametric analysis using updated descriptive information and results of measurements of interfering effects.

Figure 5. Certified Representative Standards[6]

6.0 CONCLUSION AND RECOMMENDATION

It is clear that current trends in the safeguards area will result in increasing reliance on measurement techniques as a mechanism to increase the timeliness and accuracy of special nuclear materials inventory and security control information. In this capacity, nondestructive assay techniques offer obvious potential advantage. However, before this relatively new and emerging technology can achieve broad-based implementation, it must be positively and irrefutably proven that nondestructive assay methods can meet applicable performance requirements. In the context of today's safeguards requirements, this "burden of proof" requirement includes both measurement accuracy and traceability to the national measurement system.

This paper has briefly summarized the current status of nondestructive assay methods, as applied to potential licensee safeguards measurement applications. Traceability to the national measurement system was identified as a cardinal prerequisite to the satisfaction of current NRC requirements. Shortcomings in the current system were judged to have been the result of recent rapid advances in instrument capability, coupled with sweeping changes in the scope of safeguards regulations. As a result, support systems necessary to assure adequate implementation of available nondestructive assay methods appear to be lacking. However, this lack of availability has not forestalled the development and implementation of NRC regulations relating to the use of nondestructive assay methods. Yet, no guidance is available in the form of regulatory guides or supporting services to provide bases for implementing these requirements.

It is a basic thesis of this paper that the industry could more effectively satisfy current regulatory requirements in the area of nondestructive assay technology if fewer techniques were developed, but were developed to the point of completion. The alternative is the current situation where innumerable methods are available, only a few of which can be shown to satisfy total system performance needs. Since current safeguards requirements are predicated on quantitative measurements, the only way tomorrow's real-time safeguards testing and verification methods can ever be practical is with a system which itself can be proven to be functioning properly; a system that is traceable to the national measurement system. Everyone agrees there is a problem, yet no definitive action has been taken or is being planned. In the context of the current NRC safeguards requirements, such capabilities are no longer a luxury; they are criteria for survival as a measurement alternative in licensee facilities.

Several methods for achieving a national nuclear nondestructive assay measurement system having both internal consistency and proven traceability to the national measurement system have been described. Undoubtedly there are numerous other alternatives. Extensive study and testing of these and additional methods are needed to establish acceptable methods. However, the primary requirements for achieving such a system have been identified, including:

a. An independent, unbiased, nationally recognized laboratory for standards and certification,

b. Standardization of containerization, packaging, categorization, and NDA technique selection, and

c. Extensive description of material by category.

Historically, efforts in these areas of nondestructive assay technology have been typified by too few people, working on too many problems, and accomplishing too few positive results. Today, industry, through ANSI standard subcommittee INMM-9 (Nondestructive Assay), is actively working[3] to develop consensus standards dealing with standardization and categorization. These efforts were initiated in 1975 and to date have received broad-based support. However, responsibility in the all important area of providing program guidance for the solution of independent standards and certification problems goes beyond the scope and capability of the licensee sector alone. Keepers of the national measurement system must provide such capability and assurance. To the extent achievement of these responsibilities remain incomplete the "burden of proof" requirement for nondestructive assay methods will remain unsatisfied.

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THE LASL—U.S. ERDA

NDA TRAINING PROGRAM

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I. INTRODUCTION

A wide variety of new nondestructive assay (NDA) instruments and techniques are required to measure, safeguard and control special nuclear materials (SNM) in the many different chemical and physical forms in which they are found throughout the nuclear fuel cycle. The transfer of NDA technology from the instrument development laboratory to various types of plants and facilities in the nuclear fuel cycle is an important part of the Los Alamos Scientific Laboratory's Research and Development Program in Nuclear Safeguards. To implement this technology transfer, the U.S. Energy Research and Development Administration has established at LASL the U.S. ERDA Nondestructive Assay Training Program, which is now available to essentially all qualified users (in both government and private sectors) of NDA equipment for the measurement and control of fissionable material. The present curriculum consists of a one-week course in basic passive gamma and neutron assay, emphasizing the use of portable instrumentation, and a more advanced course (one-week duration) in high resolution gamma-ray assay. An advanced neutron assay course may be made a part of the curriculum when the demand merits. The goal of these courses is to teach specific principles and practical skills which are essential to both the inspectors and the plant personnel who are responsible for conducting various assay and verification measurements.

Each course is laboratory and instrumentation oriented, with lectures covering basic theory, instrument operation, and potential problem areas. Manuals have been written which serve both as textbooks and as general reference sources. Laboratory groups are kept small (3 to 5 persons), each group having their own instrumentation. LASL instructors interact closely with the attendees, not only on the assigned course work, but also in sharing experiences gained in field-implementation of NDA techniques.

The basic course has been presented three times, the advanced course once, with a total attendance of 92 persons, representing a wide variety of U.S. government and industrial organizations (about 80% of the attendees) as well as the International Atomic Energy Agency (about 20%). This spring (May 17-21, 1976) the advanced course will be given for the second time with the enrollment limited to twenty.[1]

II. THE CURRICULUM

A. Fundamentals of Nondestructive Assay Using Portable Instrumentation.

This course is designed as a basic introduction to the principles and techniques employed in passive gamma-ray neutron assay of fissionable material. A brief course outline appears in Fig. 1. The text for the course "Fundamentals of Passive Nondestructive Assay of Fissionable Materials" by R.H. Augustson and T.D. Reilly [1], covers the basics of gamma ray and neutron production, interaction and detection and the application of these basics to the NDA of special nuclear material. Among the topics discussed in detail in the text are: gamma-ray production and interaction with matter, gamma-ray detectors, analysis of gamma-ray pulse-height spectra, quantitative gamma-ray assay, enrichment measurements, neutron production and applicable signatures, neutron detectors and neutron verification measurements.

Introductory lectures, based on the text, are given at the beginning of the gamma-ray and neutron sections of the course. In the laboratories, the class is divided into small groups of three to five students, each with an individual instructor. Instructors provide detailed discussion/clarification to these smaller groups as warranted (Fig. 2). The laboratory exercises have been published in a workbook supplement to the main text. These exercises emphasize the use of portable instrumentation but expose the student to a variety of more sophisticated laboratory equipment and procedures (Fig. 3), including multichannel analyzers, Ge(Li) detectors, and oscilloscopes.

The quantitative gamma-ray assay exercises, performed with NaI detectors and the SAM-II,[2] include the

FOOTNOTES

1. For further information write to: U.S. ERDA Nondestructive Assay Training Program, Nuclear Safeguards Research Group, R-1, MS 540, ATTN: T.R. Canada, Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, NM 87545.

2. Manufactured by Eberline Instrument Corporation. (See inside front cover.)

FUNDAMENTALS OF NONDESTRUCTIVE ASSAY USING PORTABLE INSTRUMENTATION

A. Gamma-Ray Assay Techniques
   1. Fundamentals
      a. U and Pu spectra
      b. Detector operation
      c. Attenuation
      d. Statistics of counting
   2. Enrichment Measurements
   3. Quantitative Assay-Transmission Based Attenuation Corrections

B. Neutron Assay Techniques
   1. Fundamentals
      a. Neutron production, detector operation
      b. Matrix effects, neutron scattering
   2. Assay Techniques
      a. SNAP measurement of Pu metal buttons
      b. Measurement of mixed oxide fuel rods
      c. UF_6 measurement

C. Demonstrations
   1. Random Driver
   2. Neutron Well Coincidence Counter

Figure 1. Outline of the introductory course.

Figure 2. An informal lecture by LASL instructor T. Canada.

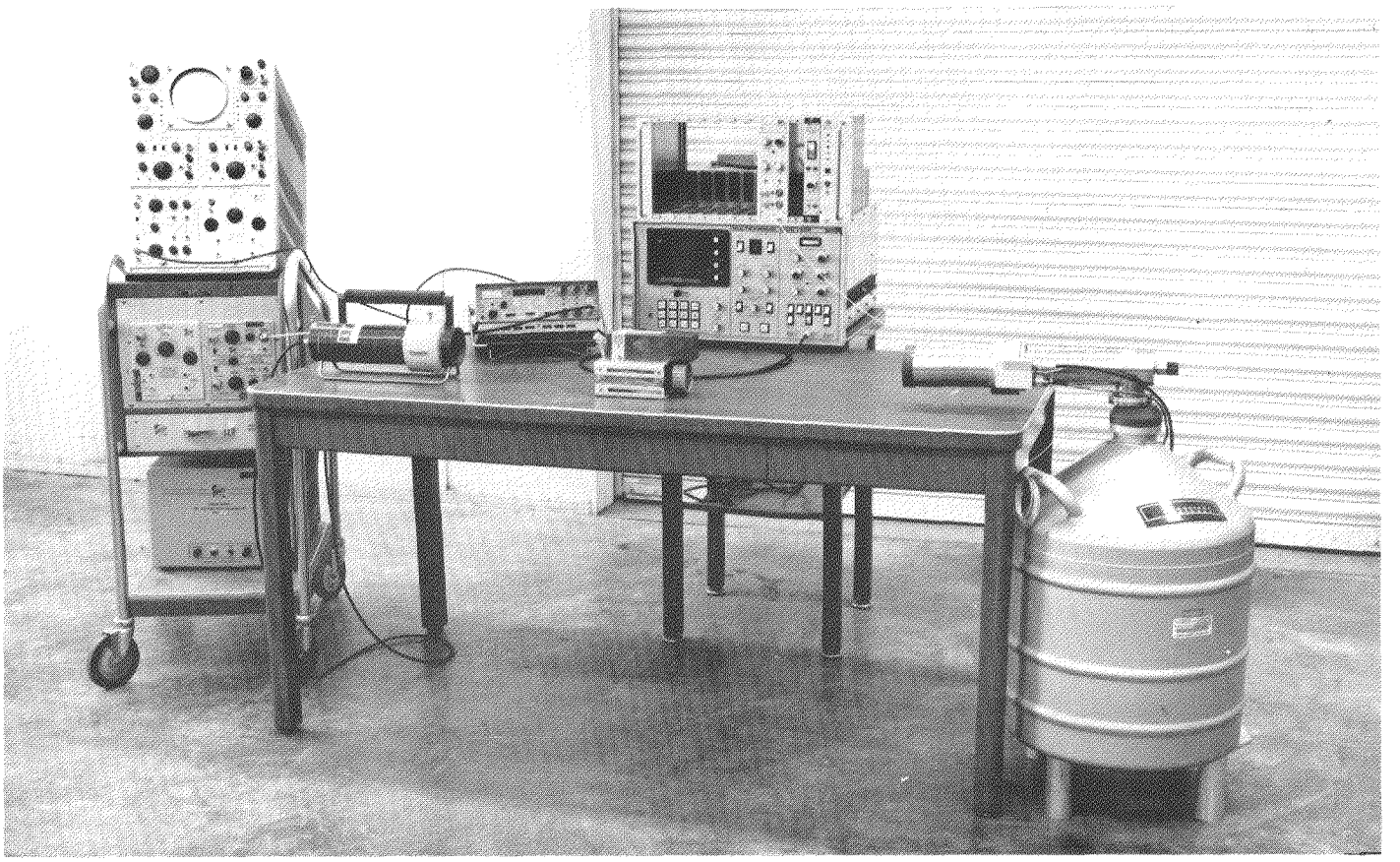

Figure 3. Some of the equipment used in the introductory course. From right to left: Ge(Li) detector, multichannel analyzer, SAM-II, NaI detector, and oscilloscope.

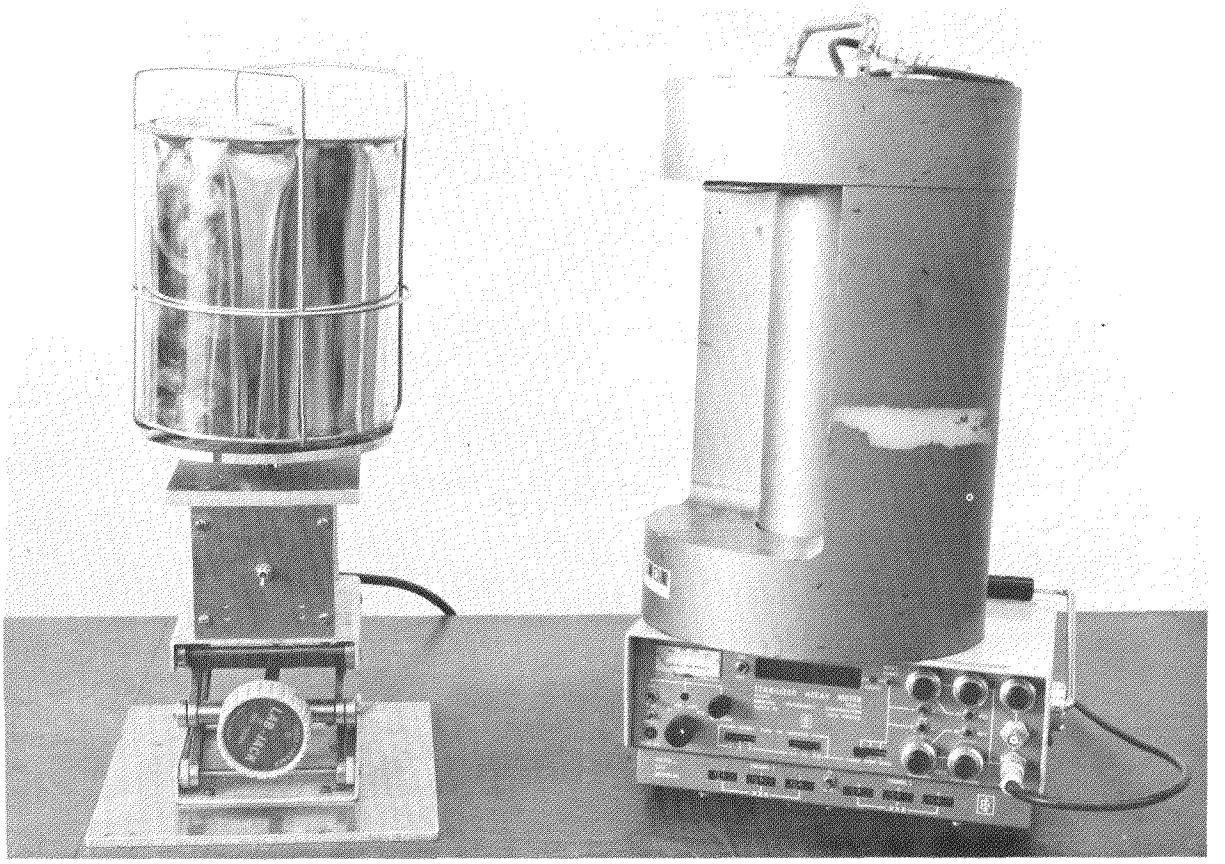

Figure 4. SNAP neutron detector and one of the sample matrix containers used in the introductory course. A series of such cans is used to show the effect of different materials on the neutron energy spectrum and detector response.

measurement of plutonium in incinerator ash (using an external transmission source), holdup measurements, and enrichment determinations of UO_2 standards and UF_6 product cylinders. The neutron assay laboratories, using a SNAP detector system [2] (Fig. 4), deal with the assay procedures for plutonium metal buttons, samples of bulk plutonium oxide, mixed oxide fuel and UF_6 cylinders.

Although the course emphasizes "hands-on" experience in small groups, several demonstrations of more advanced instrumentation are given. Typical demonstration topics are spontaneous fission neutron coincidence counters [3], low-level effluent monitors [4], and the Random Driver [5] active neutron interrogation system.

B. Gamma-Ray Spectroscopy for Nuclear Material Accountability.

The purpose of this more advanced course is to familiarize the students with the powerful techniques available for NDA of SNM using high resolution gamma-ray detectors. A brief course outline is given in Fig. 5. The course text [6], laboratory exercises, and lecture presentations are designed to emphasize the basic techniques of high resolution gamma-ray spectroscopy and the fundamental principles involved in various NDA measurements. Particular emphasis is placed upon the limits of applicability and the achievable accuracies of those measurements.

As in the fundamentals course described above, the laboratories are designed to accommodate small student groups and thus to emphasize the "hands-on" experience. Each group conducts assays with a number of detectors (small planar and large coaxial Ge(Li), intrinsic Ge), coupled to a variety of sophisticated data collecting systems (Fig. 6). Assays are made on a number of uranium and plutonium samples, including solutions with densities of SNM of from 1 to 400 g/l, plutonium mixed with low Z solids, and pure UO^2 with varying enrichment. The assay techniques used include: direct comparison of sample gamma activity with standards, correction for sample attenuation by the differential absorption of sample gamma rays [7, 8] or the transmission of an external gamma-ray source [9], the determination of total uranium or plutonium content by gamma-ray densitometry [10], and enrichment measurements [11].

As an example of the application to state-of-the-art instrumentation of some of the principles taught in the laboratories, a detailed demonstration of a fully automated segmented gamma scanner [12] is given (Fig. 7).

III. DISCUSSION

The interests, viewpoints and problems of various groups or agencies in the application of NDA technology are diverse. The inspection and verification safeguards problems of NRC, U.S. ERDA operation offices, and the IAEA can be quite different from those of production facilities, where the major concern is with plant output, product control, and simply meeting safeguards regulations. Knowledge of these problems is essential to viable research and development laboratory programs. These courses provide an opportunity for an exchange of these differing viewpoints and the discussion of the associated problems.

The interaction does not end with the completion of the formal courses. Rather they serve as a foundation for future consultations on new or complex assay problems. The texts for the training program courses—over 700 copies of which have been distributed—have broadened significantly the number of individuals involved in these consultations.

Technology transfer is an important yet difficult process requiring the active involvement of all parties. The ERDA Nondestructive Assay Training Program has proven to be an effective method of bridging the gap between the NDA instrument developer, the safeguards and accountability inspector, and the in-plant user of nondestructive assay equipment.

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GAMMA-RAY SPECTROSCOPY FOR NUCLEAR MATERIAL ACCOUNTABILITY

A. General Techniques of Gamma-Ray Spectroscopy
- **1. Optimization of resolution**
- **2. Count rate effects**
- **3. Statistics of counting measurements**

B. NDA Techniques
- **1. Sample counting**
- **2. Corrections for self-attenuation**
  - **a. Differential absorption**
  - **b. External source transmission**
- **3. Gamma-ray densitometry**
- **4. Enrichment measurements**

C. Applications of Principles

D. Demonstration of Automated Gamma-Ray System

Figure 5. Outline of the advanced course on gamma-ray assay techniques.

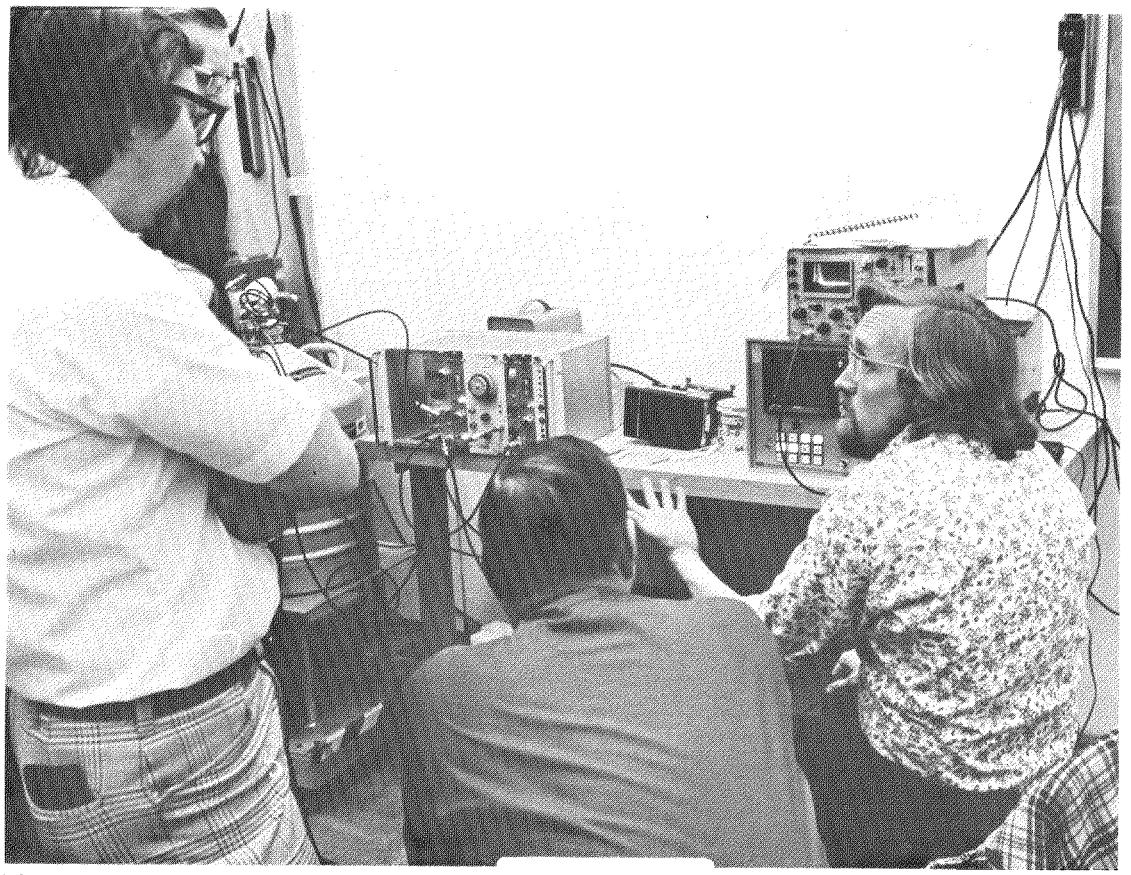

Figure 6. LASL instructor, R. Augustson, explains enrichment measurement procedures to laboratory group. A Ge(Li) detector system is used to measure a series of cans filled with UO_2 of differing enrichment.

Figure 7. LASL instructor, D. Reilly, demonstrates operation of a segmented gamma scan (SGS) system. The pictured system is a versatile data acquisition system for laboratory use. Dedicated SGS systems are much smaller and simpler to operate.

Temporal Response Methods for Dynamic Measurement of In-Process Inventory of Dissolved Nuclear Materials*

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A. INTRODUCTION

In this paper, we discuss the current results of an ongoing analytical study of a dynamic inventory method that appears to have some important attractive features. A number of facets of the method remain to be investigated, but the analysis is now at a stage where the method's potential value as a nuclear materials management tool ought to be assessed by the industry. It is for that purpose that this paper has been written.

Nuclear materials management in a reactor fuel reprocessing plant includes the performing of closed material balances at frequent enough intervals to assure a current and accurate accounting of special nuclear material (SNM). The need for such accounting arises both from the high monetary value of the SNM being processed, and from the strategic value of the SNM. The strategic value has caused U. S. Federal Regulations and international agreements to be developed, under which the required precision in SNM accounting is specified [1] [2].

A closed material balance is defined to mean the algebraic sum of inventory at the beginning of the period, receipts, shipments, and measured waste, during the period, less the inventory at the end of the period [3]. In the case of chemical reprocessing plants with SNM in solution, the measurements of beginning and ending inventories have required the plant operations to be stopped, and all process equipment drained into measurement tanks. We refer to this process as a "physical" inventory. A physical inventory may interrupt plant operations for several days, or more. As an alternative to shutting down the plant, it is possible to infer the quantity of in-process SNM while the plant is operating, if certain conditions can be satisfied. We refer to such methods as "dynamic" inventory techniques.

Dynamic inventory methods will be of practical importance if they can provide accurate enough estimates of the amounts of in-process SNM, while causing less disruption of plant operations than would be imposed by physical inventories at the required frequency. This report describes an analytical study of a class of dynamic inventory methods which appears to offer the required accuracy, with somewhat less severe operating restrictions than earlier proposed dynamic inventory methods. Furthermore, the technique described here could be used to continually update the estimated in-process inventory, virtually in real time.

The first proposed dynamic inventory method was the tracer step displacement technique [4] [5]. To our knowledge, this is the only method that has been actually demonstrated in an operating reprocessing plant. In the step method, a large special batch of feed material is prepared with an SNM isotopic composition that is different from the in-process material, containing say 10% of the total Pu in the form of the 239 isotope instead of, say 40%, as might be the normal in-process composition. At T_0, the instant of time when the in-process inventory is to be determined, the special feed batch is introduced to the plant as feed material, and simultaneously the output and waste streams are switched into calibrated containers designated for the inventory measurements. At first, these containers receive the materials that comprised the normal process streams (i.e., containing none of the special-feed batch). The product and waste streams are sequentially batched for the inventory, and eventually these batches begin to contain tracer material. Ultimately, after all the material present in the process at T_0 has been displaced by the special feed batch, an isotopic analysis of the collected product and waste-stream batches will indicate that they contain only material from the special feed-batch. The inventory measurements are complete at that point, except for analysis of the collected batches of product and waste material. That analysis consists of a batchwise measurement of

* Work sponsored by U.S. NRC

the fraction of the tracer isotope (^{239}Pu in the present example), and a calculation of the in-process inventory at time T_0 as follows [6]:

$$I = \sum_{i=1}^{n} \frac{C_i - C_D}{C_I - C_D} K_i V_i \qquad (1)$$

where I = mass of in-process inventory of SNM at time T_0

V_i = i^{th} batch volume

K_i = i^{th} batch mass concentration of SNM (e.g., g/liter Pu)

C_I = isotopic fraction of tracer isotope, contained in the in-process material

C_D = isotopic fraction of tracer isotope in the special batch of displacing material

C_i = isotopic fraction of tracer in the i^{th} product batch

Equation (1) expresses a simple mass balance on the tracer isotope; the derivation is available in earlier papers on dynamic inventory methods. Important features of the tracer step displacement method are:

1. The special displacing batch must be large enough to sweep virtually all of the in-process material out of the plant;
2. The collection and segregation of inventory batches must be continued until only the tracer batch emerges in the product and waste streams;
3. The isotopic composition of all the in-process material at time T_0 must be uniform (C_I).
4. The isotopic composition of the displacing feed batch must be uniform (C_D).

If these requirements are satisfied, the displacement step method allows the measurement of in-process inventory without shutting the plant down, with an accuracy determined by the precision with which the parameters in Eq. (1) are measured.

Tracer pulse methods, the subject of this paper, differ from the tracer step displacement method in several fundamental aspects:

1. rather than displacing the in-process material, pulse methods use the continuing process flow as a carrier for the pulse of tracer material, which has its characteristic isotopic composition;
2. if normal plant operations cause fluctuations of the input isotopic composition of the SNM of interest, as might result from variations in the histories of fuel batches being fed into the reprocessing plant, then such fluctuations can be used instead of intentionally introduced pulses.
3. when using pulse methods, it is not necessary that the in-process material have a uniform isotopic composition throughout the plant.

The above advantages offer incentives for the study and consideration of pulse methods for dynamic inventory measurements. Pulse methods do have certain requirements that restrict their application. They require that the plant be maintained at steady-state (as regards total inventory but not isotopic composition) during the measurement, contrary to the requirements of the tracer step displacement method. This is because pulse methods determine the in-process inventory during a finite time interval, rather than at a discrete instant of time; consequently, the inventory must be constant during the measurement, and therefore steady-state must exist. Also, pulse methods involve the analysis of the isotopic composition of many more samples than the step method. Automated sampling and measurement of isotope ratios to within about 1% accuracy will be required to realize the full usefulness of pulse methods. This instrumentation need appears to be within the present state-of-the-art, as will be discussed.

B. DYNAMIC INVENTORY BY MEASURING THE TEMPORAL RESPONSE OF A PLANT

In a plant operating at steady state, with a constant inventory of nuclear material over time interval T_t the inventory can be measured by determining the residence time of the average particle of nuclear material in its travel from plant input to output. If this average residence time is t_r hours and the feed rate of nuclear material is F kg/hr, the in-process inventory of nuclear material is:

$$I = t_r F \qquad (2)$$

where I = the in-process SNM

Equation (2) simply formalizes the concept that if the "average" particle takes t_r hours to traverse the plant, the amount of material introduced into the plant between the entrance and exit times of this particle would be $t_r F$. This is the amount of material that would be held in the plant (i.e., the inventory) at the time the "average" particle exits. Since it is assumed that the plant is operating at steady-state for these measurements, the quantity of in-process material is constant, and therefore Eq. (2) gives the in-process inventory. If the plant contains pockets or chambers of SNM solution that are stagnant (having no exchanges with the throughput of the plant), the SNM in those stagnant pockets will not be included in the inventory measurement by either the pulse or the step displacement methods. Next, the basic method for determining t_r experimentally by the injection of an idealized pulse of tracer material will be described.

Regardless of the form into which subsequent equations are cast, the basic problem is the determination of t_r. The average residence time t_r can be measured in a plant operating at steady state if a quantity L kg of tracer material is injected into the inlet flow in a pulse

of infinitesimal width, and a measurement is made of the elapsed time for that tracer pulse to appear at the outlet. In the simplest case where there is no mixing, the tracer would preserve its idealized pulse shape all during its course through the plant, and the measurement of residence time would be exceedingly simple and obvious. In a real plant, mixing and dispersion in time will occur, with the result that the tracer will appear at the outlet in a distended pulse, the shape of which is determined by the nature of the flow through the plant. Suppose that between time t and t + dt (where time zero corresponds to the time of pulse injection at the inlet) a quantity of tracer CFdt is observed leaving the plant at the outlet. In this notation, C is the concentration of tracer in the nuclear material (i.e., the isotope fraction of tracer isotope). The residence time of that sample of tracer is t, and the sample contains a fraction CFdt/L of the total L kg of injected tracer. The average residence time of the injected pulse is the weighted summation of residence times of various samples, where the weighting factor is the fraction of total tracer material in the given sample. That is,

$$t_r = \int_0^T t\frac{CF}{L}\,dt = \frac{F}{L}\int_0^T Ctdt \qquad (3)$$

and, from Eq. (2),

$$I = \frac{F^2}{L}\int_0^T Ctdt \qquad (4)$$

In the above derivation, it was tacitly assumed that the injected tracer was unique with respect to the materials normally present in the plant throughput. This is not necessary, and is generally not the case. The derivation of Eqs. (3) and (4) is valid with the substitution of $C(t)-C_0$ in place of C, where C(t) designates the total concentration of the monitored isotope and C_0 the background concentration of that isotope in the normal throughput. Hence, Eq. (4) can be rewritten:

$$I = \frac{F^2}{L}\int_0^T [C(t)-C_0]tdt \qquad (5)$$

The inventory, I, determined in Eq. (5) is the quantity of nuclear material in process during the time the injected tracer pulse propagates through the plant.

An infinitesimal inlet pulse of tracer allows the simple derivation of Eq. (5), but is not a practical form to use in plant operations. It can be shown that Eq. (5) with modified limits of integration as in Eq. (6), applies to any symmetrically shaped input disturbance of finite width, so long as time-zero is chosen as the midpoint of the input disturbance.

$$I = \frac{F^2}{L}\int_{-T_1}^{+T_2} [C(t)-C_0]tdt \qquad (6)$$

where T_1 = sampling period prior to midpoint of symmetrical input pulse

T_2 = sampling period subsequent to midpoint of symmetrical input pulse.

The limit of integration T_1 in Eq. (6) must be such as to start the integration at least as early as the beginning of the finite input pulse, and T_2 must be such as to continue integration until virtually all of the tracer material has passed through the plant.

Regarding the independent variable, which has been chosen as time in the discussion until now, cumulative mass throughput of nuclear material could just as well serve as the independent variable, and is often more convenient. With g as the cumulative feed, we have:

$$g = \int_0^t Fdt \qquad (7)$$

Upon introduction of an idealized pulse in the feed stream, the tracer material follows the many paths available to it. Each portion of tracer arrives at the system exit with the portion of the feed that followed the same path as the tracer. The holdup (inventory) associated with a given path is simply the amount of feed that followed that path as the input pulse progressed from input to output. Numerous parallel paths may have the same path length, and hence, the associated tracer material from numerous paths may reach the exit simultaneously. The amount of tracer associated with an element Δg of feed arriving at the exit after g units of feed have passed through the system is $(C-C_0)\Delta g$. The fraction of total tracer is

$$\frac{(C-C_0)\Delta g}{L}$$

Hence, the holdup (inventory) of nuclear material following paths that result in exit during the interval Δg is

$$\Delta I = \left[\frac{(C-C_I)\Delta g}{L}\right]\cdot g$$

The total holdup (inventory) of the entire system is the summation of all paths, or

$$I = \Sigma\Delta I = \frac{1}{L}\int_0^G (C-C_I)g\,dg \quad (8)$$

This is equivalent to equation (5) with g replacing Ft, and dg replacing Fdt. Hence, all results derived from equation (5) with t as independent variable still apply, except that the independent variable is now g.

B.1 Errors in the Simple Pulse Response Method

Errors in inventory determinations by the finite pulse method arise from the combination of errors inherent in measuring C(t), C_0, t, F, and L, or their corresponding variables in Eq. (8), plus errors introduced by departures of the real plant from the assumed idealized conditions of steady state. Random errors in F^2 and L as used in Eq. (6) would combine as the square root of the sum of their squares. Errors involving the integrand require a somewhat more complicated analysis.

Let C(t), or C_0, or both be subject to instrument random noise or to random fluctuations in the actual isotope composition of the monitored product stream. Represent these fluctuations as pulses of random magnitude (positive or negative) occurring at random times (a uniform probability distribution in time). In this formulation, a train of random impulses m_i, each weighted by its time of occurrence, is added to the integral in Eq. (6).

$$I = \frac{F^2}{L}\int_{-T_1}^{+T_2} [C(t)-C_0]\,t\,dt + \Sigma_i m_i t_i \quad (9)$$

Each m_i represents an erroneous input of C(t) Δt at t_i. The magnitudes of the various m_i are described by a probability distribution with a mean of zero and a mean-square magnitude $\overline{m^2}$. The mean rate of occurrence of impulses m_i is V events per unit time. The expectation value of the error due to noise or fluctuations can be shown to be [7]

$$E\,(\overline{\varepsilon^2})_I = V\,\overline{m^2}\,\frac{F^3}{3L^2}\,[T_1^3 + T_2^3] \quad (10)$$

where $(\overline{\varepsilon^2})_I$ = mean squared inventory error due to spurious random isotope fraction fluctuations, either real or instrumental

$E(\overline{\varepsilon^2})_I$ = expectation value of $\overline{\varepsilon^2}_I$

V = mean rate of occurrence of spurious impulsive signals

$\overline{m^2}$ = mean squared magnitude of spurious signals

F, L, T_1, T_2 as defined in Eq. (6).

In instances where the quantity $V\,\overline{m^2}$ results from real fluctuations in isotope composition at the input and output of the plant, considerable improvement can be achieved by including those real fluctuations in the analysis. That is, measured fluctuations at the input can be viewed as part of the excitation of the plant, in combination with the finite pulse that is deliberately introduced. This leads to the use of correlation methods by which the residence time is inferred from a correlation of inlet and outlet perturbations in isotope composition, a subject which occupies much of the following discussion. In the limiting case where the fluctuations in isotopic composition are large, the deliberate introduction of a tracer pulse could be dispensed with altogether, and a running computation of in-process inventory could be performed on those naturally occurring perturbations. Use of the correlation methods discussed below would also eliminate the need for symmetry in an intentionally injected tracer pulse. Furthermore, if random measurement errors are significant, correlation methods provide a means of inferring the statistically best estimate of the impulse-response and in-process inventory of the plant.

B.2 Correlation Methods

If the plant behaves as a stationary linear system, it is possible to deduce the idealized impulse-response of the plant by correlating observations of the input and output perturbations of isotope composition. Once the impulse-response has been inferred, the in-process inventory can be computed via Eq. (4). If the input and output parameters are observed exactly, the computation of impulse can be carried out by determining the plant's transfer function as the ratio of the Fourier transforms of the output to that of the input. The impulse-response is then the inverse Fourier transform of the transfer function [8]. However, if the input and output measurements include random errors due to sampling, instrument errors, etc., the correlation requires a statistically based method, such as a Weiner filter [9] [10]. This turns out to be a more satisfactory computational method, even in the absence of random errors. The Weiner filter computation of a plant's impulse response forms the foundation of much of this paper, and so a short derivation of it is appropriate.

Referring to the diagram of a generalized system in Figure 1, the input signal x(t) represents a time varying perturbation of isotope composition in the feed stream entering a plant. The resultant perturbation of isotope composition leaving the plant is z(t), which is observed with superimposed noise (random error) and is perceived as y(t). Let the unknown impulse-response

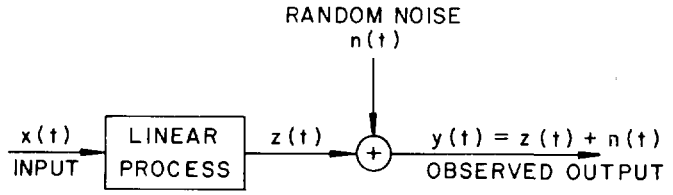


Fig. 1 Generalized System Block Diagram

of the plant be C(t)*, and let the settling time of the system be T_s. At times greater than T_s after an idealized impulse input, the response of the plant is virtually zero. The introduction of a finite settling time T_s avoids integrations over infinite intervals. Then the system shown in Fig. 1 can be described as:

$$z(t) = \int_0^{\infty} x(t-\tau)\, c(\tau)d\tau = \int_0^{T_s} x(t-\tau)c(\tau)d\tau \quad (11)$$

and

$$y(t) = z(t) + n(t) \quad (12)$$

where $n(t)$ = random error

and τ = time lag, the independent variable in the impulse response.

The method used here to obtain a statistical estimate of the impulse response C(t) minimizes E^2 the expected value of the error squared, where

$$E^2 = \int_a^b [z(t) - y(t]^2\, dt$$

$$= \int_a^b [\int_0^{T_s} x(t-\tau)C(\tau)d\tau - y(t)]^2\, dt \quad (13)$$

where a and b define the time interval over which y(t) is observed.

For known x(t) and y(t), the problem is to find $C'(\tau)$ such that E^2 is minimum. It has been shown that the condition for minimizing E^2 is [9]:

$$\int_0^{T_s} C'(\theta)\phi_{xx}(\tau,\theta)d\theta = \phi_{xy}(\tau) \quad (14)$$

where θ is a dummy variable

*C(t) is the response of the exit isotope-fraction, as the consequence of an ideal unit impulse in input isotope fraction.

and

$$\phi_{xx}(\tau,\theta) = \int_a^b x(t-\tau)x(t-\theta)\, dt \quad (15)$$

$$\phi_{xy}(\tau) = \int_a^b y(t)x(t-\tau)\, dt \quad (16)$$

for $0 \leq \tau \leq T_s$; $0 \leq \theta \leq T_s$; $a \leq t \leq b$

In order to obtain C′ from equations (14), (15), and (16), when y(t) and x(t) are available as sampled data, the following procedure is employed, where capital letters denote matrices and lower-case letters denote vectors. In the sampled-data format with N pairs of x and y data, the integral in Eq. (14) becomes a summation, which is most conveniently expressed in matrix algebra, as in Eq. (17).

$$\Phi_{xx}\, c' = \phi_{xy} \quad (17)$$

where c′ is the vector equivalent of $C'(\tau)$

$$\Phi_{xx} = X^T X \quad (18)$$

$$\phi_{xy} = X^T y \quad (19)$$

X^T = transpose of X

$$X = \begin{bmatrix} x_0 & x_{-1} & \cdots & x_{-(k-1)} \\ x_{-1} & x_{-2} & & \vdots \\ x_{-2} & x_{-3} & & \vdots \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ x_{-(N-k)} & \cdots & \cdots & \end{bmatrix} \quad (20)$$

where k is the number of elements in c′ to be estimated. Solving (17), we obtain the desired expression for the impulse response vector c′.

$$c' = \Phi_{xx}^{-1}\, \phi_{xy} \quad (21)$$

where Φ_{xx}^{-1} is the inverse of Φ_{xx}.

Equation (21) is readily implemented by computer if sampled data x(t) and y(t) are available. The square matrix Φ_{xx} which must be inverted is k dimensional, rather than N dimensional; N, the number of data points, is generally much greater than k, the number of elements of impulse response being estimated. In practice, we obtained better results when we took first differences of the time series x(t) and y(t), and used those differenced time series as the input data for Eq. (18)-(21). Differencing the data has the effect of making them more stationary.

For the sake of illustrating the correlation method, we consider the hypothetical system shown in Fig. 2, comprised of two well-stirred tanks each containing 0.5 kg of plutonium (several isotopes). The flow of Pu-bearing solution moves through the first tank, while being mixed with the contents of that tank, and then passes as plug flow through an idealized pipe that contains an inventory of 0.5 kg. The pipe introduces a simple transport lag in the stream entering the second well-stirred tank. In this example, we will use ^{239}Pu as the tracer isotope, and will consider the ratio of ^{239}Pu to total Pu as the measured variable at the inlet to the first tank and the outlet of the second tank. An arbitrary history has been assumed for the isotope fraction of the input stream, and the mathematical equation corresponding to Fig. 2 was used to compute the history of output isotope fraction. Input and output histories are shown in Fig. 3, as a function of cumulative feed to the hypothetical plant. The assumed input history suggests the type of variation that might be seen as a result of a succession of feed batches of varying irradiation histories. A single finite pulse could have been used as the input function. However, even if a finite pulse were to be used as the tracer perturbation in a real plant, the Weiner filter computation would still be used for the analysis, in order to deal with noise.

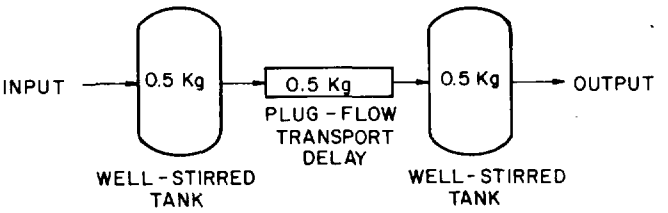


Fig. 2 Simple System for Illustration

Then sampling the input and output histories of Fig. 3 at intervals of 0.05 kg, and performing the computation indicated by Eq. (21), which is essentially a Weiner filter computation, we obtain the estimated impulse-response shown by the square symbols in Fig. 4. The transport delay shows dramatically as an 0.5 kg lag before any response appears. These estimates were ob-

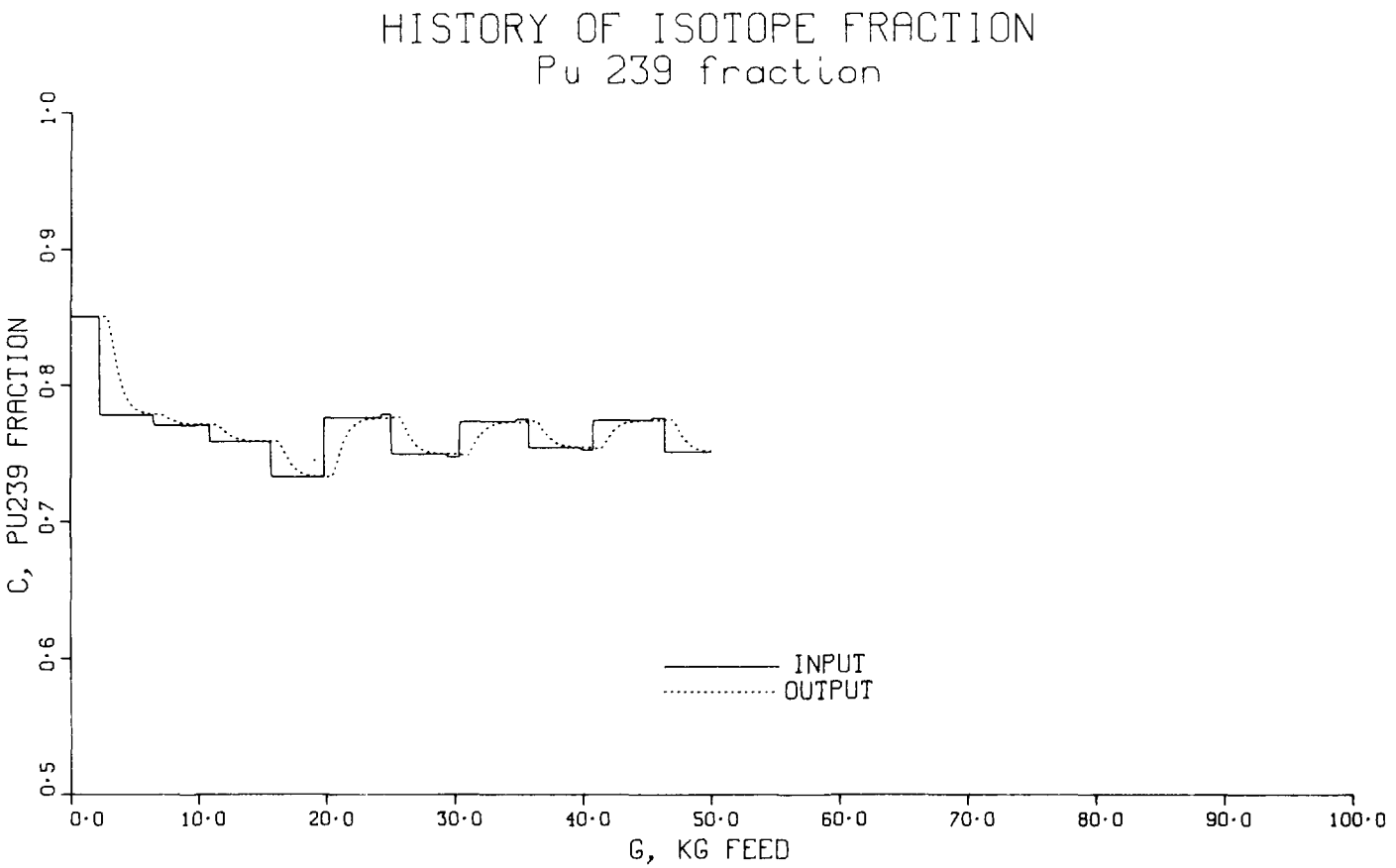


Fig. 3 Postulated Input and Corresponding Output of Simple System

tained without using any information about the system, other than the simulated observations of input and output. The dotted curve in Fig. 4 is the theoretical impulse response of the known system. Agreement between these Weiner filter computations and the theoretical response is seen to be excellent. The in-process inventory computed from the Weiner-filter estimate of impulse response, using Eq. (8), yields 1.484 kg which is about 1% less than the known 1.50 kg. In the absence of noise, as was the case here, the error is due to numerical round-off and truncation error in the computations.* The number of pairs of data points in the Weiner filter computation (N in the discussion of Eq. 21) was 1000, and the number of elements in the estimated impulse-response was 85. These parameters are not critical in a noiseless system, and much smaller values (several hundred pairs of data samples) have been used with only modest increases in computational error. The existence of noise (random error in the observation of input and output isotope composition) will introduce restrictions, as is discussed later.

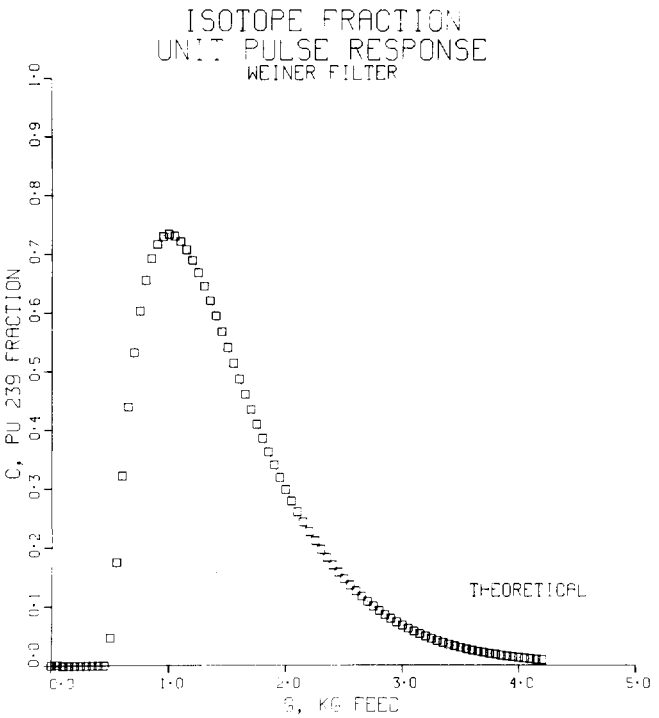
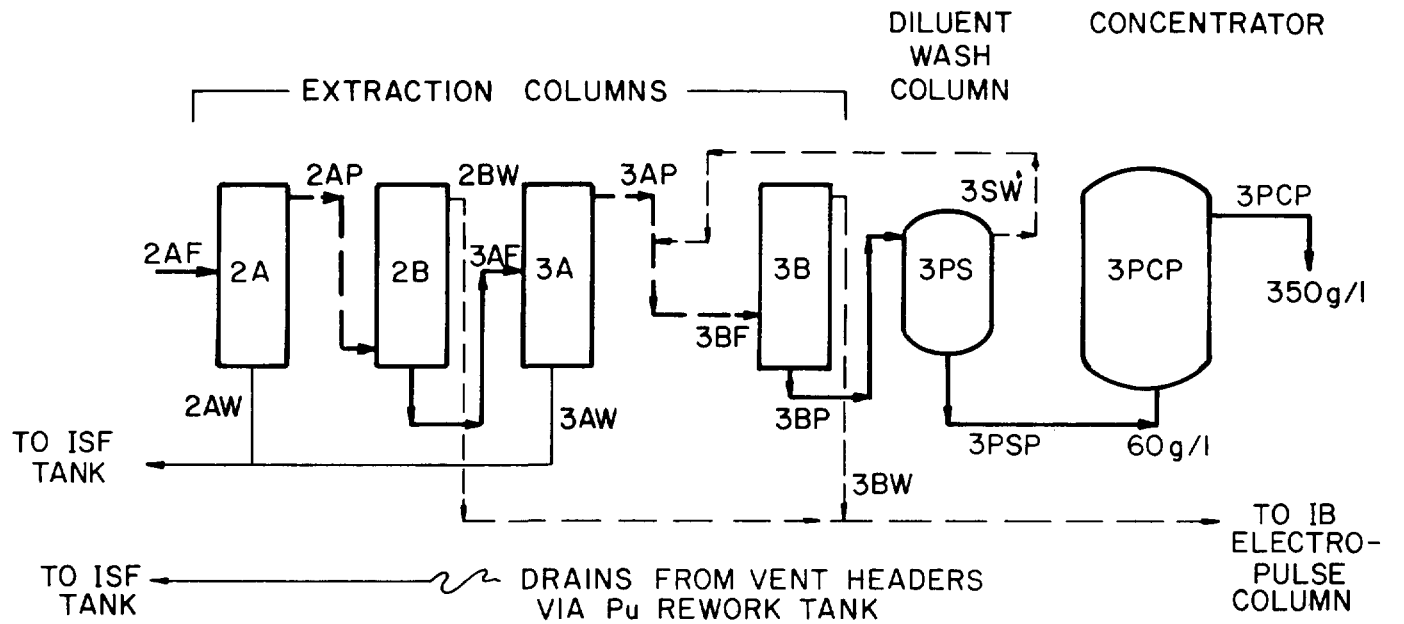


Fig. 4 Unit-Impulse Response of Simple System, Theoretical and As Computed Via Weiner Filter

Having demonstrated that the impulse of a simple system can be accurately estimated from input-output records, and that the in-process



SOLID LINES . . . . AQUEOUS STREAMS

DASHED . . . . . .ORGANIC STREAMS

HEAVY LINES. . . . Pu BEARING

LIGHT LINES. . . . .WASTE

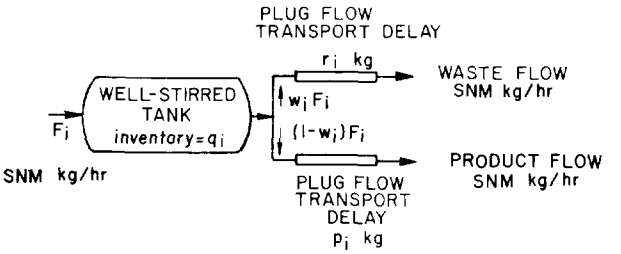
Fig. 5 Flow Diagram of Plutonium Purification Cycle in the Allied-Gulf Nuclear Services Barnwell Plant

*The major portion of the numerical error evidently is introduced in the matrix inversion process. The computations in this paper utilize the matrix inversion routine "LINV2F" of the International Mathematics and Statistics Library, Inc. The routine uses Gaussian elimination (Crout algorithm) with equilibration, and iterative improvement if necessary.

inventory calculated from the estimated impulse response is an excellent estimate of the true in-process inventory, we will now consider a more complicated plant and the effects of random measurement errors.

B.3 Correlation Method Applied to More Complicated Plants

We now consider the system shown diagrammatically in Fig. 5. This is the schematic for the plutonium purification cycle in a specific modern fuel reprocessing plant [11]. In addition to the feed stream 2AF and product stream 3PCP, there are the two waste streams shown (aqueous and organic) which will be included in the inventory. Although the schematic in Fig. 5 was available in the Final Safety Analysis Report on this plant, specific and detailed process data on capacities, rates, etc. are part of a proprietary addendum, and are not available for purposes of this study. Therefore, a set of arbitrarily assumed parameters were assigned to each of the six process stages in Fig. 5, in order to compute an output history of isotope fraction for use in Weiner filter computations. Each process stage was represented by the same conceptual model shown in Fig. 6, but with the different numerical values tabulated in Fig. 6. These assigned values result in an in-process inventory of 25.884 kg for the "plant" shown in Fig. 5*. Then, this will be the reference



STAGE NUMBER	VESSEL DESIGNATION	VESSEL INVENTORY kg	SNM FRACTION TO WASTE w	TRANSPORT DELAY	
				PRODUCT p_i kg	WASTE r_i kg
1	2A	1.0	0.01	2.9700	0.0300
2	2B	1.0	0.02	2.9106	0.0594
3	3A	1.0	0.02	2.8524	0.0582
4	3B	1.0	0.02	3.2771	0.0669
5	3PS	2.0	0.15	1.3927	0.40965
6	3PCP	4.0	—	1.8570	—

Fig. 6 Model and Parameters Used to Represent Each Stage of a Hypothetical Plutonium Purification Cycle. Parameters were assigned arbitrarily for the purpose of illustratory computations.

*The sum of all the vessel inventories, plus delay lines p_i and r_i in the table in Fig. 6 is 25.884 kg.

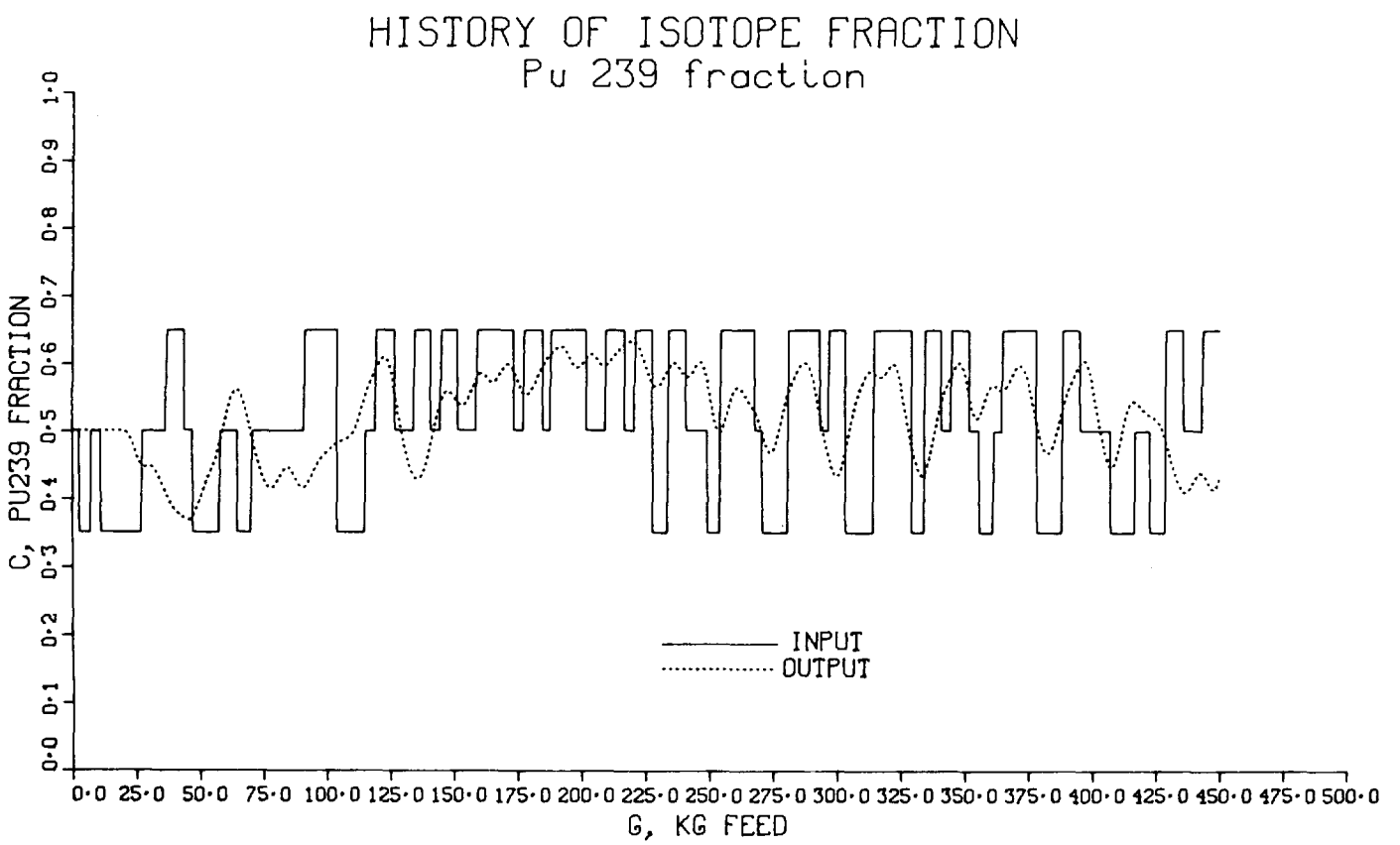


Fig. 7 Postulated Psuedo-Random Input History and Corresponding Output of Hypothetical Plutonium Purification Cycle

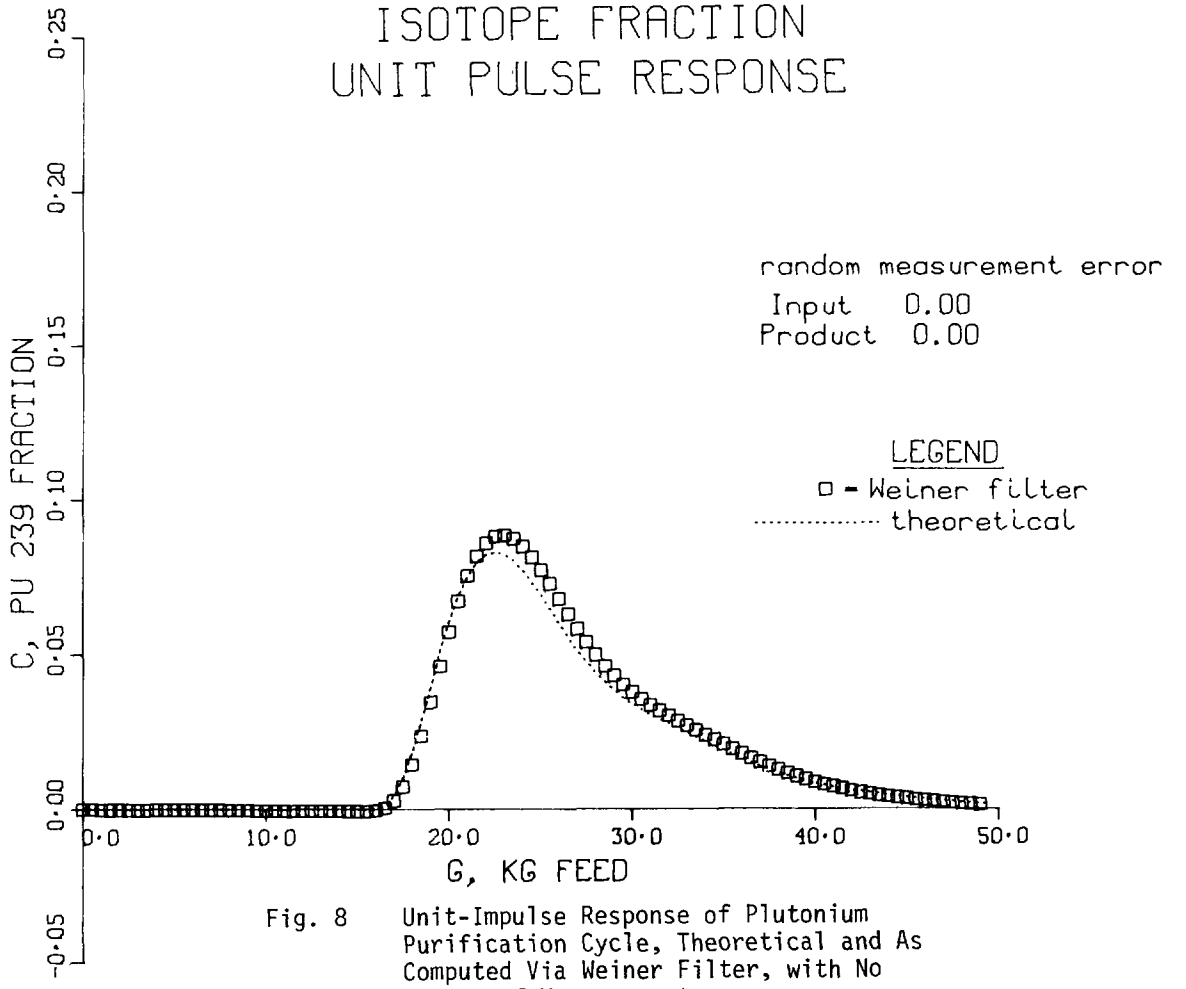


Fig. 8 Unit-Impulse Response of Plutonium Purification Cycle, Theoretical and As Computed Via Weiner Filter, with No Errors of Measurement

against which Weiner filter inventory estimates will be compared. The stage model of Fig. 6, along with the assigned numerical parameters, was chosen to produce a plant characteristic for which it is relatively difficult to obtain accurate inventory estimates, because of the long "tail" of the impulse response. It is anticipated that real extraction columns will have more nearly plug flow than the parameters of Fig. 6 represent.

A pseudo-random input function was generated for the history of ^{239}Pu isotope ratio in the feed stream 2AF. This is shown in Fig. 7, along with the computed history in the product stream 3PCP. Corresponding histories for the waste streams were also calculated but are omitted, to avoid complexity. Using the input and output histories shown in Fig. 7, plus the waste output histories, the computation represented by Eq. (21) was performed to estimate the impulse response of the plant. Note that no information on the plant, other than its input and outputs, is used. The results are shown in Fig. 8, where the symbols represent the Weiner filter computation using 900 samples of input data at intervals of 0.5 kg, with the same number of simultaneous output samples at their corresponding feed intervals (different because the feed material emerges at three output streams: product, aqueous waste, and organic waste). The dotted curve in Fig. 8 is the product stream theoretical impulse response. Similar impulse responses were calculated for the aqueous and organic waste streams. The inventory computed via the estimated impulse response is 25.704 kg, which is 0.7% lower than the exact value of 25.884 kg. Another calculation utilizing 450 samples at 1.0 kg intervals of feed yielded an inventory estimate of 25.664 kg, giving an error of 0.85% from the true quantity. This numerical error depends somewhat on the character of the input data as well as the sampling interval and data record length.

Examination of Fig. 8 will suggest that the error of the estimated impulse response (the degree to which it departs from theoretical) is greater than the 0.7% error in calculated inventory. This is true. The relatively good computed inventory results from the first-order self-correction which was included in the computation. When using Eq. (4) to calculate the inventory from the impulse response c' from Eq. (21), it is necessary to compute L as

$$F \int_0^{T_s} c'dt.$$

Then, if the computed impulse response c′ has the correct shape, but is too large or too small relative to the theoretical response, the error in L exactly compensates the error in

$$F \int c' t dt,$$

and the correct inventory is obtained. Hence, only distortions in the shape of the computed impulse response will degrade the computed inventory.

Note also in Fig. 8, the long "tail" of the impulse response, which was deliberately contrived by the choice of parameters, as mentioned earlier. Although the inventory of SNM is about 26 kg, the tail of the response extends to about 50 kg (this would be the equivalent value of T_s). If pure plug flow prevailed, the impulse response would be an idealized spike at g ≅ 26 kg.

B.4 Effects of Random Measurement Errors

The derivation of Equation (21) was motivated by the desire to extract an optimum estimate of the plant's impulse response when the observations of input and output are contaminated with random measurement errors (noise). To investigate the accuracy of the inventory estimation method when noise is present, independent Gaussian pseudo-random noise series were generated, to be added to the simulated input measurement series, and to each of the three output streams. Cases were computed with various noise levels, as described by the standard deviation of the Gaussian distribution. Figure 9 shows the estimated impulse response for a case based on the input and output series of Figure 7, but with independent noise added to the input, product, and two waste-stream "measurements". The standard deviation of the noise was 0.01, in absolute units of ^{239}Pu isotope fraction, on all measurements of ^{239}Pu isotope fraction. The magnitude of "signal" fluctuations shown in Fig. 7 is about ± 0.05 in the product stream and ± 0.15 in the input stream. The case shown in Fig. 9 employed 300 data samples from each of the four streams, at intervals of 1.5 kg SNM in the feed streams. The reasons for choosing this interval will be discussed shortly.

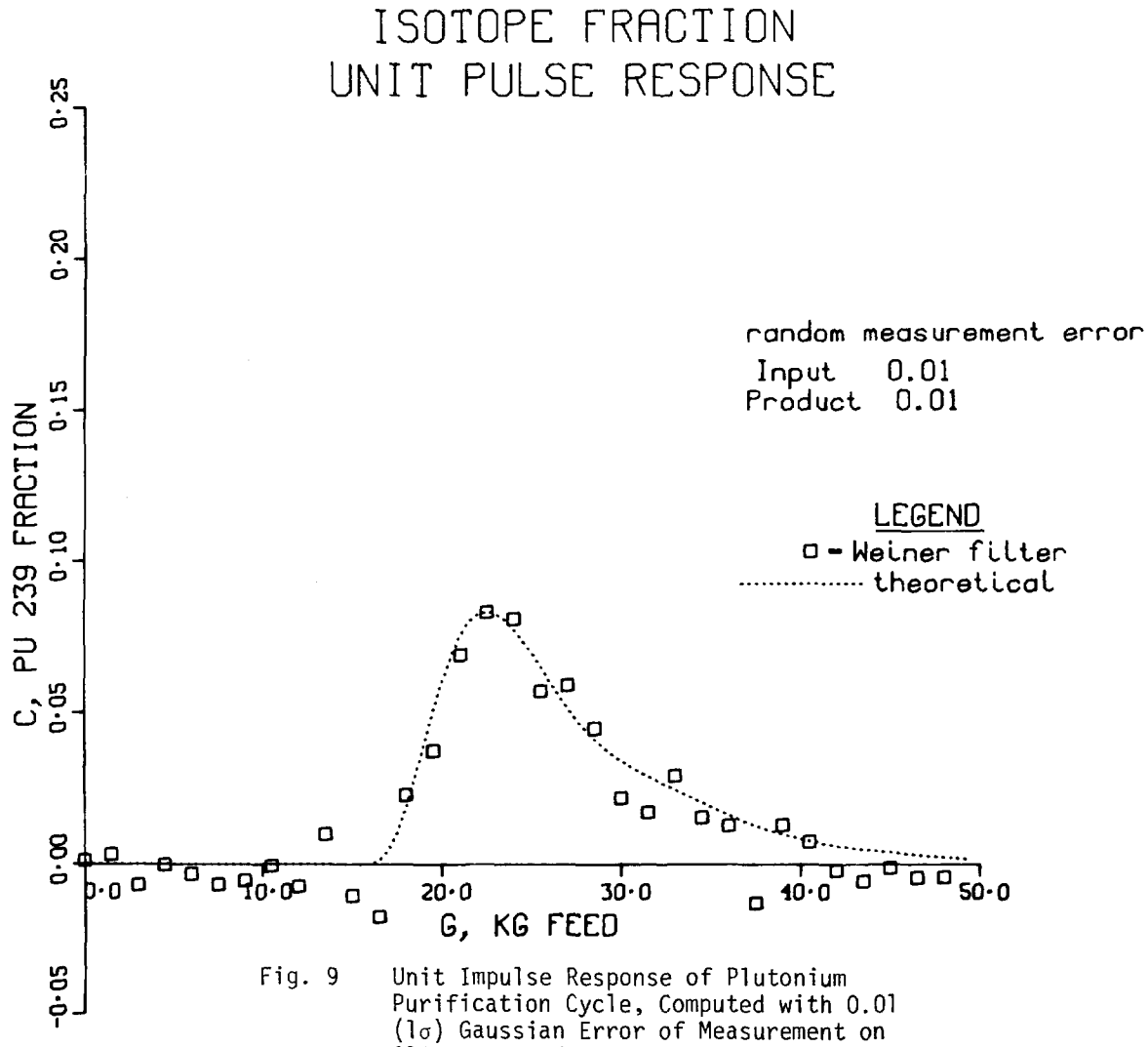


Fig. 9 Unit Impulse Response of Plutonium Purification Cycle, Computed with 0.01 (1σ) Gaussian Error of Measurement on All Input and Output Isotope-Fraction Samples

The in-process inventory calculated from the estimated impulse response shown in Fig. 9 (plus those of the two waste streams) is 25.830 kg (-0.2% error relative to correct value). The estimated impulse response and calculated inventory varies somewhat between ostensibly similar computations because the simulated random measurement error varies naturally from run to run. This is illustrated in Table I, where results from five computations are compared, each

TABLE I. Effect of Isotope Fraction Measurement Precision on Precision of Inventory Calculation

Absolute Standard Deviation of Isotope Fraction Measurement Error	0.01	0.02
Individual Estimates of Inventory for 5 Independent Cases	25.060 kg 25.080 26.307 24.676 26.506	24.536 kg 24.924 27.261 24.080 28.349
Mean	25.53 kg	25.83 kg
Standard Deviation	0.82 kg	1.87 kg
Relative Standard Deviation (based on true inventory	0.032	0.072

True In-Process Inventory 25.86 kg

For Plant Input and Product Output Isotope Fraction Histories of Fig. 7. In-Process Inventory and Error Computations Based on an Input Record Length of 459 kg, a Sampling Interval of 1.5 kg, and an Impulse Response Extending 48 kg of Feed Subsequent to the Hypothetical Impulse Input, with Estimates of the Impulse Response at 33 Equally Spaced Points in that Interval.

operating on identical plant input and output, and each having the same statistical distribution of random error of "measurement". The results in Table I are for random error standard deviations of 0.01 and 0.02 isotope fraction added to the input (feed) "measurements", the product "measurements", and both waste stream "measurements".

The inventory estimation error depends on the magnitude of signal tracer perturbation. Larger input signal perturbations reduce the inventory error, for a given random error of measurement, as a result of an improved signal-to-noise ratio. The results presented in Table I indicate that a random error of 0.02 (standard deviation, absolute) in the measurement of isotope fraction of the chosen tracer isotope will introduce a relative error of 0.07 (standard deviation, relative to true inventory) in the inventory estimate, for the assumed input and plant model.

B.5 Sampling Interval and Length of Operating Records

Short durations are desirable for dynamic inventory measurements, if only to minimize the time over which the in-process material must be held constant, and to keep plant operations as simple as possible. The minimum duration of measurements (length of operating record) by the dynamic inventory method considered here is approximately twice the settling "time", or twice 50 kg in the foregoing example [10]. This minimum for the record length can be derived heuristically by recognizing that the definition of the settling time T_s means that isotope composition perturbations in the feed stream between $t-T_s$ and t will cause responses in the product streams between $t-T_s$ and $t+T_s$. In this respect, contriving a long "tail" for impulse response, as was done in the example, imposes a longer required operating record than might be needed if mixing is actually less than assumed in the example. Random measurement error (noise) has the effect of requiring longer operating records, for any specified accuracy, because additional redundancy of input and output data is then required in order to average out the noise. A practical device for judging the adequacy of the selected record length (after using Eq. 21) is to calculate

$$F \int_0^{T_s} c'dt.$$

This should be approximately unity.

As well as minimizing the record length, it is also desirable to minimize the number of samples to be measured, for obvious practical reasons. For a given length of record, this is of course accomplished by using as large a sampling interval as possible. As it turns out, there is a theoretical optimum sampling interval (smallest is not necessarily best) for the purpose of minimizing noise effects. The optimum sampling interval for minimizing random error equals $1/2f_c$), where f_c is the plant's cut-off frequency, or the highest frequency present to any significant degree in the plant's response [10]. Examination of the simulated fluctuations in the product stream plotted in Fig. 7 indicates the highest frequency present is about 0.15 cycles per kg feed. This has been confirmed by a calculation of the spectrum of the product trace in Fig. 7. Then, with $f_c = 0.15\ (kg)^{-1}$ the optimum sampling interval for minimizing random error would be about 3 kg. Smaller sampling intervals would be expected to introduce more noise "events" without providing additional information on the relationship between plant input and output, because the output does not change significantly in an interval less than $1/2\ f_c$. Larger sampling intervals would lose information on the relationship between plant input and output.

There is another important factor, however, which influences the selection of the sampling interval and may shift the optimum interval. Computation of the impulse response via Eq. (21) produces numerical values of the impulse response at intervals equal to the sampling interval. Larger sampling intervals produce fewer points on the impulse-response curve, and hence poorer resolution of the impulse-response. Then larger sampling intervals tend to introduce systematic errors in the computed inventory, as a result of diminished resolution of the impulse-response.

Experimentation with record lengths and sample intervals for the example under discussion has shown that sampling intervals of 0.5 kg to 1.5 kg produce the best results in the present case. The 1.5 kg sampling interval produces the best reconstruction of the plant impulse response in the presence of noise, and for that reason, a 1.5 kg sampling interval was used to obtain Fig. 9. For lengthy records and low to moderate noise, the 1.5 kg sampling interval also produces more precision in the computed in-process inventory than an 0.5 kg sampling interval, but at short record lengths and large measurement errors, the 1.5 kg interval tends to fail the criterion that

$$F \int_0^{T_s} c'dt \cong 1.0,$$

and tends to show large and erratic errors. This is an empirical observation from numerous computations, and bears further study. The findings are illustrated in Table II where results of a number of trial calculations are given for various record lengths, sampling intervals, and noise levels. Each set of results in Table II was obtained by five independent computations (each with its own random noise series). It can be seen that in every case where the 1.5 kg sampling interval gave acceptable results by the

$$F \int c'dt \cong 1.0$$

criterion (only such cases were tabulated), the inventory estimates are at least as accurate and precise as for the 0.5 kg sampling interval, which requires triple the number of samples. However, the 0.5 kg sampling interval allows the shortest record length of 112.5 kg to be attained (approximately the 2 T_s limit), whereas the 1.5 kg sampling interval is unreliable at that short record length. For the 0.5 kg sampling interval, accuracy of inventory estimation is evidently not very sensitive to record length in the range of Table II, because no significant variation in precision appears across most rows of the table.

If the random measurement error of isotope fraction is 0.01 absolute (1σ), Table II indicates 4% precision (1σ) of in-process inventory can be achieved in the example, if the simulated feed, product, and waste streams are sampled for a feed duration of 225 kg at 1.5 kg intervals (150 samples in each of the 4 streams, for a total of 600 samples). The record length of 225 kg corresponds to about 9 in-process inventory amounts. In terms of time, if the throughput rate is 1 inventory amount per day (an average residence time of 1 day), the measurements in the above example would extend over 9 days. During this time the plant would be operating normally, except for the injection of tracer pulses, the drawing of samples, and the restriction that liquid levels and SNM concentrations be maintained constant, in order to keep a constant SNM inventory. If the set of parameters in Fig. 6 had been chosen to produce less mixing, the impulse response would have had a shorter tail, the settling time, T_s, would have been shorter, and a shorter record length could have been achieved.

TABLE II. Inventory Calculations For Various Durations of Measurement (Record Lengths)

Measurement Precision (1σ)	Sample Interval kg		Record Length 112.5 kg	225 kg	450 kg	Row
0.02	1.5 kg	No. Samples	75	150	300	
		Mean Inventory			25.8 kg	1
		Std.Deviation, kg	*	*	1.9 kg	
		Std.Deviation, %			7.2%	
	0.5 kg	No. Samples	225	450	900	
		Mean Inventory	26.1 kg	27.8 kg	25.2 kg	2
		Std.Deviation, kg	2.5 kg	2.4 kg	1.9 kg	
		Std.Deviation, %	9.6%	9.3%	7.2%	
0.01	1.5 kg	No. Samples	75	150	300	
		Mean Inventory		24.8 kg	25.5 kg	3
		Std.Deviation, kg	*	1.1 kg	0.8 kg	
		Std.Deviation, %		4.3%	3.2%	
	0.5 kg	No. Samples	225	450	900	
		Mean Inventory	25.6 kg	26.7 kg	25.4 kg	4
		Std.Deviation, kg	2.5 kg	1.4 kg	1.0 kg	
		Std.Deviation, %	10%	5.2%	3.9%	
0.005	1.5 kg	No. Samples	75	150		
		Mean Inventory		25.0 kg	Not	5
		Std.Deviation, kg	*	0.6 kg	Calcu-	
		Std.Deviation, %		2.3%	lated	
	0.5 kg	No. Samples	225	450		
		Mean Inventory	26.1 kg	26.2 kg	Not	6
		Std.Deviation, kg	0.5 kg	0.6 kg	Calcu-	
		Std.Deviation, %	2.0%	2.3%	lated	

Each mean and standard deviation was obtained from 5 individual inventory computations based on statistically stationary measurement errors having the standard deviation shown in the left-hand column. The plant input and output histories of Fig. 7 were used with Gaussian measurement errors superimposed. The true in-process inventory is 25.88 kg.

* These cases exhibited erratic results, indicating that this combination of sampling interval, measurement error, and record length produces large systematic errors for the assumed plant.

It has been argued by others [4] that columns produce nearly plug flow, and if so, the foregoing example would be conservative in its estimate of the required record length. Even short record lengths would require a large number of samples to be analyzed for isotopic composition, and the practical usefulness of the temporal response method may ultimately depend on finding a satisfactory technique for sampling and measuring the isotopic composition of the streams. Recognition of this need has motivated some thinking about possible means of performing the measurements. One promising concept is described in the following section. If that method, or some other, is successful in making possible very rapid measurements of isotopic composition, there could be the additional benefit of reduced error magnitudes by virtue of redundancy of samples, within the scheme of sample-interval record-length as outlined above. That is, if each sample in the 1 kg interval were composed of, say, 4 independently drawn subsamples the random error would be approximately half the individual subsample error, and the inventory error would be approximately halved.

C. A POSSIBLE OPTICAL METHOD FOR ACTIVE RAPID MEASUREMENTS OF ISOTOPE COMPOSITION*

Existing methods for determining the isotopic composition of SNM require relatively long counting times or elaborate and lengthy sample preparation procedures. The optical methods considered here offer a potentially more rapid and easily automated system.

The following sequence of operations is envisioned:

1. Extraction of a small sample from the bulk material (liquid solution or powder).
2. Vaporization of the sample in a sealed test cell, with the production of sufficient atomic Pu or U for the measurement.
3. Measurement of absorption or emission at the wavelengths of the isotopes of interest.
4. Calculation of isotopic composition from the relative strengths of absorption or emission at the isotope lines.

Steps 1 and 4 appear to involve available technology, and will not be discussed here. Step 2, the production of a vaporized sample containing atomic Pu, appears possible by several approaches, especially for liquid samples. Conventional atomic absorption spectroscopy produces atomic samples by vaporization in a flame or in a high temperature graphite tube. Adaptation of these methods appears possible, with modifications to accommodate the needs for a tightly sealed system. Alternatively, a pulsed neodymium, ruby, or CO_2 laser focused on a droplet or small particle could vaporize and atomize the sample. This would have the potential for vaporizing solid or powder samples.

Regarding Step 3, the atomic spectra of several Pu isotopes have been measured with a wavelength accuracy better than one part in 10^7 in the visible and near visible spectral regions [12]. The wavelength of a specific atomic electronic transition shows a small dependence on nuclear mass; such isotope shifts of about 10^{-2} nm have been measured for some of the stronger emission or absorption lines (e.g., 594.5 nm) of ^{239}Pu and ^{240}Pu. By the use of tunable dye lasers and precision Fabry-Perot interferometers it appears possible to obtain data which are directly related to the relative abundances of isotopes in an apparatus which could be made compatible with an industrial environment and could be automated for routine measurements with a cycle time of about one minute. Both absorption and emission appear suitalbe for the optical measurements. The technique of quantitative absorption measurements with a tunable dye laser and an intra-cavity sample (a flame in the laser cavity) has been demonstrated with a sensitivity 10^2 better than conventional atomic absorption spectroscopy [13]. The presence of an absorber in the laser cavity selectively and quantitatively reduces the laser output at the wavelength of the absorber. In the present application, the intra-cavity absorption measurement could be performed with the test cell (where atomic Pu or U is produced momentarily) located in the laser cavity. The laser output would be measured at the two wavelengths corresponding to absorption lines of the two isotopes to be compared, plus a third reference wavelength containing no lines. Measurement bandwidths would be on the order of 10^{-3} nm, obtained by three Fabry-Perot interferometers, each tuned to one of the three wavelengths of interest. It also may be possible to perform the absorption measurements with the test cell external to the laser cavity, if the great sensitivity of the intra-cavity method is not needed. The extra-cavity absorption measurement potentially involves a simpler installation in a plant.

Wavelength-discriminated emission from the two isotopes of interest is another possible optical method for isotope composition measurements. The emission may be excited optically (e.g., a tunable laser covering the spectral region of the two isotope absorption-emission lines) or may result from excitation introduced by the sample atomization process. Measurement of relative isotopic abundance would be done by two detectors, each viewing the sample in appropriate geometry through Fabry-Perot interferometers set at the two isotope wavelengths.

Optical methods offer potential for an on-line rapid identification of bulk SNM, through virtually continuous measurement of isotopic composition. The major research needs at present concern (1) the method for vaporizing the sample so as to obtain measurable fractions of atomic species, and (2) the selection of the simplest technique from among the several available for determining relative isotopic abundances.

D. SUMMARY AND CONCLUSIONS

Summarizing briefly, this analysis has demonstrated that a plant's temporal response to perturbations of feed isotope composition can be used to measure the in-process inventory, without suspending plant operations. The main advantage of the temporal response technique over the step-displacement method are (1) it (the temporal response method) obviates the need for large special feed batches, and (2) it obviates the requirement that all the in-process material have a uniform isotopic composition at the beginning of the measurement. The temporal response method holds promise for essentially continuous real-time determination of in-process SNM. The main disadvantage or problem with the temporal response method is that it requires the measurement of the isotopic composition of a great many samples to moderately high accuracy. This requirement appears amenable to solution by a modest effort in instrument development.

*The authors are pleased to acknowledge the contributions of Dr. David W. Green on the subject of measuring isotopic composition by optical spectroscopy. The present section is from an unpublished document by D. W. Green and S. M. Zivi.

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TECHNICAL PROGRAM PLANNED—Making plans for the 17th annual meeting of the INMM to be held in Seattle, Wash., June 22-24, are four of the five members of the Technical Program Committee. From left are Bill DeMerschman (who is doubling as local arrangements chairman), Westinghouse-Hanford; Bob Keepin, program director for the Nuclear Safeguards Program at the Los Alamos (New Mexico) Scientific Laboratory (LASL), and chairman of the Seattle meeting; Glenn Hammond, Division of Safeguards and Security, ERDA, Washington; and Gary Molen, nuclear materials safeguards, Allied-General Nuclear Services. Not shown is Joerg Menzel of the Arms Control and Dispatch Agency (ACDA). (LASL Photo by Bill Jack Rodgers).

INMM-8 PILOT PROGRAM

By Louis W. Doher
Rockwell International
Golden, Colorado

Pilot Program for Replica Mass Standards (Uranium Hexafloride Cylinders) as Created by ANSI N15.18, "Mass Calibration Techniques for Nuclear Materials Control"

The publication of ANSI N15.18, "Mass Calibration Techniques for Nuclear Materials Control" is a reality. This standard was developed under the direction of INMM 8 and by writing group INMM 8.1 co-chaired by **Manley Fortune,** Union Carbide Corporation, and **John Murrell,** Goodyear Atomics Corp. It creates an NRC funded program for the assignment of mass values to in-house Uranium Hexafloride (UF_6) cylinder standards using replica mass standards (RMS) with mass values assigned by the National Bureau of Standards.

The artifact concept, as promulgated in ANSI N15.18, became a reality during the early phases of Subcommittee INMM 8 and Task Force 8.1 writing efforts. During the early research efforts, the UF_6 cylinder artifact concept, using NBS values, appeared to provide the only practical method of intraplant and interplant comparison and thus, resolution of shipper/receiver differences, and therefore was considered for inclusion in N15.18. Upon the request of the task force and concurrence of Subcommittee INMM 8, the chairman of ANSI N15 petitioned and received approval and confirmation from the then U.S. Atomic Energy Commission (USAEC) Directorate of Regulatory Standards, to fund and administer a UF_6 cylinder artifact calibration program supported by ANSI N15.18. The National Bureau of Standards agreed to be a part of the program and assign the standard mass values of the cylinders and the associated uncertainty values. The USAEC contracted Union Carbide Corporation, Nuclear Division to obtain the cylinders and the New Brunswick National Laboratory to administer the program.

Now that ANSI N15.18 has been published, the replica mass standards of the UF_6 cylinders have been manufactured and transported to NBS for mass value assignment—what is to be done with the program? To answer this question, **Paul Pontius** of the National Bureau of Standards, Consultant to INMM-8, has proposed a pilot program between UF_6 measurement facilities which are represented on the INMM 8.1 writing group. The pilot program will include:

1. Training sessions.
2. Calibration of in-house standards according to ANSI N15.18.
3. Establishing control of production weighings according to ANSI N15.18.
4. Material accountability standard measurements.
5. Data reduction.
6. Publication of results.
7. Replica Mass Standards ready for industry use.

These pilot activities are scheduled to begin during March, 1976 and will be completed approximately one year later. During this period, any questions concerning the availability of the replica mass standards should be delivered to Mr. Pontius, Chief, Mass, Length, and Volume, National Bureau of Standards, Room A-211, Building 220, Washington, D.C. 20234.

It is planned that the conclusions, precautions and data handling which result from the pilot program will be published in the Spring, 1977 issue of the INMM Journal.

Members of INMM 8.1 on "Mass Calibration Techniques for Nuclear Material Control": Mr. Doher, Chairman, Rockwell International; **Joseph M. Cameron,** NBS; Mr. Fortune, Union Carbide; **William A. Higinbotham,** BNL; **D.J. McGuire,** Dow Chemical; **J.M. McKibben,** DuPont; **John S. Murrell,** Goodyear; Mr. Pontius, NBS; **Ken Saunders,** NRC; **Stanley P. Turel,** IAEA (formerly NRC); and **Charles M. Vaughn,** General Electric.

MEASUREMENTS, BIASES AND UNCERTAINTIES

By A. Lee Harkness
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A recent paper [1] in this journal, and later comments [2],[3] on that paper, indicate that there is a considerable amount of confusion in the area of measurements, biases, and uncertainties. It seems that most of this confusion results from the use of one term to identify two related but quite different quantities and then to attribute the characteristics of one of these quantities to the other. For example, the term "systematic error" is widely used to describe both a bias in a measurement and the uncertainty in that bias. Another example is when the same term is used for a measurement and the true value of the attribute being measured. The second of these has a definite constant, although unknown, value. The first will have a variance due to the randomness of the individual measurements.

The following is a description of the views on this subject that I believe are held by the majority of people in the analytical fields. For simplicity, ideal conditions are assumed. The measuring system is considered to be stable, that is, the true value of the bias in the system is a constant for any given sample over the time required for the calibration and measuring processes. If this is not so then there is a problem which can be pointed out by the statistician, but must be solved by the analyst. All random variables are considered to be normally distributed. In a complex measuring system there may be many sources of bias and randomness. This does not concern us because they will naturally be combined within the system to give a single characteristic value and its variance.

When a physical attribute of a given item (weight, volume, chemical composition, etc.) is measured a number of times using a specific system (defined here to include operator, instrument, method, etc.), the individual values will vary over some range defined by the standard deviation of an individual measurement. It is a well-known fact that, as the number of measurements increases, their average will approach a constant value which is characteristic for that attribute in that item as measured by that system. Simultaneously, the standard deviation of an individual measurement will approach a constant value which is characteristic of the measuring system. This standard deviation is a measure of the range about the characteristic value within which a single measurement will fall with a probability of 0.68269. The standard deviation of the average is equal to that of an individual measurement divided by the square root of the number of measurements. It is then obvious that the standard deviation of the average approaches zero as the number of measurements increases indefinitely. That is, the average becomes identically equal to the characteristic value. This relationship between the standard deviation of the average and that of an individual measurement is derived from the fact that the individual measurements are random and independent. This means that positive and negative deviations, of equal magnitude, of individual measurements from the characteristic value will occur with equal frequency, and so will tend to cancel as the number of measurements increases.

Unfortunately, it is a common practice to use the term "random error" when speaking of the standard deviation. This is troublesome to the uninitiated because it implies that it could have been avoided, or corrected, as with a bookkeeping error or typing error. Such is not the case. The standard deviation of a single measurement is an uncertainty which is characteristic of the measuring system and it can be changed only by modifying the system.

The characteristic value of an attribute, as estimated by the average of a number of independent measurements, is frequently not equal to the true value

of that attribute. When there is such a difference between the characteristic and true values, whether or not this fact is known, it is called a bias. The measurements required to determine the magnitude and direction of the bias will themselves have uncertainties which are random in nature. That is, the uncertainty in the bias estimate can be reduced by increasing the number of measurements included in its determination. If a standard is involved in the bias determination, any uncertainty in its value will be a systematic uncertainty in that bias estimate and is also the limiting value of the total uncertainty.

A systematic uncertainty is one which affects the uncertainty of all measurements in the same way. The uncertainty in a bias measurement, for example, becomes a systematic component in the total uncertainty of all measurements in which it is used as a correction. This is because although the standard deviation of the bias estimate says nothing about the precise difference between the measured and true value of the bias, whatever this difference is it will be the same for all measurements to which it is applied as a correction. The average of a number of measurements which have been corrected using the same identical bias measurement, therefore, has an uncertainty which has two components: a random one which tends to zero as the number of measurements increases indefinitely, and a systematic (or constant) one which is the same as that component of the uncertainty in an individual measurement which, in turn, is equal to the total uncertainty in the bias determination. The uncertainty in the bias estimate is also a composite which, in the limit of an infinite number of measurements, becomes equal to the uncertainty of the standard used in its determination.

The current confusion is between measurements which have not been corrected for existing bias and measurements having systematic uncertainties. Such uncorrected measurements are simply incorrect or incomplete ones, and as such, are not conducive to a completely rigorous statistical treatment. A bias affects all uncorrected measurements in the same way, whereas a systematic uncertainty such as is introduced in making a bias correction affects the uncertainty in all measurements in the same way.

A second source of confusion seems to be due to the use of the term "bias" for both the bias as defined above and the value resulting from its measurement. The first of these is a constant and has no variance associated with it. The second is an estimate of the first based on the average of a number of measurements, each of which has a random error, and therefore this estimate does have a variance. To be rigorous one should use the term "standard deviation of the bias measurement" rather than "standard deviation of the bias." This dual use of the word "bias" is so widespread that there is little hope of changing the situation. However, if the distinction between a bias and its measured value is clearly understood there should be no ambiguity, the context in which the word is used should make it clear which value is meant. The measurement of a bias and the application of this measurement in producing corrected measurements from biased ones should be considered to be an integral part of the measuring process. This is entirely analogous to the use of tare weights in obtaining net weights from gross weights.

Consider a measuring system which has a standard deviation of unit weight equal to σ. Suppose also that this system has a bias which will be estimated by the difference between the average of m measurements, x_i, on a standard sample and the true value which, for simplicity, is known to be T with no uncertainty. This same bias estimate, $\bar{\theta}$, will then be used to correct each of the n measurements, y_i, of an unknown sample to obtain an estimate of its true value $\bar{Y}_c$.

$$\bar{\theta} = \bar{X} - T \tag{1}$$

$$\sigma_{\bar{\theta}} = \sigma_{\bar{X}} = \sigma/\sqrt{m} \tag{2}$$

$$\bar{Y}_c = \frac{1}{n} \Sigma(y_i - \bar{\theta}) = \frac{1}{n} \Sigma y_i - \bar{\theta} \tag{3}$$

$$= \bar{Y} - \bar{\theta} \tag{4}$$

Equation (3) demonstrates the perhaps obvious fact that the same identical value for $\bar{Y}_c$ is obtained when the individual results are corrected for bias and then averaged as when the individual results are averaged and the bias correction applied to this average. The variance of this corrected average is obtained by applying the error propagation equation to equation (3).

$$\sigma^2_{\bar{Y}_c} = \Sigma(\partial \bar{Y}_c/\partial y_i)^2 \sigma^2 + (\partial \bar{Y}_c/\partial \bar{\theta})^2 \sigma^2_{\bar{\theta}} \tag{4}$$

$$= \sigma^2/n + \sigma^2_{\bar{\theta}} \tag{5}$$

$$= \sigma^2 (1/n + 1/m) \tag{6}$$

The second term on the right side of equation (5) is the variance of the bias estimate. The equivalent equation (6) shows that this value can be reduced

by increasing m, the number of measurements on the standard used to estimate the bias, but not by increasing the number of measurements on the unknown, n.

It is the bias estimate and its standard deviation which have each been called systematic error by some, or constant and variable components of the systematic error respectively by others. This implies that they can be interchanged or combined in some way. Such is not the case. There are two classes of parameters in the distribution function. The first class describes the position of the distribution curve on the attribute value axis. The bias estimate, along with the mean of a number of measurements and the true value, is a member of this class and is an estimate of the displacement of the measured distribution curve from the unbiased, or the true curve. The standard deviation of the bias estimate, $\sigma_{\bar{\theta}}$, belongs to the second class of parameters which describe the width of the distribution curve. This $\sigma_{\bar{\theta}}$ describes the widening of the measured distribution curve in correcting to the true distribution curve due to the uncertainty in the bias correction.

It should be noted that although one can operate in the usual way on corrected individual measurements to obtain a corrected average, the same is not true for computing the standard deviation. This is because in making the transformation $y_i - \bar{\theta} = y_{c_i}$ the tacit assumption is also made that $\bar{\theta}$ is known absolutely, i.e., its standard deviation is zero. If the standard deviation of the mean is now estimated in the usual way from the n, y_{c_i} values, the result will be $s/\sqrt{n}$, where s is an estimate of σ, neglecting the standard deviation of the bias. This is the same identical value that would result from computations on the n uncorrected values, y_i.

It should also be pointed out that if the average of a number of bias measurements should be small, even equal to zero, there will still be its standard deviation, $\sigma/\sqrt{m}$, which should be included in future computations. The only time that this component can be legitimately neglected is when there is sufficient experience in the form of a large number of measurements that $\sigma_{\bar{\theta}} = \sigma/\sqrt{m}$ is reduced to a negligible quantity relative to other errors.

There are other sources of systematic uncertainties than that introduced in making bias corrections. For example, suppose that one is determining the average uranium-235 content, $\bar{X}$, in a quantity of material by combining a number of total uranium measurements with a number of isotopic measurements. The correct way would be to combine the average of the total uranium measurements, $\bar{U}$, with the average of the uranium-235 isotopic measurements, $\bar{I}$.

$$\bar{X} = \bar{U}\,\bar{I} \tag{7}$$

The variance of $\bar{X}$ is

$$\sigma^2_{\bar{X}} = (\partial\bar{X}/\partial\bar{U})^2\,\sigma^2_{\bar{U}} + (\partial\bar{X}/\partial\bar{I})^2\,\sigma^2_{\bar{I}} \tag{8}$$

$$= \bar{I}^2\,\sigma^2_{\bar{U}} + \bar{U}^2\,\sigma^2_{\bar{I}} \tag{9}$$

Suppose that the individual uranium measurements, u_i, are multiplied by the average isotopic value, $\bar{I}$, to obtain individual values for the uranium-235 content, x_i. If these are averaged and the variance computed in the usual way, the expected result will be $\sigma^2_{\bar{X}} = \bar{I}^2\,\sigma^2_{\bar{U}}$, neglecting the second term on the right side of equation (9). This term, $\bar{U}^2\,\sigma^2_{\bar{I}}$ represents a systematic component to the total variance in $\bar{X}$.

If each of the n, y_i measurements are corrected by a separate, independent bias measurement, θ_i, the above discussion does not hold. If the variance of the average is computed in the usual way from the separate corrected values it will have the expected value $\sigma^2_{\bar{Y}_c} = 2\sigma^2/n$, where σ^2 is the variance of both y_i and θ_i. This is the same as the expected value of $\sigma^2_{\bar{Y}_c}$ computed using the error propagation equation and $\sigma^2_{\bar{Y}}$ and $\sigma^2_{\bar{\theta}}$, the variances of the averages of the uncorrected measurements and the bias estimate respectively. These, of course, are equal because each contain the same number of measurements made with the same system. This is not an identity and is not expected to hold exactly for a finite set of y_i and θ_i pairs of data. This is because the variance $s^2_{\bar{Y}_c}$, estimated from the corrected values, y_{c_i}, depends on the pairing of the measurements and their bias measurements. As the number of measurements increases, and if the pairing can be assumed to be made in a random way, then the variance of the corrected values will approach $2\sigma^2$ and the variance of the average of n corrected values, computed in either way, will approach the same value, $2\sigma^2/n$.

A question which has been discussed somewhat widely is when should a bias correction be made and when can (or

should) it be neglected. This requires that one make the same type of judgment decision that frequently has to be made when using statistical data in comparing two values. The usual answer is to consider the measured difference between two values to be real if this difference would occur 5% or less of the time when there is, in fact, no difference. With the bias, being itself the difference between two finite values, the question is whether it is significantly different from zero. I see no valid reason to deviate from the usual t test at the 95% confidence level. It has been suggested that bias corrections be made when $t = \bar{\theta}/\sigma_{\bar{\theta}}$ is greater than 0.1. For an infinite number of degrees of freedom, only 7.9% of the bias measurements will be equal to or smaller than this when the bias is truly equal to zero, and this percentage decreases with a decreasing number of degrees of freedom. It is far more probable, if this criterion is used, that measurements will be "corrected" for a nonexisting bias than that an existing bias will be neglected.

A bias estimate and its standard deviation are two completely different entities. The first is a measure of accuracy or the displacement of the characteristic value, as estimated by the mean of a number of measurements, from the true value of the attribute being measured; the second is a measure of precision or the degree of scatter of the individual measurements and their means about the characteristic value. The two cannot be combined in any way nor can one be substituted for the other. If individual measurements on a production sample are corrected using the same average bias estimate for each, the distribution of the corrected values will be exactly the same as that of the uncorrected values. This means that although the expected value of the mean of the corrected values is the true value, the expected value of the standard deviation of this mean will be the same as the expected value of the standard deviation of the mean of the uncorrected values thus neglecting the contribution of the standard deviation of the bias estimate. A correct procedure would be to compute the average and its standard deviation for both the uncorrected measurements and the bias measurements and then combine these according to the usual rules for the propagation of errors. If each of the individual measurements are corrected by a separate independent bias measurement then the resulting corrected values will have the proper distribution reflecting the standard deviations of both the measurements and their bias. The expected value of the mean will be the true value and the expected value of the standard deviation will be the correct one.

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SPEAKER'S BUREAU SLOWED BUT NOT DOWN

To those of you who responded to Safeguards Chairman Dennis Wilson's questionaire on a Speaker's Bureau, don't think we have forgotten you. Unfortunately, we are still seeking a Chairman for INMM Public Relations, but until we find such I faithfully promised Dennis that I would not let the matter die.

All of you are now on computer addressed labels and will soon be hearing from me relative to what is taking place. Some progress is being made and some new things are happening that should get us off to a good start.

Meanwhile, if you did not respond to the questionaire but are interested in trying to counter some of this bad and often unjust publicity that's going around, drop me a note at Oak Ridge National Laboratory, P.O. Box "X", Oak Ridge, Tennessee 37830. I'll put your name on our list and include you in all future mailings. —Roy Cardwell.

A NOTE ON A BIASED BIAS ESTIMATE

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ABSTRACT

The procedure of not making bias corrections to a measurement process unless statistical tests indicate a non-zero bias results in long-term biased bias estimates unless the long-term bias is zero. The two cases considered are when there are and are not short-term variations in the bias.

A Note on a Biased Bias Estimate

Introduction

This particular subject is difficult to discuss since it concerns the bias of a bias estimator. This is the reason for the somewhat sparse accompanying narrative and comments on the result are saved for later in the text.

Suppose that $\hat{\theta}$ is an unbiased estimate of θ, the bias in a measurement process. It is assumed that $\hat{\theta}$ is normally distributed with a standard deviation $\sigma_{\hat{\theta}}$, i.e., $\hat{\theta} \sim N(\theta, \sigma_{\hat{\theta}})$. Bias corrections are made to the measurement process by subtracting $\hat{\theta}$ from the observations if $|\hat{\theta}| > z_{1-\alpha/2}\sigma_{\hat{\theta}}$, where $z_{1-\alpha/2}$ is the $100(1-\alpha/2)\%$ tile point of the $N(0,1)$ distribution. Otherwise the process is not corrected for bias. If $|\theta|$ is near $z_{1-\alpha/2}\sigma_{\hat{\theta}}$, bias corrections will be made about half the time. Let $\tilde{\theta}$ denote a variable such that

$$\tilde{\theta} = \hat{\theta} \text{ if } |\hat{\theta}| > z_{1-\alpha/2}\sigma_{\hat{\theta}}$$

$$\tilde{\theta} = 0 \text{ if } |\hat{\theta}| \leq z_{1-\alpha/2}\sigma_{\hat{\theta}}.$$

The average value of $\tilde{\theta}$ is the long-term estimate of θ. Since $\hat{\theta}$ is unbiased, it appears that $\tilde{\theta}$ is biased unless $\theta = 0$, i.e., unless the measurement process itself is unbiased.

Consider the procedure which eventuates in $\tilde{\theta}$. Since $\hat{\theta}$ is unbiased

$$\theta = \int_{-\infty}^{\infty} \hat{\theta}\,dF(\hat{\theta}) = \int_{-\infty}^{z\sigma} \hat{\theta}\,dF(\hat{\theta}) + \int_{-z\sigma}^{z\sigma} \hat{\theta}\,dF(\hat{\theta}) + \int_{z\sigma}^{\infty} \hat{\theta}\,dF(\hat{\theta})$$

where $z\sigma = z_{1-\alpha/2}\sigma_{\hat{\theta}}$ and

$$dF(\hat{\theta}) = \exp - \frac{1}{2}\left(\frac{\hat{\theta} - \theta}{\sigma_{\hat{\theta}}}\right)^2 \frac{d\hat{\theta}}{\sigma_{\hat{\theta}}\sqrt{2\Pi}}.$$

But if θ is deemed to be 0 when $\hat{\theta}$ falls in the interval $(-z\sigma, z\sigma)$, the bias in $\tilde{\theta}$ as an estimate of θ is $B = E(\tilde{\theta}) - \theta$, or

$$B = -\int_{-z\sigma}^{z\sigma} \hat{\theta}\,dF(\hat{\theta}) = -\int_{-z\sigma}^{z\sigma} (\hat{\theta}-\theta)\,dF(\hat{\theta}) - \theta\int_{-z\sigma}^{z\sigma} dF(\hat{\theta}).$$

Upon evaluation B becomes

$$B = -\sigma_{\hat{\theta}}\left\{\rho\,[\Phi(z-\rho)-\Phi(-z-\rho)] + [-\Phi(z-\rho) - \Phi(-z-\rho)]\right\}, \quad (1)$$

where $\theta = \rho\sigma_{\hat{\theta}}$, and where $\Phi(y)$ and $\phi(y)$ are, respectively, the zero mean, unit variance cumulative and density functions of the normal distribution. Figures 1 and 2 give, respectively, B and $E(\tilde{\theta})$ as functions of $z_{1-\alpha/2}$ and $\theta = \rho z_{1-\alpha/2}$.

Conclusions

1. The absolute value of the bias increases with $z_{1-\alpha/2}$. If θ, the process measurement bias is positive $\tilde{\theta}$ underestimates θ. If θ is negative $\tilde{\theta}$ overestimates θ.
2. The maximum of the absolute value of the bias in $\tilde{\theta}$ occurs when $|\theta|$ is somewhat less than $z_{1-\alpha/2}\sigma_{\hat{\theta}}$.
3. For $z = 2$ the maximum of the absolute value of the bias is about $0.67\,\sigma_{\hat{\theta}}$ which occurs when $|\theta|$ is about $1.4\,\sigma_{\hat{\theta}}$.

A. Generalization

The results in this note are descriptive. Given a certain set of conditions the results

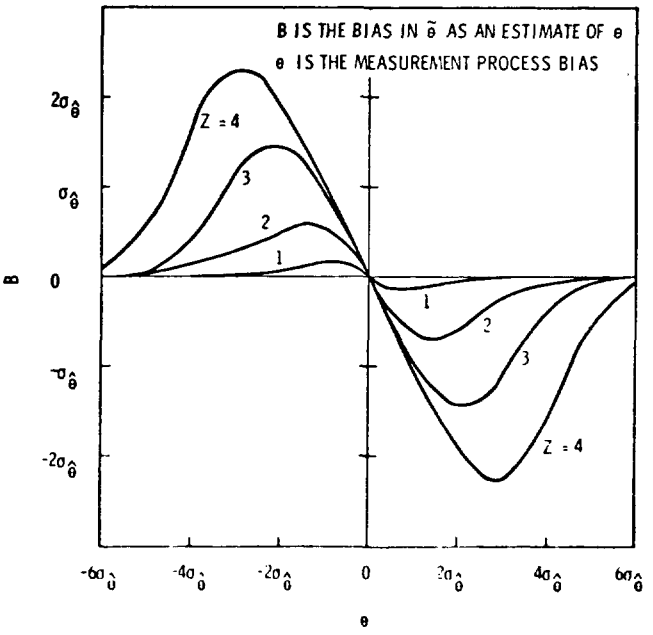

FIGURE 1. The Bias in $\tilde{\theta}$ as an Estimate of θ

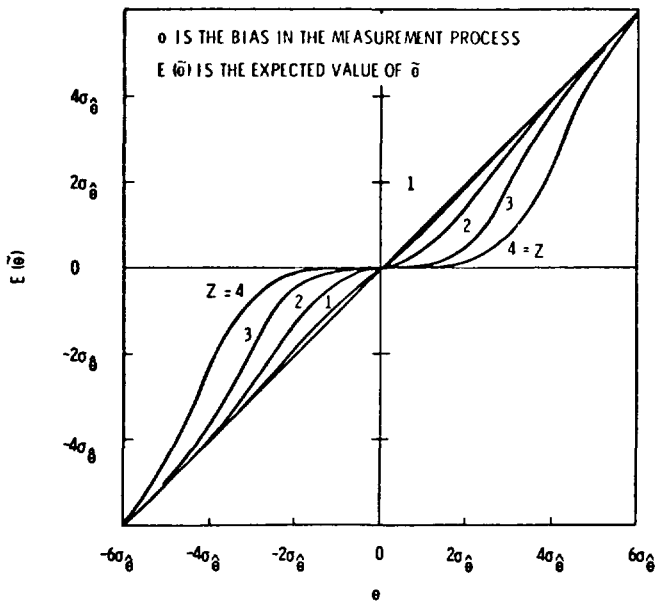

FIGURE 2. $E(\tilde{\theta})$, the Expected Value of $\tilde{\theta}$ as a Function of θ

then follow. The purpose here is to understand the long-term consequences of a bias correction procedure. To these ends the following generalization is made. Assume the long-term measurement process bias is θ but the distribution of θ', the short-term biases, is normal with standard deviation $\sigma_{\theta'}$. $\tilde{\theta}$ is defined as before. The long-term bias of $\tilde{\theta}$ is then given by

$$B = -\int_{-\infty}^{\infty}\int_{-z\sigma_{\hat{\theta}}}^{z\sigma_{\hat{\theta}}} \hat{\theta}\, g(\hat{\theta},\theta')\,d\hat{\theta}\,d\theta'$$

where

$$g(\hat{\theta},\theta') = \frac{1}{\sigma_{\hat{\theta}}\sigma_{\theta'}(2\Pi)} e^{\frac{1}{2}\left[\left(\frac{\hat{\theta}-\theta'}{\sigma_{\hat{\theta}}}\right)^2 + \left(\frac{\theta'-\theta}{\sigma_{\theta'}}\right)^2\right]}$$

$$B = \sigma_{\hat{\theta}}\left[\sqrt{1+\lambda^2}\left\{\phi\left(\frac{z-\rho}{\sqrt{1+\lambda^2}}\right) - \phi\left(\frac{-z-\rho}{\sqrt{1+\lambda^2}}\right)\right\} - \rho\left\{\phi\left(\frac{z-\rho}{\sqrt{1+\lambda^2}}\right) - \phi\left(\frac{-z-\rho}{\sqrt{1+\lambda^2}}\right)\right\}\right]$$

Where $\theta = \rho\sigma_{\hat{\theta}}$, $\sigma_{\theta'} = \lambda\sigma_{\hat{\theta}}$.

For $\sigma_{\hat{\theta}}$ known, typical z values are about ±2. Figure 3 shows the value of B, expressed in $\sigma_{\hat{\theta}}$ units, for $|z| = 2$, as a function of λ and ρ.

Added Comments

The purpose of a note like this is to describe a property of an estimator. Idealized conditions are assumed to facilitate the solu-

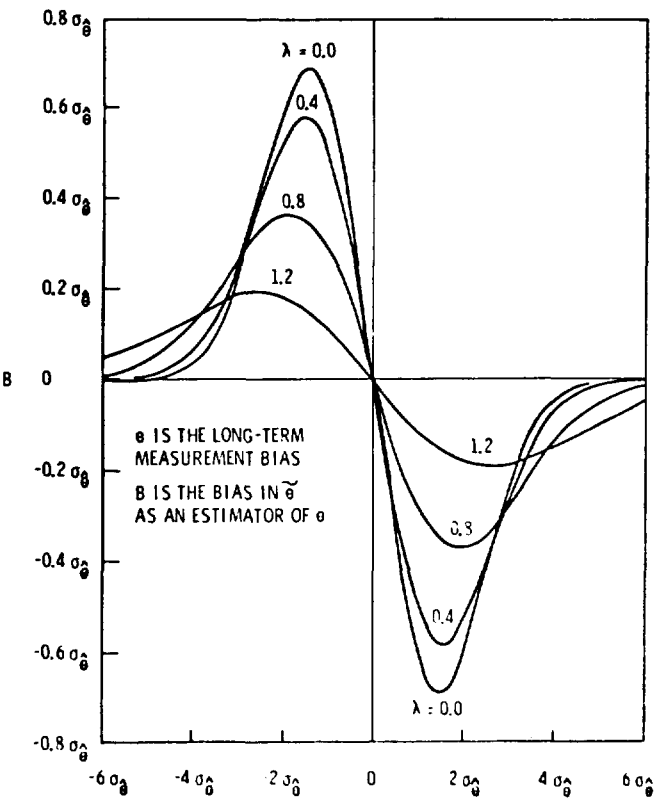

FIGURE 3. The Bias in $\tilde{\theta}$ as an Estimate of θ in the Case Where $|z| = 2$ and $\lambda = \sigma_{\theta'}/\sigma_{\hat{\theta}}$

tion and to aid in understanding the problem. The models may only approximate reality but are needed for guidance.

As used here bias in one sense refers to a property of a measurement process. In another sense used it refers to a statistical property of an estimator of the measurement bias. Bias is only one property by which an estimator can be judged. The mean-square deviation (MSD) may be more useful since it includes both the estimator's bias and variance.(1) For the estimator $\hat{\theta}$ bias and the MSD are defined, respectively, as $E(\tilde{\theta}-\theta)$ and $E(\tilde{\theta}-\theta)^2$. When bias corrections are always made the MSD of the bias estimator can be larger or smaller than the MSD when a bias correction is made only when a statistical test indicates a non-zero bias.(1) The MSD depends on the magnitude of θ, the bias, relative to $\pm z_{1-\alpha/2}\sigma_{\hat{\theta}}$, the critical points of the statistical test. If bias corrections are always made ($z_{1-\alpha/2} = \infty$, $\alpha = 0$), the bias estimators are unbiased. As this article indicates the bias of $\tilde{\theta}$ is not zero unless $\theta = 0$. Though not formally proved herein the results indicate that $\tilde{\theta}$, the long-term bias estimate has less bias than the estimate zero, which is the assumed bias when bias corrections are never made, (unless $\theta = 0$). The note is not meant as a criticism of $\tilde{\theta}$ for biased estimators are often used.(2) A biased estimator with a smaller MSD, for example, may in many applications be preferred to an unbiased estimator with a larger MSD.

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SEATTLE PRESS CONFERENCE—INMM's enterprising public relations committee chairperson, Dick Parks, of Olympic Engineering in Seattle, arranged a pre-annual meeting press conference during the February meeting of the INMM Executive Committee. The press conference was very well attended and included remarks by Bob Keepin, Fred Forscher and Bill DeMerschman. Mr. Parks will be handling public relations activities at the 17th INMM meeting June 22-24 at the Washington Plaza Hotel in Seattle.

SOME STATISTICAL ASPECTS OF THE CALIBRATION AND USE OF LINEAR MEASURING SYSTEMS

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ABSTRACT

Some statistical aspects of results obtained from a measuring system where the measurement might or might not be directly of the property of interest, but is at least linearly related to it, are described. The systems are restricted to those subject to calibration with known standards. It is shown that, because the system must be examined for two types of bias, neither a valid estimate of a sample property nor of its variance can be made if only a single standard is used. It is shown that, when more than one standard is used, the obvious estimate of the sample property is biased; an unbiased estimate is derived, as well as its variance. Testing the null hypotheses of no bias is described and equations to be used if these are accepted are given. The effect of accepting a null hypothesis which is not true has not been discussed.

INTRODUCTION

The most common measuring systems are linear and are of two broad types. Either the measurement is a direct one of the property of interest, as in the use of a balance to determine mass, or the property of interest is to be inferred from the measurement, as in an NDA system where mass is to be inferred from a radioactive count. Most generally in nuclear materials management, the systems will be calibrated by measurements of standards so that they can be applied subsequently to the assay of other samples. It will be a property of any such system of sufficient resolution that the measurements will be random variables. In this discussion it is assumed that the result of the measurement is the sum of an expected value, inherent to the actual make-up of the system, and a normally distributed random variable of zero expected value and fixed variance. Thus the discussion is applicable to a stable system or to one recalibrated each time it is used, and will be restricted initially to the direct measurement type.

When a measurement y is made of the property whose true value is μ, with such a system, the expected value of y is

$$E(y) = a_o + b_o \mu \qquad (1)$$

where the ideal values of a_o and of b_o are zero and unity, respectively. These are not necessarily the expected values for the system, however, which is said to be biased if a_o and b_o do not have those ideal values. There will be bias independent of μ if $a_o \neq 0$ and bias proportional to μ if $b_o \neq 1$.

SINGLE CALIBRATION STANDARD

It is the purpose of the calibration to infer, from measurements on a production sample of unknown true value η, a statistically describable estimate of η. Since it must be assumed, a priori, that neither a_o nor b_o have their ideal values, there are two unknowns which must be estimated before an estimate can be made of the value of η, and this cannot be done with only one piece of information, a single calibration standard.

Partly for the sake of completeness and partly as an introduction to subsequent sections, the form which an unsuccessful attempt to estimate the variance in the measured value of η would take will be shown also. A measurement of the known true value of the standard, μ, will be designated y, a measurement of the unknown true value of the sample, η, will be designated v, and the system variance will be designated σ^2. If m measurements are taken on the standard with averaged result $\bar{y}$, the only way the bias, $\bar{\theta}$, can be defined is

$$\bar{\theta} = \bar{y} - \mu$$

Following this calibration, n measurements are made on the sample with averaged result $\bar{v}$. This result corrected for bias is

$$\bar{v} - \bar{\theta} = \mu + \bar{v} - \bar{y} \ ,$$

where μ is a non-random variable and $\bar{v}$ and $\bar{y}$ are independently distributed. The expected value of $\bar{y}$ is given by equation (1) and, of $\bar{v}$, by equation (1) with μ replaced by η. Consequently, after slight algebraic manipulation,

$$E(\bar{v}-\bar{\theta}) = \eta + (b_o-1)(\eta-\mu).$$

The desired variance is

$$E[(\bar{v}-\bar{\theta}-\eta)^2] = E[(\mu-\eta+\bar{v}-\bar{y})^2]$$

where, again, μ and η are non-random variables. Since, for instance,

$$E[(\bar{y}-a_o-b_o-\mu)^2] = \sigma^2/m,$$

it is easy to show that

$$E[(\bar{v}-\bar{\theta}-\eta)^2] = \sigma^2(1/m+1/n)+(b_o-1)^2(\eta-\mu)^2$$

Since b_o is unknown and cannot be estimated nor, of course, can it be assumed that $\eta=\mu$ since the determination of η is the object of the calibration and sample measurement, the variance in an estimate of η is as unknown as the estimate itself.

Multiple Standard Calibration; Expected Values

When more than one standard is used, each will be measured one or more times. For convenience, let the total number of such measurements be, again, m. If m_i observations are taken on the standard of known value μ_i,

$$m = \Sigma m_i ,$$

$$\bar{\mu} = (\Sigma m_i\mu_i)/m .$$

If $\bar{y}$ is the grand mean of all these observations,

$$\bar{y} = a+b\bar{\mu} , \qquad (2)$$

where a and b are the usual least squares estimate of a_o and b_o. Again, let $\bar{v}$ be the average of n observations on a sample of true value η. Let η^* be the estimate of η obtained directly from the calibration equation; that is

$$\eta^* = (\bar{v}-a)/b .$$

Equation (2) is used to eliminate a, so that

$$\eta^* = \bar{\mu}+(\bar{v}-\bar{y})/b , \qquad (3)$$

in which $\bar{\mu}$ is a non-random variable and $\bar{v}$ has the properties described in the previous section. It can be shown (1) further, that $\bar{y}$ and b are independently distributed, $\bar{y}$ as described previously and b normally with expected value b_o and variance σ^2/q^2, where

$$q^2 = \Sigma m_i\mu_i^2-m\bar{\mu}^2$$

In equation (3), b^{-1} appears, so that the determinations of the expected values of η^* and its variance are not straightforward. It is straightforward to arrive at

$$E(\eta^*) = \bar{\mu}+(\eta-\bar{\mu})E(b_o/b) ,$$

however, so that the problem on the first expected value is reduced to determination of $E(b_o/b)$.

The necessary manipulation is done more conveniently if, rather than working with b and b_o, the substitutions

$$x = qb/(\sigma\sqrt{2})$$

and

$$x_o = qb_o/(\sigma\sqrt{2})$$

are made. Further straightforward manipulation leads to

$$E(b_o/b) = (x_o/\sqrt{\pi})\int_{-\infty}^{\infty} x^{-1}\exp[-(x-x_o)^2]dx ,$$

where usual methods break down because of the presence of x^{-1} in the integrand.

The argument of the function E is x_o. Differentiation with respect to x_o leads to its differential equation,

$$\frac{dE}{dx_o} = E/x_o-2x_oE+2x_o ,$$

for which a convergent series solution can be found. However, since x_o is the value of b_o divided by the square root of twice its variance, the larger is x_o the more precise is the calibration, but the convergent series becomes unsummable; the terms alternate in sign and those having the maximum absolute value are reached far down the series, before they again become small (see Appendix for further discussion). However, an asymptotic solution for large values of x_o is

$$E(b_o/b) = 1+(1/2)x_o^{-2}+(3/4)x_o^{-4}+. \qquad (4)$$

Only the first two terms are needed at this point, though the third will be needed later. One finds

$$E(\eta^*) = \eta+(\eta-\bar{\mu})\sigma^2/(qb_o)^2 . \qquad (5)$$

The fact that $E(\eta^*) \neq \eta$, so that η^* is a biased estimate of η, will be discussed later.

The expected value of the variance, $E[(\eta^*-\eta)^2]$, contains b^{-2} and leads to a divergent integral. In order to obtain a sensible result, which one feels intuitively must exist for a realistic situation of the sort being discussed, the argument can be made that it is highly unlikely that one would find $b \lesssim 0$ for a system of useful pre-

cision designed to have $b_o = 1$. One can then truncate the normal form at some small value of b, δ say, set the probability that $b < \delta$ equal to zero, and then multiply the normal form by an additional normalizing factor so that the probability that $\delta \leq b < \infty$ is unity (2). It then turns out, for x_o as large as might be expected here (see Appendix), that one finds, to ample accuracy, the result he would get from the full normal distribution by ignoring the infinite discontinuity at b=0. It is in this evaluation of the variance that the last term in equation (4) is needed; the variance turns out to be

$$E[(\eta^*-\eta)^2] = (\sigma/b_o)^2[1/m+1/n+(\eta-\bar{\mu})^2/q^2] \quad . \quad (6)$$

Since an estimate of b_o exists in this case, one expects to be able to make estimates of η and its variance and, if desired, discuss the probability that a and b are, in fact, different from zero and unity, respectively.

Multiple Standard Calibration; Experimental

It was found in the previous section that η^* is a biased estimate of η; $E(\eta^*)$ from equation (5) is not equal to η, though that equation suggests an unbiased estimate.

When the least squares estimates, a and b, were calculated the estimate, s^2, of σ^2 will have been calculated also. In detail, if y_{ij} is one of the observations made of the standard, μ_i,

$$s^2 = \frac{\sum_i \sum_{j=1}^{m_i} (y_{ij}-a-b\mu_i)^2}{m-2} \quad .$$

If equation (5) is rewritten as

$$\eta = E(\eta^*)-(\eta-\bar{\mu})\sigma^2/(qb_o)^2 \quad ,$$

and it is recognized that the second term on the right will be small compared to the first if the precision is good, one is led to examine $E(\eta_e)$ where

$$\eta_e = \eta^*-(\eta^*-\bar{\mu})s^2/(qb)^2$$

To do this, it is to be noted that, in the process of showing that $\bar{y}$ and b are independently and normally distributed (1), a third independently distributed variable is found to be the total sum of squared residuals from which s^2 is calculated. The ratio of that sum to σ^2 has the chi-square distribution, from which it can be shown that

$$E(s^2) = \sigma^2$$

and, hence, to the first power of σ^2, that

$$E(\eta_e) = \eta$$

Thus, η_e is the best estimate of η; the distinction stems from the fact that an average of reciprocals will be greater than the reciprocal of an average.

Again, to the first power of σ^2, however, the expected variance in η_e remains that in η^* as given by equation (6). Consequently, the experimentally determined estimate of that variance is to be found by applying the error propagation formula to the η^* of equation (3). In doing so, it is to be remembered that $\bar{\mu}$ is a non-random variable, $\bar{v}$ is independent of $\bar{y}$ and b, but the latter two were calculated from the same set of observations. The result, written in terms of η_e, is

$$s^2(\eta_e) = (s/b)^2[1/m+1/n+(\eta_e-\bar{\mu})^2/q^2] \quad (7)$$

in agreement with equation (6) in the sense that non-random variables in that equation have, here, been replaced by their estimates.

Equation (7) will have a rather flat minimum at $\eta_e=\bar{\mu}$, and $s^2(\eta_e)$ will rise rapidly if η_e is out of the range covered by the standards. The latter, then, should be so chosen that $\bar{\mu}$ is near the center of any range expected in the samples, and the individual standards should span a somewhat greater range.

Statistical Significance of Parameters

In a system where the property of interest is measured directly, the null hypotheses are that the non-random variables a_o and b_o are zero and unity, respectively. The value of worrying about the validity of these hypotheses is moot. Some of the arguments will be mentioned here, and the equations which follow from their acceptance will be set down. One aspect that will not be examined here is the effect of making a so-called error of the second kind, accepting the null hypothesis when it is not true.

There are some advantages, possibly minor, to accepting the hypotheses if that can be done safely. Since, algebraically, only one observation on each of two distinct standards suffices to determine a and b, (m-2) observations, or degrees of freedom, remain for the estimation of the system variance. Thus, for each of the two null hypotheses that is accepted, a degree of freedom is gained, for that variance estimation, without increasing the number of observations. Evaluations of η_e are simplified and there could be a helpful saving of space in a small computer.

A problem could arise, however, with the meaning of "safely". Hypothesis testing is done at some pre-assigned confidence level. Generally this is the 95 per cent level, sometimes 99 per cent, but whether either of these is appropriate for nuclear materials management, where special risks are involved, does not seem to have been clearly established. A related problem for which a generally applicable solution does not even exist is the degree of equivalence between the tails of actual distributions and those of the normal distribution.

When a and b are calculated, the variances of these quantities, $s^2(a)$ and $s^2(b)$ respectively, will also be calculated. Then

$$t_a = |a|/s(a), \quad t_b = |b-1|/s(b)$$

have Student's t-distribution with (m-2) degrees of freedom. Only the larger of these is tested at the pre-assigned confidence level. Since a is being tested against the known value, zero, and b against the known value, unity, it is a one-sided or one-tailed, test that is to be made. For example, if one chose to work at the 95% confidence level, and ten observations were made, the critical value of t is 1.860. If the calculated value of t_a were the larger and was 2.5, it would be concluded that a value that large is sufficiently unlikely to have occurred by chance if a were, in fact, zero, that the calculated value of a must be accepted. Conversely, if the calculated value was 1.5, it might be concluded that a is, in fact, zero and the data recalculated under that constraint. In this case,

$$\eta_e = (\bar{v}/b)[(1-s^2/qb)^2]$$

is the best estimate of η; its variance is

$$s^2(\eta_e) = (s/b)^2[1/n+\eta_e^2/(\Sigma m_i \mu_i^2)]$$

where s^2 and b^2 are, of course, the newly calculated values. Since only b was calculated

$$s^2 = \frac{\sum_i \sum_{j=1}^{m_i} (y_{ij}-b\mu_i)^2}{m-1}$$

Similarly, if the hypothesis that b is unity was accepted on the first test,

$$\eta_e = \bar{\mu}+(\bar{v}-\bar{y})$$

with variance

$$s^2(\eta_e) = s^2(1/n+1/m)$$

Here

$$s^2 = \frac{\sum_i \sum_{j=1}^{m_i} (a_{ij}-\bar{a})^2}{m-1}$$

a_{ij} being, of course, $(y_{ij}-\mu_i)$.

Finally, if both hypotheses were accepted,

$$\eta_e = \bar{v}$$

with variance

$$s^2(\eta_e) = \frac{\sum_i \sum_{j=1}^{m_i} (y_{ij}-\mu_i)^2}{mn}$$

Summary and Discussion

Various aspects of the statistics of a measurement process have been examined. It was assumed that the observation and the property of interest were linearly related, that the parameters of the process were fixed in time, and that the system is to be calibrated by the measurement of standards. The emphasis was on a system where the property is measured directly rather than inferred through the measurement of a related property, though the discussion could be adapted readily to the latter. The principal difference would be expected to be related to the slope, b_o. If, for instance, mass is to be inferred from a radioactive count, the ideal value of a_o is still zero and, in theory, an ideal value of b_o could be derived. In practice, however, this usually is not done. Then no testing of b against b_o could be done; but, otherwise, the discussion would be unchanged. In particular, more than one standard still must be used since, in order to determine η_e, b must be known even if it cannot be tested for bias.

It was argued that, when the property of interest is measured directly, the system should be investigated for bias which is independent of the magnitude of the property and for bias which is dependent on that magnitude. The simplest case of the latter was chosen, that the bias was directly proportional to the magnitude; with this it was demonstrated that neither an unbiased estimate of a sample value, nor of its variance, could be made if only a single standard is used.

For the case of several standards, the best estimates of sample means and variances were given, including those where it might be decided, after test, that one or the other, or both, of the biases described above was absent. Since such tests are statistical in nature, involving estimated probabilities rather than certainties, decisions based on them could still be in error. The effects of such erroneous decisions were not examined here.

The discussion was restricted to an investigation of what might be called the "local" system of measurement. That is, standards were accepted as being known. For accounting of nuclear materials, variances in standards, if known, must be carried along, particularly if they are comparable to the variances given by the local system for estimated means of the true values of the standards. Otherwise, they have no effect on the investigation of the local system except in one way. If the local system appears to be biased, it is not impossible that it is the standards themselves which are biased. Their values would have been determined by some other "local" system. The user of standards

should be well informed as to their reliability.

After a system which is not routinely recalibrated each time it is to be used has become well documented, its subsequent stability can be checked with a single standard. It is unlikely that a_o, b_o, and the variance would change simultaneously in such a way as to yield the original means and variance for that standard. It would be well, however, to not always use the same standard for such a recheck.

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(2) Winslow, G. H., in "Techniques of Metals Research," Vol. VII, Part I (Interscience, New York, 1972), R. F. Bunshah, ed., Chapter 9, p. 426.

(3) Reference (1), p. 71.

APPENDIX

The quantity x_o is the ratio of the slope to its standard deviation, divided by $\sqrt{2}$. Even if that standard deviation were ten per cent of the slope, not a very precise measure, $x_o \sim 7$. As a slightly worse case, suppose one counted standards (having a good clock) of 500 and 600 counts, with five observations on each, and took σ to be $\sqrt{550}$. If $b_o=1$, $x_o \sim 4.77$.

The convergent series solution for $E(b_o/b)$ mentioned in the text is

$$E = \sqrt{\pi} \sum_{n=1}^{\infty} (-1)^{n-1} x_o^{2n}/\Gamma(n+1/2)$$

At $x_o=5$, the maximum term is at n=25 and is $\sim 1.02 \times 10^9$. On a machine which carries 12 significant digits, the summation breaks down, at $x_o=5$, yielding 0.97917. The correct solutions are greater than unity for $x_o > \sim 0.94$; at $x_o=5$ the asymptotic solution, to one more term than given in the text, is 1.02132. At $x_o=4$, the convergent series yields 1.03479 and the asymptotic series yields 1.03464.

The most unfavorable case, above, is a counting example. First, then, it is noted that the leading factor multiplying the normal density function in the approximation of the Poisson function for large expectation value, μ, is $\exp(1/24\mu)(3)$. Even at μ as low as 500 this differs from unity by only 9×10^{-5}. Consequently, the normal function and those based on it are applicable.

From the t-distribution for 10 degrees of freedom one can find that the probability of finding $0 < qb/\sigma < 2qb_o/\sigma$ is less than unity by only 5.5×10^{-5}. If the normal distribution is truncated at $b=\delta$, the additional normalizing factor is $\{1-N(q\delta/\sigma - qb_o/\sigma)\}^{-1}$ where N is the normal probability distribution function. At $N=10^{-4}$, δ is 0.45, far from zero. The smaller is δ, the smaller is N, and $(q\delta/\sigma - qb_o/\sigma)$ becomes equivalent to $-\infty$ long before the infinite discontinuity at $\delta=0$ takes over. Consequently, when one comes to the integrand having x^{-2} as a factor in the evaluation of $E[(b_o/b)^2]$ he can safely proceed to the one having x^{-1} as a factor by integrating by parts.

NEW BOOK EVALUATES ROLE OF SCIENCE

OF ACCEPTABLE RISK: Science and the Determination of Safety, by William W. Lowrance, Ph.D. Harvard University, Publication Date: March 24, 1976; Cloth, $8.95, Paper, $4.95.

Life for most human beings is in many ways safer today than ever before. But hazards to life are ever-present, and decisions about acceptable risk must be made daily by each person. And leaders in business and the professions—above all, officials elected or appointed to high public office—are responsible for decisions about our safety that require ever-deeper understanding of complex issues by individual citizens.

Of Acceptable Risk is the first book of its kind. It uses a variety of case studies to illuminate and clarify the scientific and sociopolitical principles that relate to public safety. A reading of this book will provide any concerned individual with a solid basis for understanding the issues of safety in modern society and for addressing contemporary problems with imagination and temperance. It is indispensable for everyone who must make sensible judgments and effective decisions about safety and risk in different contexts—personal as well as social.

Author William W. Lowrance is a modern scientist with a strong social conscience who views science as one of the humanities and who approaches scientific issues in human affairs in the spirit of the great natural philosophers of the past. A Research Fellow with Harvard University's Program for Science and International Affairs, Dr. Lowrance's interests include safety and risk, the relationships between civilian nuclear power programs and the international proliferation of nuclear weapons, the nature of the ethical responsibilities of scientists, and relationships between science and art.

Few topics dominate the daily news more consistently than public safety, health and welfare. A distinguished scientist, Dr. Samuel Epstein, recently told a U.S. House of Representatives committee:

> "There has been a massive increase in the incidence of cancer in the 20th Century. Most human cancers are environmental in origin and hence preventable ... The problems are political and economic..."

What is to be done about risks to human health? Who decides which risks are acceptable and what are the terms? **Of Acceptable Risk** illuminates these fundamental problems.

INDEX OF ARTICLES (1972-1976)

Editor's Note: Vol. I, No. 3, and Vol. II, No. 3, Vol. III, No. 3 and Vol. IV, No. 3 are proceedings of the annual meetings of INMM. Copies of the tables of contents for those proceedings are available on written request to the editors.


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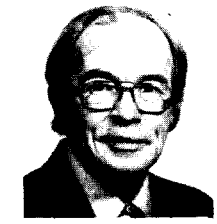
Harkness

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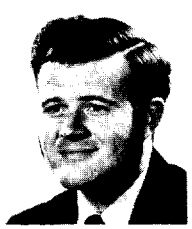
Douglas Reilly (Ph.D., Physics, Case Western Reserve University, 1970) is a staff member in the Nuclear Safeguards Research Group at Los Alamos Scientific Laboratory. His main activity is the application of gamma-ray spectroscopy to nuclear material accountability.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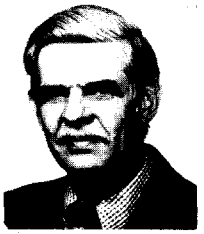
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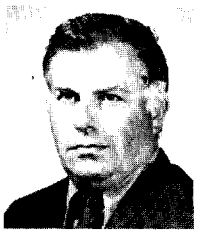
Stewart


Winslow


Zivi

Kirkland B. Stewart (M.S., University of Puget Sound) is a senior research scientist in the Safeguards Systems Studies Section of Battelle Northwest, Richland, Washington. He has worked in applied statistics for twenty years and has done work in the statistics of safeguards for about 15 years. He has had publications in Technometrics, the IMS selected tables project, the IAEA proceedings on safeguards techniques and the INMM proceedings of their annual meetings.

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George H. Winslow (D.Sc., Carnegie Institute of Technology) has recently transferred to the Quantitative Verification and Safeguards section of the Special Materials Division, from the Chemistry Division, at Argonne National Laboratory. He originally joined the Argonne staff in 1946. He is co-author, with E.M. Pugh, of the college text, **The Analysis of Physical Measurements** (Addison-Wesley, 1966), and is author of the chapter, **Data Evaluation and Analysis,** Techniques of Metals Research, Volume 7, Part 1 (Wiley, 1972, R.F. Bunshah, ed.). Among his publications while in the Chemistry Division were those in the fields of alpha-decay theory, optical pyrometry, optical properties of urania and graphite, vaporization behavior of graphite and potassium, and statistical mechanical modeling of non-stoichiometric crystals, principally reactor fuel materials.

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GENE I. ROCHLIN is a member of the Department of Physics at the University of California, Berkeley. He broadened one of his courses, a popular liberal arts physics survey, to include a treatment of technology and its social problems—an impetus to preparing this set of readings. Professor Rochlin is a solid-state physicist with research interests in low temperature and statistical physics. He received his B.S. (1960), M.S. (1961), and Ph.D. (1966) degrees from The University of Chicago.

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