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OF
NUCLEAR
MATERIALS
MANAGEMENT

FEATURE ARTICLES

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EDITORIAL

DR. WILLIAM A. HIGINBOTHAM
Brookhaven National Laboratory
Upton, New York

At the urging of some of its members the Institute has broadened its scope to include transportation of nuclear materials and radioactive waste management. This does not mean that any less attention will be paid to international safeguards and to national control and accounting for nuclear materials. It is expected that the Institute will be strengthened by this careful extension in scope and membership, while still avoiding the problems of size which afflict the broader-based professional organizations. The special strength of the Institute has come from its ability to bring together the relatively few individuals who are engaged in the development and application of safeguards on a more-or-less personal basis.

A major concern regarding the transportation of nuclear materials is safety. Another is the possibility of theft or sabotage of radioactive shipments, which is a national safeguards' concern. A third concern has to do with accounting for and protection of international shipments, which is closely related to international safeguards.

Management of nuclear wastes also has safeguards connotations. IAEA safeguards may be terminated when the Agency decides that the material has been consumed or diluted in such a way that it is no longer usable from a safeguards point of view. For accountancy reasons, the nuclear content of such waste discards should be measured and verified. For waste disposal, it is important that these and other measurements be made.

It is conceivable that some countries may decide to bury spent reactor fuel in such a way that it might be recovered sometime in the future. Obviously, this raises questions as to how safeguards might continue in such a case.

Since reprocessing has not developed as rapidly as had once been expected, consolidation of spent fuel for storage in reactor pools and a variety of schemes to store spent fuel at power reactor sites or elsewhere are being developed. Any of these schemes will call for significant changes in safeguards procedures. It will be important to develop appropriate safeguards methods along with the development of these alternative spent fuel storage techniques.

Returning to safeguards in general, the Institute should be a medium for discussing fundamental safeguards principles as well as for exchanging information on safeguards techniques. The Journal has carried some philosophical papers in the past. This issue contains a provocative article by Charlie Hatcher which proposes a simple formula for quantifying the effectiveness of IAEA safeguards. My first reaction to any such proposal is that the idea is absurd. On more careful study, the paper presents a way to think about the relationships between such technical and political factors as the intensity of the safeguards activities performed, the estimated probabilities that inspections might detect a diversion (should it occur), the credibility of the safeguards operations as viewed by different audiences, and the possibility that a given nation might attempt diversion, also as viewed from different perspectives.

Charlie Hatcher invested a considerable amount of thought and effort in drafting this model. It started with a preliminary draft which was published in the winter 1982 issue of the Journal. After receiving a number of comments on that draft, he wrote a revised draft which he sent to 20 or so individuals. They responded with detailed criticisms, to each of which he replied. This version reflects these exchanges.

In my view, this is a constructive paper which should stimulate discussion on this most important and most difficult subject. As one of the correspondents said: "Progress comes from those who offer targets to criticize." It is a lot more difficult to break new ground than to criticize such proposals. The editors welcome your comments, and invite alternative suggestions.

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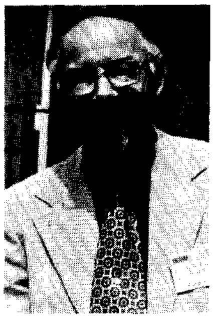
CHAIRMAN'S COLUMN

JOHN L. JAECH
Exxon Nuclear Company, Inc.
Bellevue, Washington



I have been attending meetings of the INMM Executive Committee since 1974. One topic for discussion that has surfaced repeatedly at these meetings is the role that the INMM should play in public information. We have appointed Public Information Chairmen and Committees, some of which have been very active in putting together programs related to public information at the annual meetings, in setting up Speakers' Bureaus, in promoting press releases, and in a number of other ways, some of which have met with some degree of success and others which never really became airborne.

In the current administration, we have no Public Information Committee as such. This is not because we see no need for public information activities, but rather because it's difficult to define the role that such a committee should play. With our limited resources, we see little point in paralleling the efforts of other groups who publish and distribute pamphlets and booklets promoting nuclear energy, and even sponsor full page advertisements in national publications. Such activities are laudatory, and I know many of our members have made use of such materials and perhaps participated in those activities to some extent.

If any of you readers have ideas on what we as an Institute can do further in this area, please convey them to me. My personal feeling is that the most can be gained if we act as individuals to create public awareness of nuclear energy, especially among that segment of the population who are opposed to nuclear energy because of a poor understanding of this energy source.

Having spent most of my career at Hanford where nuclear energy was well understood and accepted, I did not fully appreciate how such understanding (and, therefore, acceptance) was centered rather exclusively at places like Hanford, Oak Ridge, Los Alamos, and similar nuclear-oriented communities. Now that I live in the Seattle area, my eyes have been opened and I see the need for creating such understanding at the grass roots level. It does little real good for us believers to talk among ourselves; we are already convinced. Our goal should be to reach the nonbelievers.

The opportunity to act in this direction was provided to me in early Spring of 1984 when I was given the task of developing a five week series of one-hour sessions on "Understanding Nuclear Energy" for a Sunday morning adult class in a large, centrally located downtown Seattle church. By bringing in guest speakers, we put together this series, covering such topics as the fuel cycle, the status of nuclear energy throughout the world, radiation and criticality, nuclear materials safeguards (of course), and reactor safety, including a very fine presentation on the Three Mile Island incident. The series was well-received, much appreciated, and did a lot of good in reaching that vitally important segment of the population whose support we, as an industry, must have in the future. Cannot we as individual INMM members promote similar endeavors, if not in *churches, in clubs and in similar groups? I think we have a real* opportunity here; an opportunity and also a challenge. It is not enough that you and I are supportive of nuclear energy; a broader support base is needed. Perhaps we can inspire one another in these efforts by publicizing our local activities through news items printed in our INMM Journal. What is your reaction?

On another subject, at the most recent meeting of the INMM Executive Committee held in early March in Albuquerque, your Committee elected the initial six Fellows of the INMM. This election was held following the provisions of the Bylaws dealing with membership grades and was recently approved by a large majority of the INMM membership. To review, election to the grade of Fellow first requires that the candidate be nominated by at least five members of the Institute (See Article II, Section 5 of the Bylaws). Other steps are detailed in the cited section, but the final election requires the approval of the Executive Committee.

How the Executive Committee approaches this election is not specified in the Bylaws, except that it requires the approval of two-thirds of the Committee. Because of the upper limit on the number of Fellows that the Institute may have at any one time (5% of the membership), your existing Executive Committee felt that restrictions should be placed on the number elected in any given year. Operating under these formal restrictions, which may conceivably be changed by succeeding Executive Committee actions, the initial election was limited to six Fellows.

Someone has likened the Fellow election process to that used in elections to the Baseball Hall of Fame. Each of us probably feels that there are deserving baseball greats who have not yet been accepted in the Hall of Fame; there is little we can do about that. Each of us probably also feels that there are deserving individuals who should be designated Fellows of the INMM; we *can* do something about that. Participate in the nomination of the candidate of your choice at the next invitation to do so. Previously nominated individuals must be renominated to be considered for election in 1985.

TRAINING COORDINATOR'S REPORT

DEAN D. SCOTT
Battelle, Pacific Northwest Laboratory
Richland, Washington

One of the many aspects of the INMM is to provide its membership and the nuclear community with educational opportunities in the fields of Safeguards, Security, Transportation and Waste Management. At the present time, these educational efforts are being met through the diligent individual endeavors of several Institute members.

In order to facilitate these members and the INMM, the Executive Committee has instituted a new position of Training Coordinator. While serving in this capacity, it is my intent to solidify the educational program into a more structured format. My first endeavor will be to take each of the four fields and define basic educational needs. The next steps will be to develop a curriculum from those needs; identify individuals to teach courses and workshops; and establish a nation-wide training itinerary.

If you have any suggestions, preferences, or complaints, I would like to hear from you. Please feel free to contact me at the Columbus, Ohio meeting or drop me a line at:

Dean D. Scott
Battelle, Pacific Northwest Laboratory
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Deadlines for technical manuscripts (requiring review) and news articles, etc. (not requiring technical review) are given in the annual schedule noted below. As a convenient reminder to colleagues in your organization, you may wish to post this schedule.

Issue	Technical* Manuscripts Due	News** Articles, etc. Due	Publication Mailing Date
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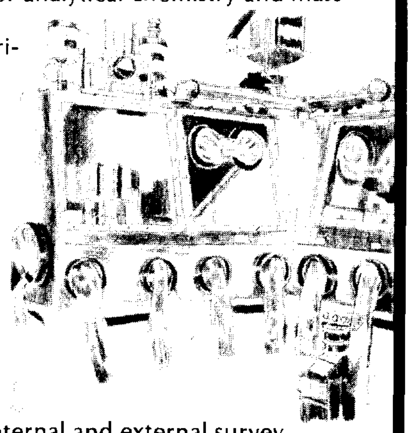
Winter	October 1	December 1	January 1

*To submit a technical article (requiring review), send three copies to Dr. William A. Higinbotham, TSO, Building 197, Brookhaven National Laboratory, Upton, Long Island, New York 11973 (phone 516/345-2908, or FTS 666-2908). One copy should be sent to Editor, NUCLEAR MATERIALS MANAGEMENT, INMM Headquarters, 8600 West Bryn Mawr Avenue, Chicago, Illinois 60631 U.S.A. (phone: 312/693-0990).

**News articles, photos (with captions, of course), book reviews, summaries of technical presentations, guest editorials, technical notes, etc. should be submitted by the appropriate deadline to the Editor at INMM Headquarters.

Glove Boxes Available

Battelle's Columbus Laboratories is offering for sale three stainless steel glove boxes previously housed in its former plutonium facility. These units were used for analytical chemistry and mass spectrometry and would be appropriate for any similar work requiring a containment system.



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INMM CALENDAR OF EVENTS

OCTOBER 11-12, 1984
Executive Committee Meeting
Westin Hotel
Seattle, Washington

OCTOBER 23-26, 1984
Physical Protection Systems
and the Insider Threat
Best Western Inn of the Hills
Kerrville, Texas

JANUARY 13-15, 1985
Spent Fuel Storage II
Hyatt Regency Washington on Capitol Hill
Washington, D.C.

MARCH 3-5, 1985
Waste Management TWG Seminar
Hyatt Regency Washington on Capitol Hill
Washington, D.C.

JULY 21-24, 1985
26th Annual Meeting
Albuquerque Regent Hotel
Albuquerque, New Mexico

RALPH E. CAUDLE HEADS WACKENHUT ADVANCED TECHNOLOGIES CORPORATION

CORAL GABLES, FLORIDA—Ralph E. Caudle, formerly Director of the Department of Energy's Office of Safeguards and Security, has been named President of Wackenhut Advanced Technologies Corporation (WATCO).

Based in Reston, Virginia, WATCO is a newly created subsidiary of The Wackenhut Corporation, one of the world's largest international security and investigative organizations whose headquarters are in Coral Gables.

Four separate Wackenhut technological security and systems services have been merged into WATCO. They include the Systems Division, the Advanced Technologies Division, the Security Programs Division and NUSAC, Incorporated, a former subsidiary which produces quality assurance and approved training programs for the nuclear industry.

Mr. Caudle, a retired Air Force Colonel whose military service included combat tours in Korea and Southeast Asia, joined the Department of Energy in 1975 as Director, Division of Operations, Office of Military Application.

In 1981 he was promoted to head DOE's Office of Safeguards and Security, with responsibility for protection of nuclear weapons materials and facilities as well as all DOE classified information.

The Wackenhut Corporation's operations extend across the United States and into Canada, the United Kingdom, Western Europe, the Middle East, the Far East, Australia, New Zealand, Mexico, Central America, Panama, South America and the Caribbean.

A REMINISCENCE, 1944

Chapter 2

R.D. SMITH

My biggest problem in writing these anecdotes is where to begin. There is so much. And it is rich in both pathos and humor. The rain in early 1944 was unbelievable. We'd get off at three from day-shift, and no Victorian (or perhaps a modern) person would believe the preparations we made. The girls took off their skirts, shoes, and stockings and usually put on a rather large raincoat. Then they went to the buses with a big bundle in their arms.

And the men were in the same fix. We'd take off our pants, shoes, and socks, wrap the whole mess up in a bundle, put on our long raincoats, and head for the bus. I suppose we all looked silly with our bare legs and feet sticking out from under those raincoats; and maybe I am silly to be so proud of the whole thing. How can anyone be proud of being in mud up to one's knees? But we were all proud.

There was a poignant quality in all this that is difficult to describe. I'll try. Here were all these lovely, nubile girls. Here were all these virile, young men. Nobody made "a pass," at least in the presence of anyone else. It was sort of like we had all become Victorian; we were about half naked but only half tempted.

And we were jolly. I find that there is a theme in these peculiar accounts which is the singing. It was because there was an esprit de corps the like of which I've never seen before or since. Everyone did what each was asked to do because the assumption was that it would help WIN THE WAR! We all helped each other. So far as I can remember there was almost no politicking for personal advancement; and there was virtually no "goofing off." Everyone was apparently completely dedicated. That's why we sang!

When Evelyn was here in the Summer of 1944, we would rent an unused room in one of the newly built houses. This is what the Army called "separate quarters." The single guys were to stay with the troops in such rather sorry arrangements as the Army provided for our housing. But the married guys, who were I suppose assumed to be older and more settled in their ways, were given this privilege. There's where I had the Army. I was one of the younger men in the Special Engineer Detachment (SED), which is what we were called. Although we'd been married almost two years, I was still only twenty-one.

In January 1945, Evelyn came back. She had decided that breaking that stupid teaching contract ($1,700 a year!) wasn't such a bad idea. She immediately got a job at Y-12 in one of the "singing" laboratories at considerably more than that figure, and we continued in "separate quarters."

Y-12 was good to us. We were always permitted to be on the same shifts, rotating or whatever. But "separate quarters" as we had them then got to be intolerable, even *after* we got rid of the bedbugs. Very early that Spring there was a hot, hot day. Evelyn and I had come home from a long night-shift and we were so tired we were in shock. We went to bed and lay sweating until we finally fell asleep.

We hadn't been asleep for an hour when all of a sudden there was a roar. I looked out the window, and there was our well-meaning landlady hosing down the roof. There is no way a frame, one-story house will not roar when being hosed down. We'd been through chickens under the floor when we'd awaken to the silly cackle of a hen who had produced something, but that hosing down did it!

We had to have something better. I went to the barracks area and, as they say, I talked around. There *was* something going on; a guy named Lesch needed twelve more families to fill the cabins at Cove Lake State Park at Caryville, Tennessee. They called them "cabins" at that time, but it was more like a one-story motel; the cabins being interconnected in the sense that row-houses are. Lesch easily got his necessary twelve subscribers. I signed up for cabin nine.

There was more than the thirteen cabins. There was a restaurant and kitchen. They were ours. There was the park. It was ours. There were rowboats on the lake. They were ours. And Cove Lake, itself, with it's geese and ducks and fish was ours. For a total of $650 a month, we thirteen families essentially bought a state park!

It was tremendous for us and good for Tennessee. In years like those, there was almost zero tourism what with gasoline rationing and the many other problems. For example, you couldn't buy a tire; or if you could, it wouldn't be quite the right size. I saw some pretty funny looking cars. So Tennessee came out a winner, or at least not as big a loser as it would otherwise have been. And we thirteen G.I. families were in clover.

There was certainly no problem with transportation. I read somewhere that Oak Ridge had the biggest bus system in the world at that time. Judging from highway 25W it was probably true. The olive drab G.I. buses flowing both ways reminded me of circus elephants each holding the preceding one's tail in its trunk. They came from Harlan and Middlesboro, Kentucky, Jellico, LaFollette...from all over and all for free. For shopping or other excursions we always had the thumb and the uniform. It was almost like having our own car.

One evening in early 1945, Evelyn and I decided to take in a carnival at the ballpark in Lake City. We hitched a ride. The car radio was on. It was announced that FDR had died. We both began to cry—no big sobs or wailing—just big tears running down our cheeks. The man asked did we still want to go to the carnival. We said yes. But, all the fun was gone. I remember Evelyn saying, "We have lost our leader." We had, but neither of us knew what a feisty little man Harry Truman was. So for us the carnival was a bust and we left in about half an hour and hitched back home to Cove Lake.

Speaking of the park, it had a ranger. He was a really nice guy. He tried to enforce state rules although he knew the rules were dumb, and so did we. As a result he must have been a very frustrated man. For example, there were supposed to be "fish" days and "swim" days. On days when you could fish, nobody was to swim and vice-versa. You can imagine how that worked out. We swam whenever we felt like it and likewise with the fishing. The poor guy walked around shaking his head.

There was a small dock down from the cabins from which we either fished or swam. It wasn't in good repair then and it's gone now. Evelyn and I, coming off day-shift and arriving at Cove Lake about 5:00 p.m., would sometimes get our fishing gear and walk down the hill catching grasshoppers for bait as we went. Fishing gear for us was a small wooden contraption around which you could wrap your, maybe, 12-foot line and one hook. We had no poles. You could get what we had for about a quarter in any Five and Dime.

We did this quite a few times. Our take might be three crappies for Evelyn, one strike and a few nibbles for me. It seems I am just not a fisherman. The fish Evelyn caught tasted mighty good. And, once in a long while, I would catch one worth keeping myself.

There was one day we did this I'll always remember. We went down to the dock and just sat resting. Evelyn started pulling them in. We switched sides of the dock. She kept pulling them in. Once in a while I'd have a nibble. She caught eleven good sized crappies and said she'd holler when she was ready. Before she left she wrapped her line around a nail in the dock and left it in the water. I was to bring it up when I came. She hollered and I unwound the line and got a fight. She caught fish even when she wasn't there! This one was an 11½-inch catfish.

Now, I'm not one to be afraid of varmints, but that catfish was most formidable. I didn't know whether those barbels were poisonous or not. So without unhooking it, I carried it up to the cabin sort of at arm's length. Evelyn was amused at my worry and assured me the animal was harmless. She had previously caught bull-heads (a closely allied species) in upstate New York. She also knew how to prepare it for the pan which she explained. So, I got a sharp knife and my pliers and we had Tennessee catfish. Delicious!

Evelyn is not only knowledgeable; she is ingenious. We had all those crappies. They were all cleaned and ready to go. But, what two people could eat eleven good-sized crappies after that catfish? So Evelyn got a large bowl, put in the crappies, and completely covered them with table salt—good old sodium chloride. A rather predictable thing had happened by morning. Here was a bowl of very rich brine in which the crappies were slightly withered and hardened.

They were the best substitute for bacon I've ever had. We simply took them out of the brine, rinsed them, and fried them in butter. They didn't last a week. *The neat thing about this technique is that* no refrigeration is required.

Why am I hung up on fish? Mainly, it's because we couldn't get any meat! There simply wasn't any in the stores. We would buy Chef Boy-Ar-Dee spaghetti dinners in a box because the little can of sauce that came with it, *did* contain a little ground beef. We did most of our grocery shopping at Woodson's in LaFollette. They got to know us. Once in a while the guy behind what had been the meat counter would beckon me. He would have saved a pound of bacon or sausage or something for us. We took it gladly. What a nice man!

Mind you, this had a queer "speakeasy" flavor. I don't *think* it was illegal, but perhaps it was. At any rate, what he sold us came from "under-the-counter." There was no meat of any kind showing. *(Ed. Note: It was not illegal. It was a form of rationing by the merchant to his customers.....otherwise a few greedy people would buy up the entire supply and either "hoard" it or sell it for a criminal profit.)*

On night-shift, I once grumbled about there being no meat. I should not have done that. One of the girls—her name was Zola—brought in a huge country ham and put it in the laboratory refrigerator. There was a note on it that it was for Evelyn and me. I was most embarrassed. I wanted to refuse the gift. But Zola was most adamant. She said they had a smokehouse full of the things. I tried to give her ten dollars. She got angry and stalked away. So I took the thing home and Evelyn and I had country ham for some weeks.

But I'm still leery about the ethics of the whole thing. A supervisor should not take gifts from employees. Zola didn't know that and was only acting in the spirit of the time. I still feel a little guilty.

I don't believe there's ever been a time like it. Today there are almost no Zolas, almost no men like the one behind Woodson's meat counter, and *no* hitches like the ones we got who would take us wherever we wanted to go even if that was not where they were going!

NEXT: My College Football Career

BOOK REVIEW

LESLIE G. FISHBONE
Brookhaven National Laboratory

BORN SECRET—THE H-BOMB, THE *PROGRESSIVE* CASE, AND NATIONAL SECURITY
A. DeVolpi, G.E. Marsh, T.A. Postol, and G.S. Stanford
Pergamon Press, New York, 1981, xiii, 305 pp., $17.50

"Our future will be more secure if secrecy is minimal." Important political decisions relating to national security will be more intelligently made if the public has more, rather than less, access to information thereupon. And finally, ending the superpower arms race will do more to prevent the spread of nuclear weapons than will secrecy and controls on technologies. These are the main themes of *Born Secret,* which couches its arguments around the notorious *Progressive* case of 1979.

Born Secret is three books in one: first, it relates the facts of the *Progressive* case, including the participation of the authors; second, it gives a legal analysis of the major issue in the case, secrecy; and third, it presents the authors' views on the role of secrecy in the larger questions of nuclear-weapons proliferation and national security. For the purposes of this review, I accept the book's recounting of the facts of the case as correct.

DeVolpi, Marsh, Postol, and Stanford, who were at the time of the case all scientists at Argonne National Laboratory, became involved on the side of the defendants in the case of the *United States of America, Plaintiff, versus the Progressive, Inc., Erwin Knoll, Samuel Day, Jr., and Howard Morland, Defendants,* filed on March 8, 1979, in the U.S. District Court for the Western District of Wisconsin; Judge Robert Warren presided over the case. The U.S. Government went to court to prevent publication of Morland's article, "The H-Bomb Secret," in the *Progressive,* of which Knoll was editor and Day was managing editor. Voluntary efforts to prevent publication had failed. The courtroom battle largely involved affidavits, submitted primarily by nuclear-weapons experts and U.S. Government officials up to the Cabinet level on the one hand and outside experts in law and nuclear technology on the other. Many of the Government's affidavits were themselves submitted in secret and were unavailable to the defendants; furthermore, the Government presented no live testimony that would have been subject to cross-examination. The Government successfully obtained a temporary restraining order on March 9 and a preliminary injunction on March 26 against publication. A motion by the defendants to have this injunction vacated was denied by Judge Warren in a decision on June 15; the motion was based on new evidence, namely, a mistakenly declassified official report on weapons work found in the public section of the library at the Los Alamos National Laboratory. The *Progressive* et al immediately appealed to the Seventh Circuit Court of Appeals in Chicago. On September 17, before the appeal process was over, the Government withdrew its suit because another periodical, the *Madison Press Connection,* published a letter by another party to Senator Charles Percy of Illinois that gave the essence of Morland's article; the *Progressive* thereupon published the latter. Many of the secret affidavits submitted to the District Court in the original suit were subsequently declassified.

Legally, the injunction granted by Judge Warren was based on his acceptance of the Government's primary arguments. The first argument, regarding questions of evidence, was that Morland's article contained Secret Restricted Data within the meaning of the Atomic Energy Act. The second argument, regarding questions of law, was that the Act provides for injunctive relief, is constitutional, and applies to all, not just those in official Government work (hence the material in question is "born classified"). The defendants had chiefly and unsuccessfully counterargued that the material in the article was already in the public domain and that the provision of the Atomic Energy Act granting injunctive relief is unconstitutional.

The question of whether the material was or was not already public revolved around prior publications by Government scientists, the deducibility of the material in Morland's article from principles of physics and from the prior publications, and the technical level of detail necessary in a publication to allow it to be significantly exploited by a foreign country. The authors discuss at some length the concepts in Morland's article and argue why they would be readily deducible by competent physicists from previously available information and why, given the lack of technical specification, the article could provide only slight, if any, assistance to a new fusion-weapon designer.

The question of constitutionality involved, among other things, the decision of the Supreme Court in the 1971 case, *New York Times Co., Petitioner, versus United States. United States, Petitioner, versus the Washington Post Company et al.,* the famous Pentagon Papers case. There, a majority ruled that prior restraint on publication can outweigh First Amendment rights only in extremis, a condition frequently summarized in terms of Justice Potter Stewart's concurring (not the agreed majority) opinion that prior restraint is justified only if publication "will surely result in direct, immediate, and irreparable damage to our Nation or its people." An important difference between the *Progressive* and Pentagon Papers cases is that no specific legislative act authorizing injunctive relief governed the latter. The material in that case involved National Security Information, whose handling is governed by an executive order of the President (most recently Order 12356 by President Ronald Reagan on April 6, 1982). Nevertheless, Judge Warren held that prior restraint of Morland's article was justified not just by virtue of the provisions of the Atomic Energy Act, but even within Stewart's demanding standards. The authors of the book argue instead and in detail that these conclusions were erroneous. Of course the authors are scientists, so their legal analysis should be compared with those of experts in law, some of whom they cite.

One additional legal issue raised was whether publication of technical information enjoys the same constitutional protection as publication of other, e.g., political and historical information.

Except for the precedent of a temporary injunctive ban against publication, prior restraint, the legal issues in the case were never fully resolved, as some surely would have been had the case gone on to the Supreme Court.

An engaging question posed but not answered in the book is why the U.S. Government chose to litigate the case at all: what was the exact decision-making process? If subsidiary goals of classification policy are to avoid drawing attention to sensitive information derived by private parties and to refrain from verifying it (which, the authors aver, the Government did implicitly by litigating and explicitly in its affidavits), why, after Morland submitted his article to the Government for comment, was the policy abandoned of issuing the terse statement "No Comment"? The same reply could have been given after uncontested publication. Or to put the question another way, why did the Government miscalculate on the pragmatic level of believing that no others would derive or publish the material, as happened?

Ultimately, the authors are concerned with national security. They argue that excessive secrecy leads to an electorate and a Congress poorly versed to make the best possible policy choices. They criticize the secrecy involved in the decisions to use fission bombs on cities in World War II and to develop fusion bombs. Volumes have been written about these decisions; they remain contentious.

Regarding contemporary issues, the authors feel that excessive secrecy about technical capabilities of strategic-missile systems and of arms-control monitoring systems inhibits the informed debate that could stop the arms race. I feel here that much technical information is widely available and that details about weapons designs and monitoring systems are not essential for public discussion of the basic policy questions.

In considering national-security issues through treaty, authorization, or appropriation debates, the U.S. Congress presumably has access to the relevant secret information. Given that a strategic-arms treaty not capable of being reasonably well verified would never be ratified and that reasonable assessments of the strategic forces of our adversaries are available, anyone deciding to accept or reject a given arms-control treaty must balance the risk of deception against the risk of a continued arms race. Such national-security decisions are based, for better or worse, on a constellation of facts and political perceptions.

Voters rarely, if ever, decide Presidential or Congressional elections on single issues. To the degree that foreign policy concerns them at all, most voters will only consider candidates' general views on strategic arms, such as whether the SALT II treaty should have been ratified and whether a nuclear "freeze" should be adopted. Details of these questions must necessarily be left to experts once elected leaders have, by virtue of their periodic elections and the continual submission of opinions by voters, formulated general policies. In my judgment, voters have certainly had enough information available in recent years to give general and intelligent direction to their elected leaders on these questions.

This information largely becomes available from official and private testimony before Congressional committees and from criticism of the policies and proposed systems in a plethora of periodicals and other forums. Vital to the criticism are informed experts, often former officials from the political party not in power. These are the people for whom details about strategic arms, monitoring systems, and related policy are important. The governing party has changed sufficiently frequently that opposition and independent experts are well-informed. Nevertheless, policies or laws mandating minimal secrecy would certainly ease the burden of both the loyal opposition and historians.

The authors quote approvingly specific proposals regarding eased secrecy—automatic declassification in most cases and better oversight by the Congress, for example—and also recommend changes in the Atomic Energy Act to eliminate the "born-classified" notion. These proposals are at odds with Executive Order 12356 and with current U.S. Government policy.

Belief that the Morland article would aid other countries in fabricating fusion weapons—fusion-weapon proliferation—was the national security issue underlying the *Progressive* case. The authors discount the connection, emphasizing instead the much more detailed design information, industrial prowess, testing, and political will needed in a fusion-weapon program. The most significant nonproliferation step that could be made, they feel, is agreement on a comprehensive nuclear-weapon test-ban treaty. This would both forestall development and deployment of new weapons by established powers as well as satisfy the pledge in Article VI of the Non-Proliferation Treaty "...to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament...." The authors do include the arguments against a comprehensive test ban, namely, the uncertainty thereby induced into existing weapons stockpiles and the possibility that verification measures may not be foolproof. (This issue is debated in the August, 1983 issue of *Physics Today* and the August-September, 1983 issue of the *Bulletin of the Atomic Scientists.*)

Also concerning proliferation, the authors deplore the policies of the Ford and Carter administrations under which the United States became an unreliable nuclear supplier, especially in its attitude toward plutonium as a nuclear fuel. It would have been and would be better to support the use of plutonium as a reactor fuel and establish strong safeguards against diversion while participating in the technological developments.

For those interested, Morland has set forth his own story at great length in *The Secret That Exploded* (Random House, New York, 1981). That book is of chief interest in giving Morland's motivations and the odyssey of his search for information. Sadly, he wrote his article in large part for publicity, knowing full well that weapons-design information is not needed for intelligent public debate on national-security issues. Much commentary about the case, including some by the authors of *Born Secret,* has also appeared in the *Bulletin of the Atomic Scientists.*

Born Secret is well-written, well-edited, and well-documented. Indeed, containing appendices (one of which is Morland's article itself), notes, a glossary, a list of abbreviations and acronyms, general and detailed reference lists, and a detailed index, the book is a model in helping readers through layers of technical and legal issues. One minor complaint is that I personally found the typeface unpleasant to read at first because of the small size and lack of serifs.

A TANK VOLUME CALIBRATION ALGORITHM

FRANK E. JONES
Center for Chemical Engineering
National Bureau of Standards
Washington, D.C.

An Algorithm has been developed to enable inference of the volume of process mixture in a tank, such as a chemical process tank, from measurements of differential pressure and temperature and values of other parameters. The differential pressure is converted to that corresponding to water at the reference temperature, 25 °C, by the use of a derived equation. This differential pressure is then used in a water calibration equation to calculate the volume of water at 25 °C. This volume is equal to the volume of process mixture at 25 °C at the same level in the tank, the desired result.

1. Introduction

Volume calibration of chemical process tanks is usually done using water as the calibration fluid at a particular temperature or in a narrow range of temperature. In the most precise and accurate systems, a calibration equation is developed which relates volume of fluid to the differential pressure measured between a point in the fluid near the bottom of the tank and a reference port above the surface of the fluid. The measurement of the density of the fluid in a tank using two bubbler tubes of different lengths has been treated in a previous paper [1]. In chemical processing, the process mixture in the tank has a different density than that of the water used in the calibration and the temperature of the fluid and the tank may be different from the calibration temperature. It is necessary, therefore, to provide an algorithm to enable application of the water calibration equation to the process mixture.

In this paper, such an algorithm has been developed. Although conceived independently, this development has a number of points in common with those in an interesting paper by Davies et al. [2]. The algorithm is quite general although it is illustrated using a specific model tank; it is thus generally applicable to chemical process tanks.

Jones [3] has published a brief account of the volume calibration of a chemical process tank, using increments of water dispensed from volumetric test measures and a differential pressure gage connected to a "bubbler" tube leading to the bottom of the tank and to a port in the top of the tank. In this system, the differential pressure between an orifice near the bottom of the tank and an orifice above the surface of the liquid is a measure of the height of the surface above the lower orifice. Dry instrument air or other gas bubbled through the lower orifice transmits the pressure at that level to one side of a differential pressure gage. The upper orifice is connected to the low pressure side of the gage. Two papers [4,5] treat the data from the calibration. The right circular cylindrical tank will be used as the model tank for this development. Keisch and Suda [6] have treated tanks of other geometrical configurations.

2. Model Tank

The model tank, sketched in figure 1, has the dimensions of a right circular cylindrical stainless steel tank. The height of the tank is 3.4 m, the diameter is 2.4 m, the vertical distance (S) from the gage to the top of the tank is 3.0 m, the inside diameter of the tubes is 0.019 m, the elevation of the longer bubbler tube above the floor of the tank is 0.019 m, the wall thickness of the tank is 0.013 m, and the coefficient of linear expansion (α) of the stainless steel is taken to be 15.9×10^{-6} $(°C)^{-1}$. The capacity of the tank is approximately 13,600 liters.

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[1] Numbers in brackets refer to the literature references at the end of this paper.

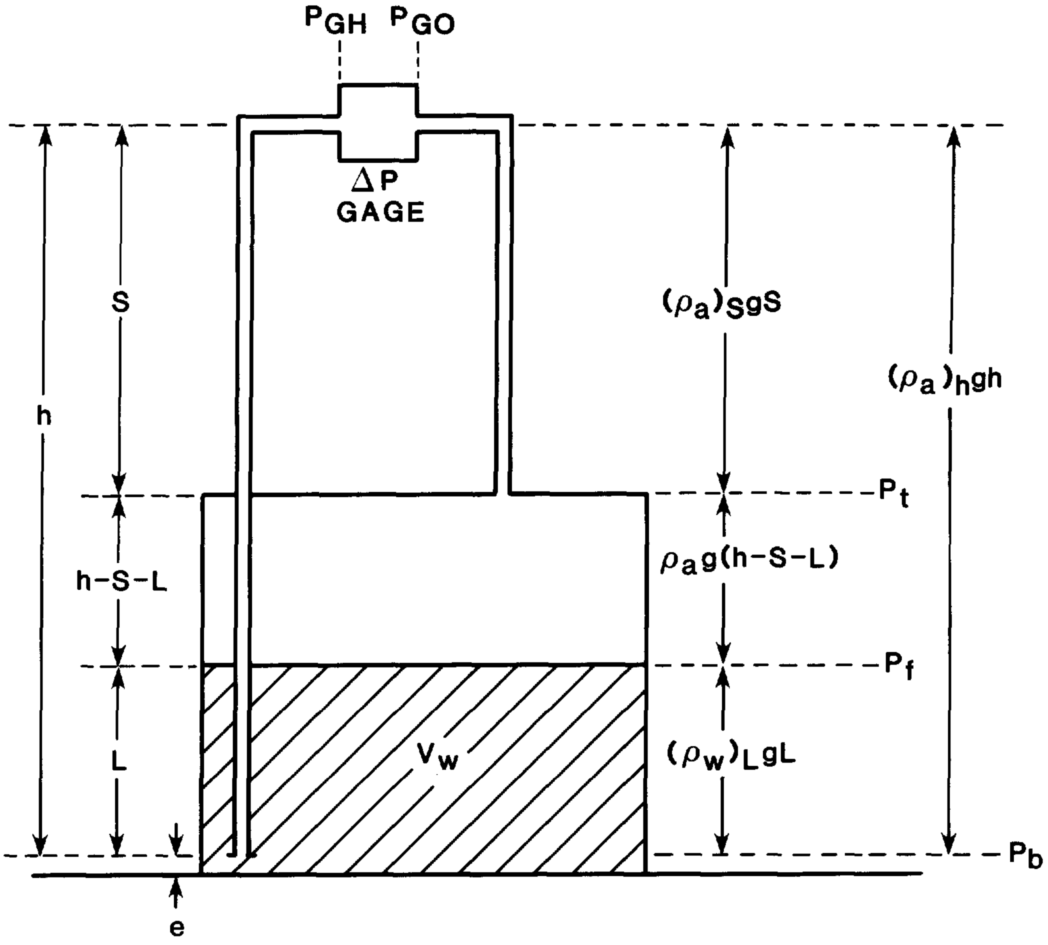

Figure 1. Sketch of the Model Tank

3. Algorithm Development

The following equations relate the pressure at either side of the gage to other parameters listed below.

$$P_{GH} = P_b + P_{tip} + P_{Dh} - (\rho_a)_h gh \tag{1}$$

$$P_{GO} = P_t + P_{DS} - (\rho_a)_S gS \tag{2}$$

$$P_b = \rho_w gL + (\rho_a)_p g(h-S-L) + P_t \tag{3}$$

$$P_{GH} - P_{GO} = \rho_w gL + (\rho_a)_p g(h-S-L) + P_{tip} + P_{Dh} - P_{DS}$$

$$-(\rho_a)_h gh + (\rho_a)_S gS \tag{4}$$

$$P_{GH} - P_{GO} = gL[\rho_w - (\rho_a)_p] + (\rho_a)_p g(h-S)$$

$$-(\rho_a)_h gh + (\rho_a)_S gS + P_{tip} + P_{Dh} - P_{DS} \tag{5}$$

P_{GH} - pressure at the "high" side of the gage.

P_{GO} - pressure at the "reference" side of the gage.

P_b - pressure at the level of the tip of the longer bubbler tube.

P_{Dh} - pressure drop in the longer bubbler tube due to flow of gas through the tube.

P_{tip} - pressure associated with the formation and the surface tension of the bubble on the tip of the longer bubbler tube.

$(\rho_a)_h$ - density of air in the longer bubbler tube.

g - acceleration due to gravity.

h - vertical length of the longer bubbler tube.

P_t - pressure at the level of the tip of the shorter tube.

e - elevation of bubbler above floor of tank.

P_{DS} - pressure drop in the shorter tube due to flow of gas through the tube.

$(\rho_a)_S$ - density of air in the shorter tube.

ρ_w density of water.

L - height of liquid surface above the tip of the longer bubbler tube.

S - vertical length of the shorter tube.

$(\rho_a)_p$ - density of air in space above liquid surface.

P_f - pressure at the liquid surface.

Other parameters introduced later in the text are:

A average cross-sectional area of the tank.

d - inside diameter of tubing.

ℓ - vertical length of the bubble on the tip of the longer bubbler tube.

R - radius of curvature of the bubble at its lowest point.

T - temperature in kelvins.

T_c - temperature at which water calibration was performed, in kelvins.

α - coefficient of linear expansion of material of which the tank is constructed.

γ_m - surface tension for process mixture and air.

γ_w - surface tension for water and air.

ρ_m - density of process mixture.

For tubing of sufficiently large inside diameter (d), $P_{Dh} - P_{DS}$ is negligible. This is easily accomplished since the pressure drop in the tubing varies inversely with d^4 [7]. In the interest of simplicity the source of gas, instrument air for example, is not shown in figure 1.

P_{tip} is given [8,9] by

$$P_{tip} = [\rho_w - (\rho_a)_h]g\ell + \frac{2\gamma_w}{R} , \tag{6}$$

where ℓ is the vertical length of the bubble on the tip, γ_w is the surface tension for air and water, and R is the radius of curvature of the bubble at its lowest point. The formation of bubbles on the tip and the time dependence of the pressure in a bubbler tube have been treated by Gaigalas and Robertson [10].

By substituting eq (6) in eq (5) and setting $P_{Dh} - P_{DS}$ equal to zero,

$$\begin{aligned} P_{GH} - P_{GO} &= gL[\rho_w - (\rho_a)_p] + (\rho_a)_p g(h-S) \\ &\quad - (\rho_a)_h gh + (\rho_a)_S gS + [\rho_w - (\rho_a)_h]g\ell + \frac{2\gamma_w}{R} \end{aligned} \tag{7}$$

4. Temperature Variation of Quantities in Eq. (7)

We now investigate the variation (ΔL, $\Delta\rho_w$, etc.) with temperature, T, of the various terms in eq (7) for a ΔT of several Celsius degrees. The first term, $gL\rho_w$, which we designate P_1, makes the largest contribution to $P_{GH} - P_{GO}$.

$$\begin{aligned} P_1 + \Delta P_1 &= g(L + \Delta L)(\rho_w + \Delta\rho_w) \\ &= gL\rho_w + gL\,\Delta\rho_w + g\rho_w\,\Delta L + g\,\Delta L\,\Delta\rho_w \end{aligned} \tag{8}$$

$$\Delta P_1 = gL\,\Delta\rho_w + g\rho_w\,\Delta L + g\,\Delta L\,\Delta\rho_w , \tag{9}$$

$$\frac{\Delta P_1}{(P_{GH} - P_{GO})} \simeq \frac{\Delta P_1}{gL\rho_w} = \frac{\Delta\rho_w}{\rho_w} + \frac{\Delta L}{L} + \left(\frac{\Delta L}{L}\right)\left(\frac{\Delta\rho_w}{\rho_w}\right) \tag{10}$$

The third term on the righ-hand side of eq (10) can be disregarded, thus

$$\frac{\Delta P_1}{(P_{GH} - P_{GO})} \simeq \frac{\Delta\rho_w}{\rho_w} + \frac{\Delta L}{L} \tag{11}$$

We now use the subscript T to indicate the values of quantities at temperature T different from the temperature, T_c, at which the water calibration of the tank was performed.

$$L_T = L + \Delta L, \tag{12}$$

$$L = \frac{V}{A} ; \; L_T = \frac{V_T}{A_T} ,$$

where V and V_T are the volumes of water in the tank when filled to the levels L and L_T. A and A_T are the corresponding average cross-sectional areas.

$$L_T = \frac{V_T}{A_T} = \frac{V \rho_w}{A_T \rho_{w_T}} , \tag{13}$$

$$\Delta L = L_T - L = \frac{V \rho_w}{A_T \rho_{w_T}} - \frac{V}{A} , \tag{14}$$

$$A_T = A + \Delta A, \tag{15}$$

$$\Delta L = \frac{V \rho_w}{(A + \Delta A) \rho_{w_T}} - \frac{V}{A} , \tag{16}$$

$$\rho_{w_T} = \rho_w + \Delta\rho_w , \tag{17}$$

$$\Delta L = \frac{V}{(A + \Delta A)} \frac{\rho_w}{(\rho_w + \Delta\rho_w)} - \frac{V}{A} , \tag{18}$$

$$\frac{\Delta L}{L} = \frac{V}{(A + \Delta A)} \frac{\rho_w}{(\rho_w + \Delta\rho_w)} \frac{A}{V} - \frac{V}{A} \frac{A}{V} , \tag{19}$$

$$\frac{\Delta L}{L} = \frac{A}{(A + \Delta A)} \frac{\rho_w}{(\rho_w + \Delta\rho_w)} - 1 = \frac{1}{(1 + \frac{\Delta A}{A})} \frac{1}{(1 + \frac{\Delta\rho_w}{\rho_w})} - 1 , \tag{20}$$

and, since $\Delta A/A$ and $\Delta\rho_w/\rho_w$ are << 1,

$$\frac{\Delta L}{L} = (1 - \frac{\Delta A}{A}) (1 - \frac{\Delta\rho_w}{\rho_w}) - 1 \tag{21}$$

$$\frac{\Delta L}{L} \simeq 1 - \frac{\Delta A}{A} - \frac{\Delta\rho_w}{\rho_w} - 1 = - \frac{\Delta A}{A} - \frac{\Delta\rho_w}{\rho_w} , \tag{22}$$

With the substitution of eq. (22) in eq (11),

$$\frac{\Delta P_1}{(P_{GH} - P_{GO})} \simeq \frac{\Delta\rho_w}{\rho_w} - \frac{\Delta A}{A} - \frac{\Delta\rho_w}{\rho_w} , \tag{23}$$

$$\frac{\Delta P_1}{(P_{GH} - P_{GO})} \simeq -\frac{\Delta A}{A}$$

$$A_T = A(1 + 2\alpha\ \Delta T) = A + \Delta A, \tag{25}$$

where α is the coefficient of linear expansion of the material of which the tank is constructed.

$$-\frac{\Delta A}{A} = -\frac{2\alpha A\ \Delta T}{A} = -2\alpha\ \Delta T, \tag{26}$$

$$\frac{\Delta P_1}{(P_{GH} - P_{GO})} \simeq -2\alpha\ \Delta T \tag{27}$$

Returning now to eq (7) and combining the second, third, and fourth terms, designated P_2,

$$P_2 = (\rho_a)_p g(h-S-L) \tag{28}$$

The variation of P_2 is treated in detail later, we therefore present here the result for ΔT of several Celsius degrees:

$$|\Delta P_2| < g(h-S)\ \Delta(\rho_a)_p \tag{29}$$

The maximum absolute value of ΔP_2 at 300 C° is approximately 0.04 (h-S) ΔT; for (h-S) equal to 3.4 m, the maximum absolute value of ΔP_2 is 0.14 ΔT Pa. For ΔT of several Celsius degrees, ΔP_2 can be disregarded.

In treating the terms $(\rho_a)_S gS$ and $-(\rho_a)_h gh$, the temperature variation is that in the air in each of the tubes which in either case is assumed to be much less than that in the air above the water. Consequently, the effects of temperature variation on these terms can be disregarded.

If we assume, in the absence of detailed information, that the shape and dimensions of the bubble change negligibly with temperature, ℓ and R are essentially constant with temperature. The variation of the next to last term, P_3, in eq (7) becomes

$$\Delta P_3 \simeq g\ell\ \Delta[\rho_w - (\rho_a)_h]$$

$$\simeq g\ell\ \Delta\rho_w \tag{30}$$

For ℓ of 0.019 m, $\Delta P_3 \simeq -0.045\ \Delta T$ Pa, which can be disregarded.

The variation of the last term, P_4, in eq (7) is

$$\Delta P_4 \simeq \frac{2}{R}\Delta\gamma_w \tag{31}$$

Using the data on γ_w of Harkins [11], $\Delta\gamma_w \simeq -1.4 \times 10^{-4}\ \Delta T\ \mathrm{Nm^{-1}}$. For R of 0.019 m,

$$\Delta P_4 \simeq \frac{2}{0.019}(-1.4 \times 10^{-4})\ \Delta T,$$

$$\Delta P_4 \simeq -0.015\ \Delta T\ \text{Pa}$$

Therefore, for T of several Celsius degrees, ΔP_4 can be disregarded.

5. Adjustments for Departure of Water Temperature from Calibration Temperature

Summarizing, it has been shown that for a variation in water temperature of several Celsius degrees, the variation in the differential pressure at the gage is given by

$$\Delta(P_{GH} - P_{GO}) = -2\alpha(P_{GH} - P_{GO})\ \Delta T \tag{33}$$

Therefore, to calculate the values of $(P_{GH} - P_{GO})$ corresponding to a temperature, T, different from the temperature, T_c, at which the water calibration was performed,

$$(P_{GH} - P_{GO})_T = (P_{GH} - P_{GO})_{T_c} + \Delta(P_{GH} - P_{GO}), \tag{34}$$

$$(P_{GH} - P_{GO})_T = (P_{GH} - P_{GO})_{T_c}\ [1 - 2\alpha(T - T_c)]\ , \tag{35}$$

where $(T - T_c) = \Delta T$.

If we now choose T to be the reference temperature 298.15K (25 °C), eq(35) becomes

$$(P_{GH} - P_{GO})_{25} = (P_{GH} - P_{GO})_{T_c}\ [1 - 2\alpha(298.15 - T_c)] \tag{36}$$

Eq (36) enables adjustment of calibration differential pressure data to the reference temperature.

The volume increments, V_c, of water introduced in the calibration are adjusted to the reference temperature by applying the principle of conservation of mass:

$$V_{25} = V_c\ \frac{\rho_{w,c}}{\rho_{w,25}}, \tag{37}$$

where $\rho_{w,c}$ and $\rho_{w,25}$ are the density of water at T_c and 25 °C, respectively.

6. Application of Eq (7) to Water and to Process Mixture

Returning now to eq (7) and using subscripts w and m to indicate water and process mixture, respectively

$$(P_{GH} - P_{GO})_w = gL[\rho_w - (\rho_a)_p] + (\rho_a)_p g(h-S) - (\rho_a)_{hw} gh$$
$$+ (\rho_a)_S gS + [\rho_w - (\rho_a)_{hw}]g\ell_w + \frac{2\gamma_w}{R_w}, \tag{38}$$

$$(P_{GH} - P_{GO})_m = gL[\rho_m - (\rho_a)_p] + (\rho_a)_p g(h-S) - (\rho_a)_{hm} gh$$
$$+ (\rho_a)_S gS + [\rho_m - (\rho_a)_{hm}]g\ell_m + \frac{2\gamma_m}{R_m} \tag{39}$$

At the same temperature the same volume of water or process mixture implies the same level, L, since the cross-sectional area is essentially the same (this will be demonstrated later).

Using eqs (38) and (39) we shall develop an equation to convert $(P_{GH} - P_{GO})_m$ to $(P_{GH} - P_{GO})_w$ at the same temperature.

$$gL = \frac{(P_{GH} - P_{GO})_w - (\rho_a)_p\, g(h-S) + (\rho_a)_{hw} gh - (\rho_a)_S gS - [\rho_w - (\rho_a)_{hw}] g\ell_w - 2\gamma_w/R_w}{[\rho_w - (\rho_a)_p]} \tag{40}$$

$$gL = \frac{(P_{GH} - P_{GO})_m - (\rho_a)_p g(h-S) + (\rho_a)_{hm} gh - (\rho_a)_S gS - [\rho_m - (\rho_a)_{hm}] g\ell_m - 2\gamma_m/R_m}{[\rho_m - (\rho_a)_p]} \tag{40a}$$

By setting $\ell_w = \ell_m \equiv \ell$ and $R_w = R_m \equiv R$, by approximating $[\rho_w - (\rho_a)_p]$ by ρ_w and $[\rho_m - (\rho_a)_p]$ by ρ_m for the smaller terms, and by approximating $[\rho_w - (\rho_a)_{hw}]$ by ρ_w and $[\rho_m - (\rho_a)_{hm}]$ by ρ_m, eqs (40) and (40a) become

$$\frac{(P_{GH} - P_{GO})_w}{[\rho_w - (\rho_a)_p]} - \frac{(\rho_a)_p g(h-S) - (\rho_a)_{hw} gh + (\rho_a)_S gS}{\rho_w} - g\ell - \frac{2\gamma_w}{\rho_w R}$$

$$= \frac{(P_{GH} - P_{GO})_m}{[\rho_m - (\rho_a)_p]} - \frac{(\rho_a)_p g(h-S) - (\rho_a)_{hm} gh + (\rho_a)_S gS}{\rho_m} - g\ell - \frac{2\gamma_m}{\rho_m R} \tag{41}$$

The mean density of air in the longer bubbler tube is estimated using the ratio of the corresponding pressure (P_f plus a fraction ϕ of the pressure head due to the liquid) to P_f, and $(\rho_a)_p$:

$$(\rho_a)_{hw} = [\frac{P_f + \phi\rho_w gL}{P_f}](\rho_a)_p = [1 + \frac{\phi\rho_w gL}{P_f}](\rho_a)_p \ , \tag{42}$$

$$(\rho_a)_{hm} = [\frac{P_f + \phi\rho_m gL}{P_f}](\rho_a)_p = [1 + \frac{\phi\rho_m gL}{P_f}](\rho_a)_p \ , \tag{43}$$

where P_f is the pressure at the surface of the liquid, and $0 < \phi \leq 1$. The introduction of ϕ avoids making explicit calculations of the mean density of air.

$$\frac{(\rho_a)_{hm} gh}{\rho_m} - \frac{(\rho_a)_{hw} gh}{\rho_w} = (\frac{1}{\rho_m} - \frac{1}{\rho_w})(\rho_a)_p gh \tag{44}$$

$$\frac{(\rho_a)_p g(h-S)}{\rho_w} - \frac{(\rho_a)_p g(h-S)}{\rho_m} = -\ (\frac{1}{\rho_m} - \frac{1}{\rho_w})(\rho_a)_p g(h-S) \tag{45}$$

noting that $(\rho_a)_S \simeq (\rho_a)_p$.

Eq (41) now becomes

$$\frac{(P_{GH} - P_{GO})_w}{[\rho_w - (\rho_a)_p]} = \frac{(P_{GH} - P_{GO})_m}{[\rho_m - (\rho_a)_p]} - \frac{2}{R}\left(\frac{\gamma_m}{\rho_m} - \frac{\gamma_w}{\rho_w}\right) \tag{47}$$

Using the data of Davies et al. [2] for a process mixture 3M in HNO_3 and approximately 0.8M in heavy metals (calculated as uranyl nitrate) at 15° C, $(\gamma_m/\rho_m - \gamma_w/\rho_w) = -\frac{1}{\rho_w}(17 \times 10^{-3}\ \mathrm{Nm^{-1}})$. For this example for a bubble of radius of curvature R = 0.019 m, the second term on the right hand side of eq (47) is equal to $(1.8\ \mathrm{Pa})/\rho_w$, which is not negligible. Eq (47) when rearranged becomes

$$(P_{GH} - P_{GO})_w \simeq \left[\frac{\rho_w - (\rho_a)_p}{\rho_m - (\rho_a)_p}\right](P_{GH} - P_{GO})_m + \frac{2}{R}\left[\gamma_w - \frac{\rho_w}{\rho_m}\gamma_m\right], \tag{48}$$

recalling that ρ_w and ρ_m are the density of water and process mixture, respectively, γ_w and γ_m are the corresponding surface tensions, and $(\rho_a)_p$ is the density (mean) of air in the space above the liquid.

R and ℓ can be approximated by the inside diameter of the bubbler tube [8]. The data of Harkins [11] for γ_w of water have been fitted in the present work to a cubic equation in t(°C); the resulting equation is

$$\gamma_w\ (\mathrm{Nm^{-1}}) = 75.675 \times 10^{-3} - 1.3762 \times 10^{-4}t - 3.938 \times 10^{-7}t^2 + 1.076 \times 10^{-9}t^3$$

Using eq. 49, the calculated value of γ_w at 25 °C is $72.005 \times 10^{-3}\ \mathrm{Nm^{-1}}$.

The potentially largest uncertainty in eq (48) is that due to the determination of ρ_m, although Jones et al. [1] have shown that it can be determined in a tank with a precision comparable to that claimed for laboratory determinations for much smaller samples.

Eq (48) enables converting differential pressure at the gage for a process mixture at the reference temperature 25 °C (or at other temperatures) to the corresponding differential pressure for water. Using this differential pressure for water, the calibration equation yields the volume of process mixture (which is equal to the volume of water). The differential pressure at the gage for water at the reference temperature and for process mixture at other temperatures can be calculated using arguments similar to those used for water.

We begin with the equation

$$(P_{GH} - P_{GO})_{m,25} = (P_{GH} - P_{GO})_{m,T} + \Delta(P_{GH} - P_{GO})_{m,T}\ , \tag{50}$$

where $(P_{GH} - P_{GO})_{m,T}$ is the differential pressure at the gage for a process mixture at temperature T, and $(P_{GH} - P_{GO})_{m,25}$ is the quantity to be inferred and substituted in eq (48).

From eq (39),

$$\begin{aligned}\Delta(P_{GH} - P_{GO})_m &= g\,\Delta(L\rho_m) - g\,\Delta[L(\rho_a)_p] + g\,\Delta[(\rho_a)_p(h-S)] \\ &- g\,\Delta[(\rho_a)_{hm}h] + g\,\Delta[(\rho_a)_S S] + g\,\Delta[\ell\rho_m - \ell(\rho_a)_{hm}] + \frac{2}{R}\,\Delta\gamma_m.\end{aligned} \tag{51}$$

From eq (36),

$$g\,\Delta(L\rho_m) \simeq -2\alpha(T_{25} - T)(P_{GH} - P_{GO})_{m,T} \tag{52}$$

Since the upper end of the longer tube and the lower end of the shorter tube are attached to the top of the tank, the only variation of (h-S) with temperature that need be considered is that of the gap between the lower end of the longer tube and the bottom of the tank. For the model tank the gap is 0.019 m and the variation $(0.019 \times 15.9 \times 10^{-6} \times \Delta T = 3.0 \times 10^{-7}\ \Delta T\ \mathrm{m})$ can be disregarded.

$$g\ \Delta[(\rho_a)_p\ (h-S)] \simeq g(h-S)[(\rho_a)_{p,25} - (\rho_a)_{p,T}], \tag{53}$$

$$-\ g\ \Delta[(\rho_a)_{hm}h] \simeq -\ gh[(\rho_a)_{hm,25} - (\rho_a)_{hm,T'}], \tag{54}$$

where T' is the temperature of the gas in the longer tube.

$$g\ \Delta[(\rho_a)_{Sm}S] \simeq gS[(\rho_a)_{Sm,25} - (\rho_a)_{Sm,T''}], \tag{55}$$

where T" is the temperature of the gas in the shorter tube.

$$g\ \Delta[\ell\rho_m - \ell(\rho_a)_{hm}] \simeq g\ \Delta(\rho_m\ell) = g\ell\ (\rho_{m,25} - \rho_{m,T}), \tag{56}$$

$$\frac{2}{R}\ \Delta\gamma_m = \frac{2}{R}\ (\gamma_{m,25} - \gamma_{m,T}) \tag{57}$$

$$g\ \Delta[L(\rho_a)_p] \simeq gL\ \Delta(\rho_a)_p + g(\rho_a)_p\ \Delta L, \tag{58}$$

$$-\ \frac{g\ \Delta[L(\rho_a)_p]}{(P_{GH} - P_{GO})_{m,T}} \simeq -\ \frac{g\ \Delta[L(\rho_a)_p]}{gL\rho_m} \simeq -\ \frac{\Delta(\rho_a)_p}{\rho_m} - \frac{(\rho_a)_p}{\rho_m}\ \frac{\Delta L}{L} \tag{59}$$

From eq (22),

$$-\ \frac{\Delta L}{L} \simeq \frac{\Delta A}{A} + \frac{\Delta\rho_m}{\rho_m} = 2\alpha\ \Delta T + \frac{\Delta\rho_m}{\rho_m}$$

$$-\ \frac{g\ \Delta[L(\rho_a)_p]}{(P_{GH} - P_{GO})_{m,T}} \simeq -\ \frac{\Delta(\rho_a)_p}{\rho_m} + \frac{2\alpha\ \Delta T\ (\rho_a)_p}{\rho_m} + \frac{(\rho_a)_p}{\rho_m}\ \frac{\Delta\rho_m}{\rho_m} \tag{60}$$

The sum of the second and third terms on the right hand side of eq (60) is approximately one order of magnitude smaller than the first for reasonable ΔT's (several tens of Celsium degrees), and may thus be disregarded. Therefore,

$$-\ g\ \Delta[L(\rho_a)_p] \simeq -\ [\frac{\Delta(\rho_a)_p}{\rho_{m,T}}](P_{GH} - P_{GO})_{m,T}$$

$$-g\ \Delta[L(\rho_a)_p] \simeq -\ \frac{[(\rho_a)_{p,25} - (\rho_a)_{p,T}]}{\rho_{m,T}}\ (P_{GH}-P_{GO})_{m,T} \tag{61}$$

The terms in eqs (54) and (55) are opposite in sign and the magnitudes depend on the temperature increases in the shorter tube, (ΔT)', and in the longer tube, (ΔT)", which are much smaller than ΔT. Consequently, these two terms represent a differential pressure of the order of 0.1 Pa and may be disregarded.

Accumulating the remaining terms in eqs (52), (53), (56), (57), and (61), eq (50) becomes

$$(P_{GH} - P_{GO})_{m,25} = (P_{GH} - P_{GO})_{m,T} - 2\alpha(298.15 - T)(P_{GH} - P_{GO})_{m,T}$$

$$- \frac{[(\rho_a)_{p,25} - (\rho_a)_{p,T}]}{\rho_{m,T}} (P_{GH} - P_{GO})_{m,T}$$

$$+ g(h-S)[(\rho_a)_{p,25} - (\rho_a)_{p,T}] + g\ell(\rho_{m,25} - \rho_{m,T})$$

$$+ \frac{2}{R} (\gamma_{m,25} - \gamma_{m,T}) \qquad (62)$$

$$(P_{GH} - P_{GO})_{m,25} = (P_{GH} - P_{GO})_{m,T} [1 - 2\alpha(298.15-T) - \frac{1}{\rho_{m,T}} [(\rho_a)_{p,25} - (\rho_a)_{p,T}]]$$

$$+ g(h-S)[(\rho_a)_{p,25} - (\rho_a)_{p,T}] + g\ell(\rho_{m,25} - \rho_{m,T})$$

$$+ \frac{2}{R}(\gamma_{m,25} - \gamma_{m,T}) \qquad (63)$$

Eq (48) then becomes, at the reference temperature 25 °C,

$$(P_{GH} - P_{GO})_{w,25} = [\frac{\rho_{w,25} - (\rho_a)_{p,25}}{\rho_{m,25} - (\rho_a)_{p,25}}](P_{GH} - P_{GO})_{m,T} \times$$

$$[1 - 2\alpha(298.15 - T) - \frac{[(\rho_a)_{p,25} - (\rho_a)_{p,T}]}{\rho_{m,T}}]$$

$$+ g(h-S) \frac{\rho_{w,25}}{\rho_{m,25}} [(\rho_a)_{p,25} - (\rho_a)_{p,T}]$$

$$+ g\ell[\rho_{w,25} - (\frac{\rho_{w,25}}{\rho_{m,25}})\rho_{m,T}]$$

$$+ \frac{2}{R}[\gamma_{w,25} - (\frac{\rho_{w,25}}{\rho_{m,25}})\gamma_{m,T}] \qquad (64)$$

Eq (64) enables conversion of differential pressure at the gage for a volume of process mixture at temperature T to the differential pressure corresponding to the same volume of water at 25 °C, the volume of process mixture is then inferred directly from the 25 °C water calibration equation. The last three terms on the right hand side of the equation are independent of the level of the liquid in the tank (above the lower bubbler tip) and they therefore cancel for transfers of process mixture at nearly constant temperature. For the model tank with a height (h-S) of 3.4 m at 50 °C, containing a process mixture of density ($\rho_{m,T}$) of 1300 kg m^{-3}, and bubbler tubing inside diameter Of 0.019 m, the approximate magnitudes of these terms are + 2.6 Pa, + 0.2 Pa, and + 0.4 Pa. For the tank inside diameter of 2.4 m, 2.5 Pa corresponds to approximately 1 liter of mixture. Under the above conditions, the magnitude of $2\alpha(298.15 - T) + [(\rho_a)_{p,25} - (\rho_a)_{p,T}]/\rho_{m,T}$ is approximately 0.1%.

The effect of expansion of the tank due to increased loading for the process solution of assumed density 1300 kg m^{-3} can be disregarded since it can be shown [12] that such expansion for the model tank would be of the order of 0.001%.

In the foregoing it has been tacitly assumed that there are no significant discontinuities in mean cross-sectional area of the tank, and thus that the surface of the liquid does not move abruptly to a region of significantly different cross-sectional area as a result of expansion, contraction, or change in liquid density. If such discontinuities were present, a piecewise calibration equation could be used to avoid the attendant difficulties. This has been demonstrated by Lechner, Reeve, and Spiegelman [4] and by Knafl, Sacks, Spiegelman, and Ylvisaker [5].

The differential pressure at the gage gives no information on the "heel" volume, that is, the volume of the liquid below the lower bubbler tip. For the model tank the gap between the bubbler tip and the floor of the tank is 0.019 m. The increase in heel volume, V_o, with an increase in temperature, ΔT, is simply $3\alpha V_o \Delta T$.

4. Summary

An algorithm has been developed to enable inference of the volume of process mixture in a tank from measurements of differential pressure and temperature and the values of other parameters. The application of the algorithm involves the following steps:

1.) The volume of the increments of water used in the water calibration of the tank is adjusted to the reference temperature, 25 °C, by the use of eq (37).

2.) The differential pressure corresponding to the increments of water is adjusted to the reference temperature by the use of eq (36).

3.) The fitting of the adjusted differential pressure and volume values to a calibration equation is discussed elsewhere [3,4,5].

4.) The differential pressure value for measurements made for the process mixture is converted to that corresponding to water at 25 °C by the use of eq (64).

5.) This converted differential pressure value is then used in the water calibration equation to calculate the volume of water at 25 °C at the same level, the desired result.

The algorithm introduces an additional uncertainty, for the model tank, of about 1 Pa which corresponds to about 0.5 liter. The residual standard deviation for the water calibration is about 0.5 liter also.

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COMPUTERIZED SAFEGUARDS INSPECTION DATA*

JOSEPH R. WILSON, SGOAP
International Atomic Energy Agency
Vienna, Austria

ABSTRACT

The International Atomic Energy Agency routinely receives reports of nuclear materials accounting transactions from its Member States. For many years, the Agency has entered these data into a data base to facilitate checking against other State reported transactions and against the data obtained by Inspectors during their inspections of nuclear facilities. While much of the checking of the State Reports data has been automated, the inspection data has, until recently, been limited to manual checking.

This paper, after giving a brief summary of the State Report data base, describes the steps that have been taken towards computerizing the inspection data, in particular, the data obtained by examination of facility records and by physical verification procedures, and discusses the planned checks, cross-checks and evaluations that this computerization makes possible.

INTRODUCTION

The International Atomic Energy Agency has more than 130 Inspectors, and a like number of supporting professionals, applying international safeguards to approximately 400 nuclear facilities and 400 other locations in just over 50 countries.

The application of international safeguards requires determining, through accounting procedures, the quantity of each type of nuclear material that should be in a facility** (usually referred to as determining the book inventory and confirming by physical verification that it is there***.

The book inventory is established in two ways: the first being based on an examination of accounting records and supporting documents at the facility during inspections, and the second being based upon reports from States to the Agency of the nuclear material inventories and inventory changes that have occurred at each facility. Until recently, only the State Reports portion of the accounting procedures had been computerized.

This paper, after giving a brief summary of the computerized State Report data base, describes the steps that have been taken towards computerizing the inspection data, in particular, the data obtained by examination of facility records and by physical verification procedures, and discusses the planned checks, cross-checks and evaluations that this computerization makes possible.

SUMMARY OF COMPUTERIZED STATE REPORTS

All countries, in accordance with various agreements, supply the Agency with reports on their nuclear material inventories and transfers. The countries that have signed the Non-Proliferation Treaty (NPT) provide for each facility a Physical Inventory Listing (PIL) at the time of each physical inventory, provide inventory change reports (ICRs) concerning the shipments, receipts and other accountability transactions of the material at the facility, and provide Material Balance Reports (MBRs) summarizing nuclear material accountability

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* In December 1983 the IAEA awarded the author the Distinguished Service Award for the work described in this paper

** Facility is used in this paper in the broad sense of an accounting unit. In practice, many facilities are individual accounting units. Some smaller ones are grouped together into a single accounting unit, and some larger ones are divided into several accounting units.

*** Safeguards is considered to have achieved its goal if the Agency can confirm, with a 95% confidence, that the material at the facility does not differ from the declared (and confirmed) book inventory by more than a pre set value, called a significant quantity nominally, the amount of nuclear material required to produce one nuclear weapon transactions for the period from physical inventory to physical inventory. These data, usually received by the Agency on magnetic tape (though some data are supplied only on hard copy and must be key-punched into the data base by the Agency), are checked for conformity to the reporting system requirements and entered into the nuclear materials accountancy data base.

These State Reports are received several months after the transactions have occurred. Once these reports are received and entered into the data base, the Agency has data on all movements between, and the inventory in, the facilities under safeguards. This allows the Agency to confirm the book transactions between each facility by routinely matching the reported shipments against reported receipts. Further, the data in the data base can be used to calculate, for each NPT and some non-NPT facilities, the book inventory for any given date. These data then can be manually checked against data obtained during inspections.

DEVELOPMENT OF THE COMPUTERIZED INSPECTION REPORTS

In 1980, a Task Force for Inspection Reports (TFIR) was constituted to review the content of the Inspection Report and to review the reporting of the inspection activities and conclusions as contained in the Agency's Statements to the Member States. This task force, by early 1981, having narrowed its focus to light water reactors (LWRs), had completed most of the modules that would be contained in the new LWR Inspection Report. At that time, TFIR envisaged the report as being one that would be completed by hand by the Inspector, with a minumum of typing required, hoping that the reports could be completed quickly. These hand-written reports were to include forms on which the accounting data was to be recorded so that these data could be inputted into the computer for later use. In various trials, however, it was found that the checking of the report accuracy still required lengthy reviews and corrections.

While it was recognized that computerization could meet the "quick summary" requirements and provide many additional advantages including computerized checking, TFIR shared the view of most Inspectors and Section Heads that computerization could not begin until several years of experience with the new format had been acquired. Beginning in March 1981, the writer, supported by the Heads of the two largest Operations Sections (responsible for inspections), took the lead into computerizing the Inspection Reports. These reports were based on the nearly completed TFIR model. The Data Proramme Develoment Section wrote the programme, based on user requirements and programme logic developed by the data unit of the Far East Section of Operations. The programme became operational in September 1981 and was placed in test operation for the last three months of that year, mainly by the Far East Section. Some reports were also computerized by the EURATOM Section and, to a lesser extent, by other sections in Operations. The trial continued through 1982, with more and more types of reports being computerized.

In April of 1982, TFIR embraced the new computerized reports. In the summer and fall of 1982, based on TFIR requirements, the programme was up-dated to conform to the completed version of the TFIR LWR Model. Instructions were issued requiring its use for all item facilities inspected after January 1, 1983.

INSPECTION REPORT CONTENTS

The Inspection Report Model for LWRs developed by TFIR contains 11 modules for data and a summary page (Module 1-15)*.
These are listed below.

Module Number	Inspection Activity	Description of Contents
I-1	Follow-up	Comments and conclusions concerning unresolved issues from previous inspections and new issues arising since the last inspection. Generally, these data are in the form of comments. If discrepancies remain unresolved, these data are quantified, if possible.
I-2	Examination of Accounting Records	The beginning inventory, ending inventory and summary of inventory changes by inventory change type are recorded. These data can be subject to quality control and a wide variety of computer checks.
I-3	Examination of Operation Records	Data concerning facility operation, as it may effect nuclear materials accountancy, are recorded. THese data can be subject to limited quality control and computer checks.
I-4	Reconciliation of Operating & Accounting Records	Data concerning the manual comparison of Operating and Accounting Records are recorded. These data can be subject to limited quality control
I-5	Comparison of Reports and Records	Data concerning the comparison of the State Reports data with the corresponding data at the facility are recorded. This activity can be largely computerized, using data from the State Reports and data from Module I-2 above.
I-6	Up-dating of Book Inventory	The inventory changes occuring since the examination period (reported in Module I-2), or previous inspection up-date period (previous Module I-6), are reported here to provide a basis for the partial verification of inventory. (see Module I-8).
I-7	Verification of Inventory Changes	Data concerning the verification of inventory changes, such as by inspector witness, by the verifications through unique identification, or by Agency seals, are reported here. These data are subject to computer matching with State Reports data and can be subject to limited quality control.
I-8	Verification of Inventory	Data to identify the nuclear material by batch, item or strata, and a record of the type of verification and the verification results are reported in this module. These data can be subject to quality control and to comparison with data, as reported in Modules I-2 and I-6, and with data obtained in previous inspections and State Reports.
I-9	Verification of Inventory at Strategic Points	Data concerning the verification of inventory changes for certain situation not reportable in Module I-7 above. (This module has very limited use.

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* Module I-12, Operator's Measurement System; Module I-13, Shipper-Receiver Differences; and Module I-14, Other Activities; while not addressed as yet by TFIR, have been included in the Computerized Inspection Report for completeness.

Module Number	Inspection Activity	Description of Contents
I-10	Surveillance	Much data is gathered by film and TV cameras, bundle counters and neutron flux monitors. These data, and data concerning monitored nuclear material movements, are reported in this module. These data can be subject to some quality control, such as comparison with data as reported in Modules I-2 and I-6 and with data obtained from State Reports.
I-11	Seals	Detailed data on seals, including material and equipment under seal, are recorded elsewhere in the computer data base. Summary data on seals and material under seal are recorded in this module. These data can be subject to quality control through comparison with the detail data in the data base and with data in this and previous Inspection Reports as reported in Modules I-7, I-8, I-9 and I-10.

QUALITY CONTROL OF COMPUTERIZED INSPECTION DATA

One of the major advantages to be realized from computerizing the Inspection Report data is that the data could be quality controlled and thus its accuracy and completeness monitored. The availability of accurate and complete inspection data in an ordered system is required for effective safeguards. Obtaining this through computerization, of course, depends upon the development of software to make the various checks with other data in the computer. This softwares under development, and several of the more important portions are now in trial operation. The checks that can be automatically made fall into the following general categories:

1. Checks against the Authority File.

   The Authority File contains information regarding the correct facility name, the number and types of MBAs (material balance areas), the Agreement type that is in force regarding the facility, etc. These form a basis for checking these data in the report.

2. Checks against the Design Information File.

   The Design Information File contains information regarding the number of inventory KMPs at the facility, the allowed inventory change codes, the allowed material description codes, the expected nuclear material types, enrichments and maximum amounts of each nuclear material catagory, etc. These form a basis for checking a number of data items in the Inspection Report.

3. Checks against the activities planned for the inspection.

   The Inspection Plan and Activity Summary had been computerized earlier. The computerization of the Inspection Report now make possible automatic checks of report data with the plan and the summary.

4. Checks against previous inspection data.

   The Computerized Inspection Report Data File contains data on the previous nuclear material inventory for the end of the most recent inspection audit period and most recent inspection up-date period, data on the seals, data on surveillance prevailing at the last inspection, data on previous inventory verification results (material that has been previously verified), some information on the location of nuclear material such as fuel assemblies, etc. Consistency checks are now possible in regard to the book inventory, seals situation, and material location at the close of the previous inspection vs the reported changes and situation found at the current inspection. Consistency checks can also be carried out between like facilities to see that values fall within expected ranges.

5. Checks against data in the State Reports.

   As previously stated, the State Reports are also computerized. While it may be several months before the State data is received, the report computerization forms a basis for checking that the reported inventories and reported inventory changes, as determined during the inspection, are consistent with the State Reports. This becomes especially important in regard to reported shipments and receipts, as these values also can be checked against the information from the corresponding facility (both in the corresponding Inspection Report and the corresponding State Report).

In the past, it has been the usual practice for the Agency Inspectors,on receipt of the State Report, to carry a copy with them on their next inspection and compare it with the facility records in order to verify that the Agency records and facility records are in agreement. This part of the inspection activity may be partially automated with the new system.

INFORMATION REPORTS FOR INSPECTOR AND FACILITY OFFICER USE

One of the first uses of the computerized Inspection Report data was the generation of the FACILITY STATUS REPORT. This print-out listed all of the data from previous inspections and arranged it with like data in groups so that the Inspector and/or Facility Officer could quickly obtain an over-view of what had been found at the facility over an extended period. He could also quickly make comparisons for an extended period regarding consistency, frequency of problems, inventory and flow changes and actions taken to resolve outstanding differences.

The FACILITY STATUS REPORT has proven very useful in presenting in one document much of the information required for the preparation of the SAFEGUARDS IMPLEMENTATION REPORT (SIR) prepared each year for the Board of Governors of the Agency.

In addition, having the Inspection Report data in the data base allows queries to be directed against the data, so that data can be quickly and automatically organized in convenient presentations for Inspector, Facility Officer and Management use.

STATEMENTS TO THE STATES

The Agency has responsibilities, according to its various agreements with the States, to provide Statements on inspections and conclusions regarding its inspection activities. Data in these Statements (the 90(a) and 90(b) Statements, so named for paragraphs in most of the agreements) should be quality checked before the Statements are dispatched to the State. This, together with associated time for corrections and re-reviews, has resulted in lengthy delays before the reports could be in the hands of the State. Thus it often is many months before the State is aware of difficulties, descrepancies, or other situations that may require State remedial action. With the Computerized Inspection Reports, however, it is now possible to computerize the preparation of these Statements, and this will, when implemented, result in Statements that are more timely, more accurate and that consistently follow a standard format.

INCLUSION IN THE REPORT OF AUTOMATED DA AND NDA DATA

NDA measurements are made at many inspections as part of the verification of nuclear material. When measurements are quantitative, the Agency can include in its Statement a confirmation of the material with an associated measurement error and confidence level. In previous years these data were usually recorded in inspection log sheets. More recently, these data are recorded on magnetic tape for further analysis. These analysis are ameanable to computerization. It is conceivable that, with sufficient development, the recorded information on tape can be read into a computer, together with the other inspection data, and the calculations of the measurement error and confidence level can be automatically calculated and included in the Inspection Report and Statement.

As part of the verification activities at many of the bulk facilities, samples are taken and sent to the Agency's Safeguards Analytical Laboratory at Seibersdorf (or one of the analytical laboratories in the Analytical Laboratory Network) for analysis. The data regarding the strata from which these samples were taken and the relation of that strata to the overall inventory at the facility are recorded in the Inspection Report. Thus it is relatively easy to develop the necessary software to evaluate the DA results in regard to the inspection and automatically include the resulting measurement error and confidence level in the Inspection Report.

OTHER LONGER-RANGE POSSIBILITIES

It is not difficult to speculate on further automation or further improvements regarding timeliness. For example, it is quite possible to invisage transmission of inspection data directly from the field, either through an Agency Field Office, or from a resident Agency Inspector, to the Agency via a data transmission network. (Several are commercially available and are considered secure by the businesses that use them). Such a system affords the possibility to move towards automated real time accountancy at strategically important facilities.

It is also possible that automatic instruments, such as various electronic seals, bundle and portal monitors, etc, could be incorporated into the system so that data from these devices could be automatically received, processed and included in Inspection Reports and in the various information reports currently used by the

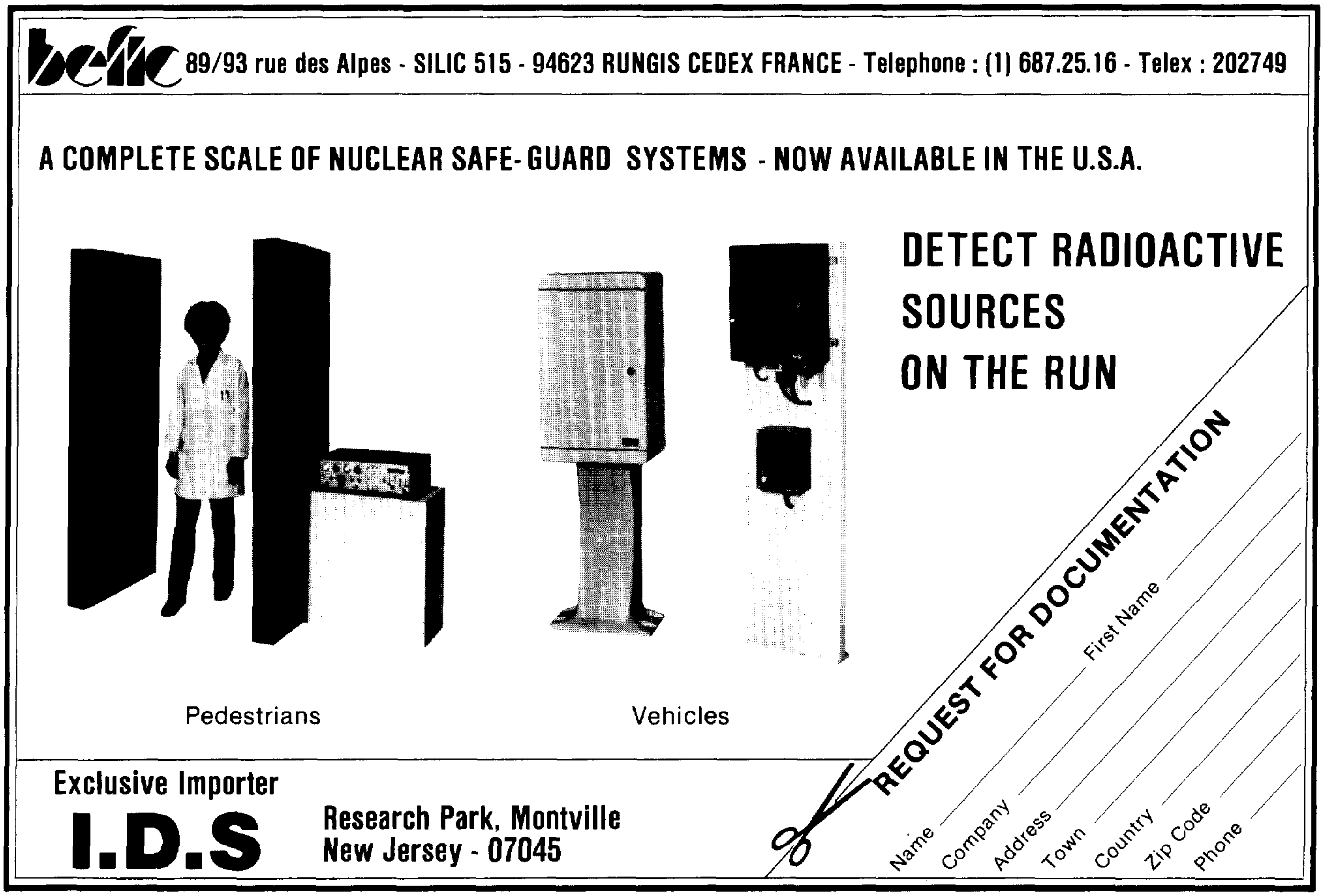
Inspetcors, Facility and Country Officers and Management.

SPECIAL RECOGNITION

The writer wishes to give special recognition to those who brought the project from its initial concept to its first trial operations. These include Messrs. Joseph Nardi, Bradford Cross, Michael Kaplan, William Holaday and Ms. Elenita Mayer.

CONCLUSION

The point of the paragraphs on long range possibilities above was only to stimulate the imagination. It will be some time, possibly a very long time, before these long range possibilties materialize. But this notwithstanding, it seems evident from the support that the computerized reports have received from the Inspectors, from the Evaluation Units, from the Standardization Unit, and from the DDG himself, that this work is a major foundation on which to build a modern, sophisticated international safeguards inspection data system that will have increasing value and importance over the years to come. And as the quality control and automatic cross-checks and comparisons now being developed become operational, the Agency's safeguards effectiveness and credibility will improve and the reports to the States and Agency's Board of Governors will be received more promptly and be more uniform and accurate.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RESOLUTION OF SHIPPER-RECEIVER DIFFERENCES

J. W. JOHNSTON
Statistics Section
and
R.J. BROUNS
Nuclear Energy Systems Section
Pacific Northwest Laboratories
Battelle Northwest
Richland, Washington

ABSTRACT

This paper describes statistical procedures for resolving significant shipper-receiver differences (SRDs) for nuclear material transfers and calculating the best estimate of the true amount of special nuclear material transferred. The resolution of an SRD should generally be accomplished by identifying and removing its causes. Logical stepwise procedures for investigating an SRD under various circumstances are recommended in this paper. It is concluded that the best estimate of the quantity of special nuclear material in a transaction is obtained by calculating the inverse variance-weighted estimates for the net weight, element fraction, and isotope fraction using the best available measurement results from the shipper, receiver, and referee laboratory.

INTRODUCTION

A shipper-receiver difference (SRD) is defined as the difference between the quantity of material stated by a shipper or supplier as having been shipped and the quantity received as measured by the receiver. As a prudent business practice, persons receiving materials measure their receipts and try to reconcile SRDs if the amount of the SRD is of significant monetary value. In addition, licensees authorized to possess more than one effective kilogram of special nuclear material (SNM) are required by Federal regulations(b) to "review and evaluate shipper-receiver differences and take appropriate investigative and corrective action to reconcile SRDs that are statistically significant at the 95 percent confidence level" (except when the SRD is 50 grams or less of ^{235}U, ^{233}U, or Pu).

The investigation of an SRD is initiated by the receiver of the SNM shipment when he concludes that a significant SRD has occurred. It needs to be recognized that the information available to the receiver from the shipper when a SRD is initially examined and judged to require an investigation is quite limited. The information available on Form 741 usually is not sufficient for assigning a probability to the statistical significance of an SRD. Comparisons based on reported limits of error or calculated paired differences at nominal "95% of confidence levels" are commonly used. The result of these comparisons provides a "flag" that stimulates further investigation. The conclusion is at first tentative; but as the investigation proceeds, the statistical significance of the SRD can be reevaluated when sufficient additional information is acquired.

Shippers and receivers usually have advance agreements about SRDs. The maximum acceptable SRDs for gross and net weights and assays of items or batches may be quite constant for each kind of material because the shipment sizes and measurement methods have not varied very much. In such cases a fixed maximum permissible SRD may be agreed to and applied uniformly. In other cases, the SRD limit must be estimated for each line item or batch in each shipment. As stated above, an estimate of the 95 percent confidence limit is approximate when only the data on the Transaction Report (DOE/NRC Form 741) are available. Other typical practices are:

- if a nonacceptable SRD for an item weight occurs the receiver notifies the shipper and offers three options:

(a) This paper includes work done for the Office of Nuclear Regulatory Research, Nuclear Regulatory Commission.

(b) Code of Federal Regulations, Title 10, Part 70, Section 70.58, revised January 1, 1981; Office of the Federal Register, General Services Administration, Washington, D.C.

(1) accept the receiver's value.

(2) witness a recalibration of the scale and a reweighing at the receiver's site and accept the value so obtained.

(3) accept return of the item, unopened, to the shipper.

- if a nonacceptable assay or isotopic difference occurs, the receiver reanalyzes the samples and reference standards to verify the previous results. If the difference is confirmed, the receiver notifies the shipper, who then sends a retained duplicate of the shippers analytical sample(s) to an outside laboratory for referee analyses. The shipper may reanalyze his samples to verify the original results, however, before resorting to referee measurements. The shipper and receiver commonly have an agreement to accept the referee laboratory result as the basis for settlement.

The investigation of an excessive SRD should have the purpose of finding the cause of the SRD as well as obtaining a resolution of the difference. For this purpose, a receiver should initiate the investigation by first checking his own measurement data for errors and performing appropriate remeasurements and tests for bias and the shipper should take similar steps.

The purpose of the following discussion is to present a logical plan for SRD investigations and some options for resolving SRDs. The plan utilizes statistical analysis and hypothesis testing as the basis for validating data and estimating the quantity of SNM in a transaction. This paper summarizes a report of Johnston, Brouns and Stewart.(1)

DISCUSSION

One of the first steps in the investigation is to assemble backup data for the measurements involved, including those of the shipper, with which to perform more meaningful statistical analyses and hypothesis tests. The backup data that should be assembled will allow the use of statistical exploratory data analysis and characterization of the statistical distributions of the measurements involved. The desired backup data are the complete shipper and receiver measurement data, their measurement standard deviations and the bias adjustments for each item and batch or lot in the shipment. From these, paired data for the net weight, percent element, and percent isotope results of the shipper and receiver can be studied where paired data exist. In addition, the standard deviations of the differences can be independently estimated if SRDs for several line items and batches or lots are available.

Using the backup data, the SRDs should be explored for trends in net weight, percent element and percent isotope differences. Stem and leaf displays, normal probability and cusum plots, and sequential plots with tests for randomness, normality and outliers are recommended approaches. In addition, revised standard errors for the weight, element and isotopic results should be calculated when new information is obtained.

The goal of the SRD investigative procedure is to achieve a best estimate of the true amount of SNM in the shipment. This is done by:

- locating the causes of the significant SRD, if possible
- correcting errors and incorporating the results of remeasurements
- calculating the best estimate from the final best values of all parties, including the referee values, if any.

The course followed during the investigation should be dictated primarily by the perceived most probable causes of the SRD. If an SRD occurs for just one or a few items in a shipment, one would recheck the data or remeasure the items to detect clerical and measurement mistakes and evaluate the measurement control data to check for an understatement of the measurement variances. On the other hand, if a significant difference is observed for many items or for a whole lot in the shipment, the investigation would first be directed toward locating a weighing or analytical bias.

For example, when a significant net weight difference occurs between the shipper and receiver data for a single or a relatively few items, the investigation would begin with:

- checking the weighing procedure and the data for clerical mistakes
- reweighing the items and some appropriate reference standards
- inspecting or testing for evidence of leakage or tampering with the container seals in transit.

If these procedures fail to resolve the difference, the investigation would continue with:

- evaluating the shipper's weighing data and supporting measurement control data

- estimating the variances of the shipper's and receiver's net weights and the SRD and performing the appropriate hypothesis test

- if a significant SRD remains at this point, the next step would be to return the items to the shipper for remeasurements or remeasure them at the receiver's site with witnessing by the shipper's representative.

A general logic diagram for investigating and resolving SRDs is presented in Figure 1. The diagram highlights three basic causes of a significant SRD and the appropriate investigative activities for each. A material defect is an actual

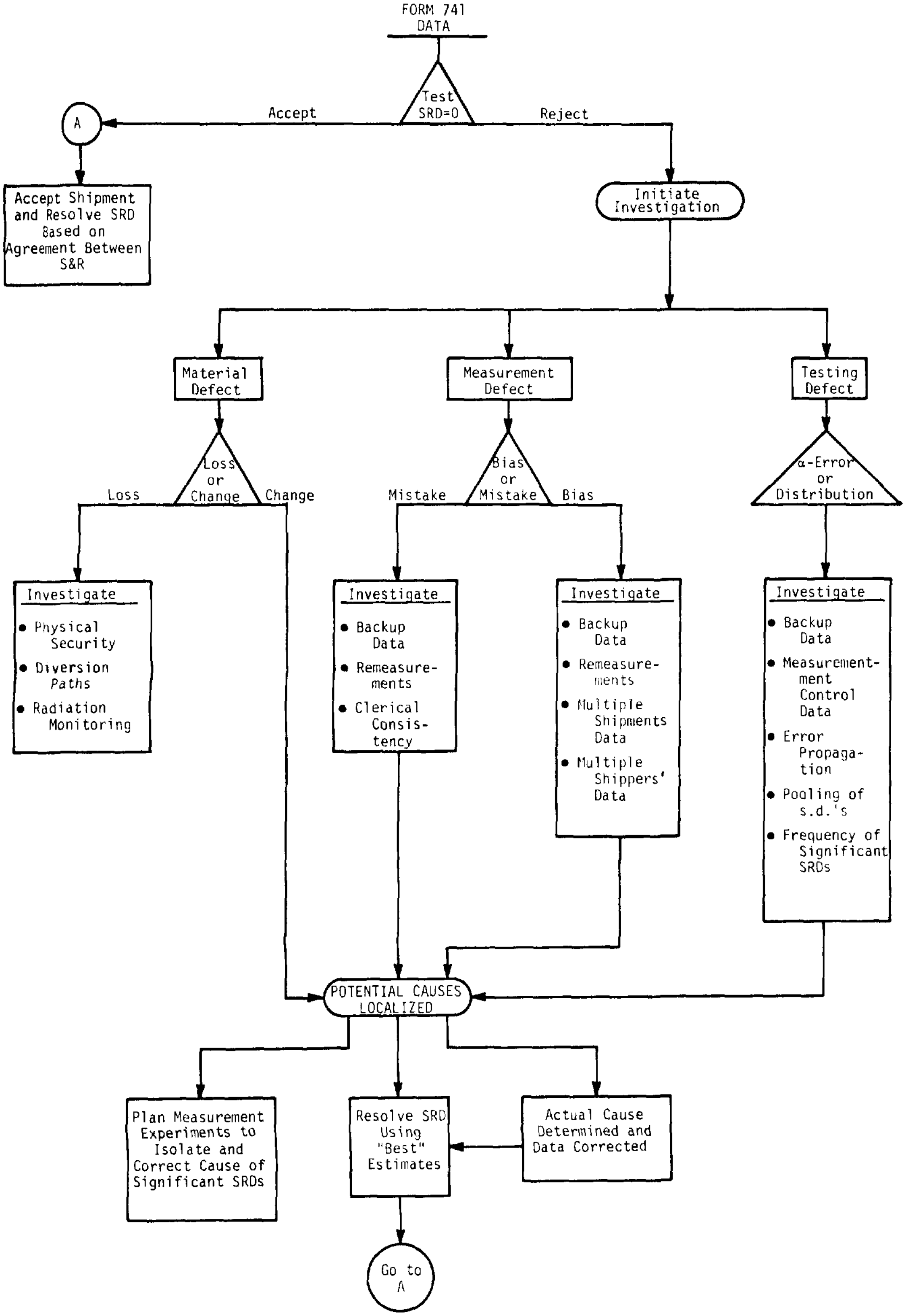

FIGURE 1. General Logic for Investigation and Resolution of SRDs

difference between the amount of SNM received, e.g., a loss by theft or leakage (hence, a check for radioactive material outside the containers), or by a change in the composition of the SNM, e.g., caused by loss or gain of moisture or oxygen. A measurement defect is caused by a mistake in measurements or data transcriptions or a measurement bias. A testing defect may be due to an extreme observation from the distribution or an inadequate characterization of the error distribution, e.g., a measurement variance was understated. In most cases, the logical steps of the investigation are to obtain the backup measurement and measurement control data, evaluate these, and if that does not resolve the SRD, begin performing recalibrations and remeasurements. At the same time the statistician should be studying the data for trends (multiple shipments data and multiple shipper's data) to find evidence for or against measurement biases.

After an investigation to determine the causes of a significant SRD has been made, verified measurements of net weight, fraction element and fraction isotope (outliers excluded), as well as validated estimates of the associated variance components, will be available.(a) Measurements and measurement control data from a referee laboratory may also be available. At this stage the cause of the significant SRD may or may not have been isolated, but a preliminary estimate of the quantity may be needed and can be developed before an SRD has been resolved.

Even if the cause of the SRD has been isolated, it may not be correctable. For example, a receiver may sample the cans of UO_2 powder as they are being loaded into a blender. That sampling procedure can not be repeated later. If the net-weight SRD is not "significant," the cause has been localized to the element factor. It may be that exchanging reserve samples and sending referee samples to another laboratory will produce element factors which are in agreement with each other and with the original results, on the basis of the between-laboratory precision of the analytical method used. Such a result would imply a testing defect in the original test. Unfortunately, there is no immediate way of correcting or improving agreement of the actual data involved, since neither the shipper nor the receiver has been shown to have a biased element fraction determination. (The measurement process could be improved for use in the future, and/or the variance estimate could include more realistic between-laboratory estimates.) However, something must go in the books for the transaction in question; that "something" should be the variance weighted estimator discussed below.

A correctable situation in the example above would be a verification that the shipper had made a transcription error for the element factor for the lot, or that one party has a bias; in these cases the best estimate may be that using only the referee's and other party's data.

"BEST" ESTIMATE OF THE TRUE AMOUNT OF SNM IN A TRANSACTION

The best estimate proposed is the weighted least-squares estimate, using inverses of variance estimates as the weights. Such estimates of mean values have been shown to be "best" in the sense that they have minimum variance among the class of unbiased estimators of the mean when the variances are known.(2) Jaech(3) discusses this kind of best estimate, and a recent article by Rao, et al.(4) compares it with other estimates. The approach recommended here involves using the best available data and the variance estimates from the measurement control information to calculate best estimates for each of the measured quantities involved in the questioned SRD. These estimates are then multiplied to get the best estimate of the mass quantity.

Exhibit 1 is a worksheet for assembling the best data for a measurement type, i.e., net weight, element fraction, or isotopic fraction measurement. One copy of the exhibit is to be filled out for each measurement type. The heading line is for noting the measurement type. Line 1 is to identify the kind of scale or chemical analysis method used. The notation is defined in the exhibit. Line 6 is for a variance component for the between-laboratory variance of the method, which should be available from the Safeguards Analytical Laboratory Evaluation (SALE) program for most analytical methods. Lines 7 to 12 are for values calculated from the listed statistics by using the formulas at the bottom of Exhibit 1.

The best estimates, $\hat{\mu}_1$, $\hat{\mu}_2$, and $\hat{\mu}_3$, for each of the three measurement types, found on line 10 of the three exhibits, are used to calculate the best estimate for each mass quantity, as follows:

1. Net Weight: $x_1 = \hat{\mu}_1$; $V(x_1) = V(\hat{\mu}_1)$
2. Element Mass: $x_2 = \hat{\mu}_1\hat{\mu}_2$

$$V(x_2) = \hat{\mu}_1^2 V(\hat{\mu}_2) + \hat{\mu}_2^2 V(\hat{\mu}_1) + V(\hat{\mu}_1)\ V(\hat{\mu}_2)$$

(a) By "validated" we mean that the data from which the variance estimates were made have been screened, additional data, if applicable, added, and the calculations checked.

EXHIBIT 1

WORKSHEET FOR CALCULATING BEST ESTIMATE OF A MEASURED VALUE

Measurement Type ____________________

	Notation	i=1 Shipper	i=2 Receiver	i=3 Referee
1. Measurement Method		____	____	____
2. Average Value	$\overline{y}_i$	____	____	____
3. No. of Msmts. for Average	n_i	____	____	____
4. M.C.(a) Random Error Variance	$s^2_{\varepsilon i}$			
5. M.C.(a) Bias Est. Variance	$s^2_{\beta i}$	____	____	____
6. SALE (or other) Between Lab Variance for Method	$s^2_{\lambda i}$	____	____	____
7. Variance Weight	w_i	____	____	____
8. Sum of Weights	Σw_i	____		
9. Estimation Contribution	E_i	____	____	____
10. Best Estimate	$\hat{\mu}$	____		
11. Variance of $\hat{\mu}$	$V(\hat{\mu})$	____		
12. Standard Deviation	$sd(\hat{\mu})$	____		

Calculations

$$w_i = n_i/[s^2_{\varepsilon i} + n_i(s^2_{\beta i} + s^2_{\lambda i})]$$

$$E_i = w_i\ \bar{y}_i/\sum w_i$$

$$\hat{\mu} = \sum_i E_i;\ V(\hat{\mu}) = 1/\sum w_i;\ sd(\hat{\mu}) = \sqrt{V(\hat{\mu})}$$

(a) Error estimates from measurement control data.

3. Isotopic Mass: $x_3 = x_2\ \hat{\mu}_3$

$$V(x_3) = x_2{}^2 V(\hat{\mu}_3) + \hat{\mu}_3{}^2 V(\hat{x}_2) + V(x_2)\ V(\hat{\mu}_3)$$

Then x_1, x_2 and x_3 are the best estimates of the mass quantities and the V are the associated variance estimates.

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A QUANTITATIVE MODEL FOR IAEA SAFEGUARDS EFFECTIVENESS

C. R. HATCHER
Los Alamos National Laboratory
Los Alamos, NM

ABSTRACT

This paper develops a simple mathematical model for International Atomic Energy Agency (IAEA) safeguards effectiveness. It is shown that $E_T = \sqrt{KCQD}$, where E_T is the effectiveness in achieving stated objectives, K is average inspection coverage, C is perceived credibility of inspection statements, Q is critical inspection coverage at facilities where there is diversion or facility misuse, and D is diversion detection probability. The four safeguards parameters (K, C, Q, and D) are systematically analyzed and are quantitatively estimated using a survey technique. Based on current trends, dramatic improvements in IAEA safeguards effectiveness are projected over the next 5 years.

The model illustrates the dual nature of international safeguards resulting from IAEA roles in providing assurance and in detecting diversion. It also suggests that one of the safeguards parameters, critical coverage Q, is in need of further attention.

I. INTRODUCTION

A. Background

This study is an attempt to develop a quantitative model for IAEA safeguards effectiveness. There has been considerable effort by others devoted to methods for quantifying IAEA inspection coverage and diversion detection probability. However, there has been no formalism developed for expressing IAEA safeguards effectiveness directly in terms of inspection coverage, detection probability, and other safeguards parameters that determine effectiveness. Without such a formalism, it is difficult to discuss many of the aspects of safeguards effectiveness in simple language. The purpose of this study is to provide a framework that facilitates discussion and analysis of the effectiveness of IAEA safeguards verification activities.

In an earlier paper,[1] factors that influence IAEA safeguards effectiveness were examined using the flow diagram shown in Fig. 1. From a number of comments on the paper, it became clear that, although the flow diagram provided an interesting way of examining IAEA safeguards effectiveness, the analysis of the flow diagram needed further work.

In the present study, the same flow diagram is used but the analysis has been considerably improved. In particular, proper emphasis is placed on detection of diversion as a safeguards objective, results are expressed in terms of conventional safeguards parameters, and technical and nontechnical considerations are treated separately.

B. IAEA Safeguards Objectives

Because IAEA safeguards effectiveness can be defined as the degree to which intended objectives are met, it is important to review the different statements of objectives. When IAEA safeguards were first being developed, the Agency was authorized "to establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose." This wording is used in both the IAEA Statute[2] and in INFCIRC/66.[3]

In implementing safeguards under the non-proliferation treaty, safeguards objectives became more specific and took on a different tone. In INFCIRC/153,[4] we find that "...the objective of safeguards is the timely detection of diversion of significant quantities of *nuclear material* from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."

More recent IAEA documents[5,6] state that "The main political objectives of IAEA safeguards are: *To assure* the international community that States are complying with their non-proliferation and other 'peaceful use' undertakings; *To deter* (a) the diversion of safeguarded nuclear materials to the production of nuclear explosives or for other military purposes and (b) the misuse of safeguarded facilities with the aim of producing unsafeguarded nuclear material."

To summarize the current situation, timely detection and deterrence by the risk of early detection are now called the technical objectives of IAEA safeguards, and assurance and deterrence are referred to as the political objectives. In practice, the IAEA applies the concepts of assurance, deterrence, and detection to safeguards agreements implemented under both INFCIRC/66 and INFCIRC/153.

C. Flow Diagram

The IAEA performs over 1500 inspections per year and generally follows each inspection with an official report or statement to the appropriate national authority. As shown in

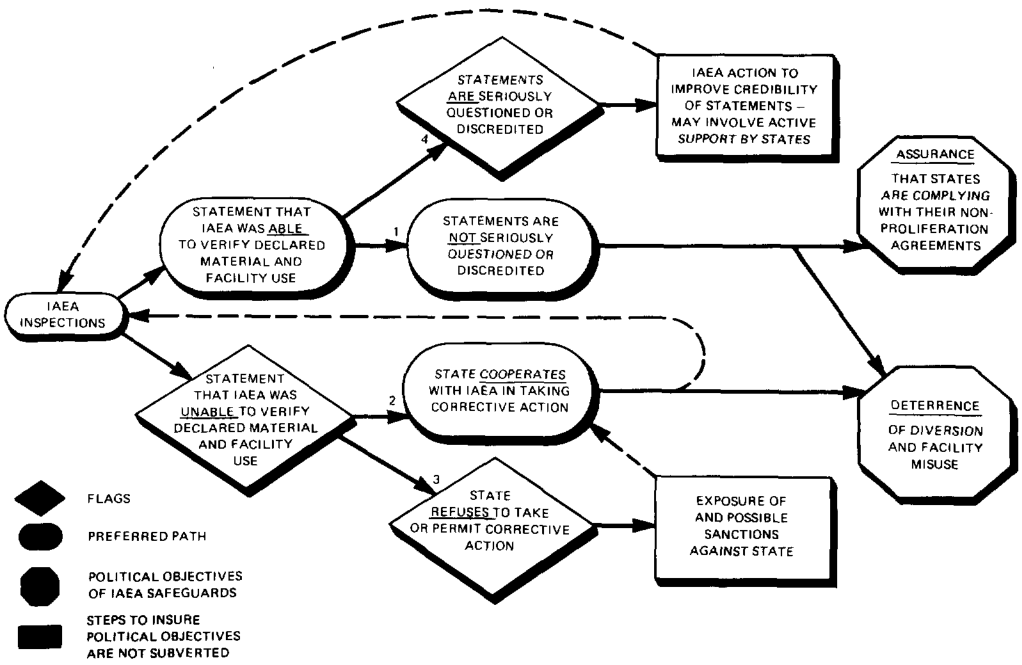

Fig. 1. Flow diagram of paths leading from IAEA inspections and the resulting verification statements to the main political objectives of IAEA safeguards, assurance and deterrence.

Fig. 1, IAEA inspection statements may take either of two forms, and responses to these statements also may take either of two forms. Consequently, Fig. 1 shows four possible paths, marked 1, 2, 3, and 4.

Following most inspections, the IAEA reports that it has satisfactorily verified declared nuclear material and facility use. The collective results of all inspection statements are summarized in the annual Safeguards Implementation Report (SIR). Because reaction to the SIR is not institutionalized and does not generally occur immediately, it is sometimes difficult to distinguish between paths 1 and 4. However, over a period of a year it should be possible to judge which categories of inspections and verification statements have met the overall expectations of the international community (path 1) and which have not (path 4).

Following some inspections, the IAEA reports that it has been unable to fully verify declared material or facility use. When this happens, reaction on the part of the national authority in cooperating with the IAEA to take corrective action is expected to be prompt (path 2). In the unlikely event that the state refuses to cooperate with the IAEA to resolve problems in achieving verification, the IAEA may withhold technical assistance, suspend the privileges of IAEA membership, and inform the Security Council and General Assembly of the United Nations (path 3).

D. Definition of Flows

N_1, N_2, N_3, and N_4 are defined as the number of transactions per year that flow through paths 1, 2, 3, and 4 in Fig. 1. N_T, defined as $N_1 + N_2 + N_3 + N_4$, is equal to the total number of inspection statements per year. $N_0 + N_T$ is defined as the number of inspection statements per year necessary to meet IAEA safeguards objectives for all material and facilities under IAEA safeguards. Therefore, N_0 is the number of inspections not performed that should occur in order to meet IAEA safeguards objectives. This new definition of N_0 is more precise than the definition used previously.[1]

II. MODEL FOR IAEA SAFEGUARDS EFFECTIVENESS

A. Effectiveness Ratio for the Case of no Diversion, E'_r

All of the flows shown in Fig. 1 can be separated into two components by defining $N_n = N'_n + N^*_n$, where n = 0, 1, 2, 3, 4, or T. N'_n and N^*_n represent components of N_n for which there has (N^*_n) and has not (N'_n) been diversion or facility misuse. For example: N'_T is the number of inspection statements per year regarding facilities where there is no diversion or facility misuse; N^*_T is the number of inspection statements per year regarding facilities where there is diversion or facility misuse.

For all facilities where there is no diversion or facility misuse, a measure of the effectiveness in meeting IAEA safeguards objectives is given by the ratio

$$E'_r = \frac{N'_1 + N'_2}{N'_0 + N'_T} = \frac{N'_T}{N'_0 + N'_T} \cdot \frac{N'_1 + N'_2}{N'_T} = KC,$$

where

$$K = \frac{N'_T}{N'_0 + N'_T} \text{ and } C = \frac{N'_1 + N'_2}{N'_T}.$$

Because diversion and facility misuse are relatively improbable for all paths in Fig. 1 except path 3, $N'_n \simeq N_n$ for n = 0, 1, 2, 4, and T. Hence, for all practical purposes,

$$K = \frac{N_T}{N_0 + N_T} \quad \text{and} \quad C = \frac{N_1 + N_2}{N_T} .$$

Recalling the definitions of N_1, N_2, N_T, and $N_0 + N_T$,

$$K = \frac{\text{(number of IAEA inspection statements issued per year)}}{\left(\begin{array}{c}\text{number of IAEA inspection statements per}\\ \text{year necessary to meet IAEA/SG objectives}\end{array}\right)}$$

and

$$C = \frac{\left(\begin{array}{c}\text{number of IAEA inspection statements issued per}\\ \text{year that appear to be accepted at face value}\end{array}\right)}{\text{(number of IAEA inspection statements issued per year)}}$$

Consequently,

K = average inspection coverage, and

C = perceived credibility† of inspection statements.

B. Effectiveness Ratio for the Case of Diversion, E^*_r

For all facilities where there is diversion or facility misuse, a measure of the effectiveness in meeting IAEA safeguards objectives is given by the ratio

$$E^*_r = \frac{N^*_2 + N^*_3}{N^*_0 + N^*_T} = \frac{N^*_T}{N^*_0 + N^*_T} \cdot \frac{N^*_2 + N^*_3}{N^*_T} = Q\,D ,$$

where

$$Q = \frac{N^*_T}{N^*_0 + N^*_T} \quad \text{and} \quad D = \frac{N^*_2 + N^*_3}{N^*_T} .$$

Recalling the definitions of N^*_2, N^*_3, N^*_T, and $N^*_0 + N^*_T$,

$$Q = \frac{\left(\begin{array}{c}\text{number of IAEA inspection statements}\\ \text{issued per year regarding facilities where}\\ \text{there is diversion or facility misuse}\end{array}\right)}{\left(\begin{array}{c}\text{number of IAEA inspection statements per year}\\ \text{necessary to meet IAEA/SG objectives regarding}\\ \text{facilities where there is diversion or facility misuse}\end{array}\right)}$$

and

$$D = \frac{\left(\begin{array}{c}\text{number of IAEA inspection statements issued per year}\\ \text{regarding facilities where there is diversion or facility}\\ \text{misuse in which the IAEA states that it was unable to}\\ \text{verify declared material or facility use}\end{array}\right)}{\left(\begin{array}{c}\text{number of IAEA inspection statements}\\ \text{issued per year regarding facilities where}\\ \text{there is diversion or facility misuse}\end{array}\right)} .$$

Consequently,

Q = critical inspection coverage† at facilities where there is diversion or facility misuse, and

D = detection probability at facilities where there is diversion or facility misuse.

C. Total Effectiveness, E_T

Total effectiveness in meeting IAEA safeguards objectives, E_T, is clearly a function of E'_r and E^*_r, but there is no obvious way to derive an expression for E_T from basic principles. Under the circumstances, a suitable approach may be to impose a set of conditions on $E_T = f(E'_r, E^*_r)$ and then to determine a functional form for E_T by induction. It appears reasonable to demand that an expression for E_T in terms of E'_r and E^*_r should satisfy the following conditions:

(1) If $E'_r = E^*_r$, then $E_T = E'_r = E^*_r$.

(2) If $E'_r \neq E^*_r$, then E_T lies between E'_r and E^*_r.

(3) E_T approaches 1 only if both E'_r and E^*_r approach 1.

(4) E_T approaches zero if either E'_r or E^*_r approach zero.

(5) E'_r and E^*_r should have equal weight in determining E_T.

Perhaps the most controversial condition imposed on $E_T = f(E'_r, E^*_r)$ is condition 5. E'_r relates to inspection statements that occur frequently but are of little consequence when judged individually; E^*_r relates to inspection statements that occur very infrequently but are of enormous consequence. Because both E'_r and E^*_r are absolutely critical to the success of IAEA safeguards, it is logical that they should have equal weight in determining E_T.

A linear average, $E_T = (E'_r + E^*_r)/2$, satisfies all of the stated conditions except condition 4. A logarithmic average, $\ell n\, E_T = (\ell n\, E'_r + \ell n\, E^*_r)/2$, satisfies all five conditions. The logarithmic average can be rewritten:

$$E_T = \sqrt{E'_r E^*_r} = \sqrt{KCQD} .$$

Derivation of this equation is based on a number of assumptions, some of which are open to further consideration. Therefore, the equation can be viewed as a proposed model for IAEA safeguards effectiveness that should be tested through practical application.

III. SAFEGUARDS PARAMETERS K, C, Q, AND D

The model developed in Sec. II indicates that four safeguards parameters (K, C, Q, and D) have equal weight in determining IAEA safeguards effectiveness. Two of the parameters describe inspection *coverage* and two describe the political and technical *quality* of IAEA inspections and the resulting verification statements. Table I lists technical and nontechnical factors that influence K, C, Q, and D. The following subsections analyze each of the parameters from a quantitative point of view.

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†Frank Houck has indicated a preference for use of the term "acceptability" rather than "perceived credibility" to describe C.

†The term "critical coverage" was suggested by Eugene Weinstock.

TABLE I. Safeguards Parameters K, C, Q, and D

Parameter	Comments	Technical Factors	Nontechnical Factors
K, average inspection coverage	• Well documented • Closely related to % PLARIE • Need to ensure that 100% PLARIE generates the number of inspection statements necessary to meet IAEA safeguards objectives	• Number and type of facilities under IAEA safeguards • Number of trained inspectors • Efficiency of IAEA safeguards approach • Quality and compatibility of SSACs	• IAEA safeguards budget • IAEA/state cooperation • Local laws and restrictions • Number of inspections permitted under safeguards agreements and facility attachments
C, perceived credibility of inspection statements	• Not well documented • Need for data gathering and analysis • C appears to be high throughout much of the world, but low in some countries	• Perceived success of IAEA safeguards • Perceived validity of IAEA safeguards approach • Perceived technical quality of IAEA safeguards inspections (related to D)	• Growing expectations for IAEA safeguards • Limits on IAEA authority • States using IAEA to air political grievances • Political activities that cast doubt on IAEA safeguards effectiveness • Perception of political bias in IAEA safeguards approach or implementation
Q,[a] critical inspection coverage	• Limited data available • No satisfactory approach found for making Q significantly larger than K • Q approximately equal to K at present • Essential to timely detection	• Information from inside and outside the safeguards regime • Response by IAEA management	• Policy of IAEA to provide equal treatment to all member states • Possible state action to reduce or delay inspection coverage
D, detection probability	• Limited data available • IAEA goal is 90 to 95% • Theory established for MC&A • Engineering approach being developed for C&S • Need for better estimates for both MC&A and C&S, including theory and implementation	• Type and size of facility • Diversion concealment methods • IAEA safeguards approach • Man-days per inspection • Thoroughness of audits • Reliability of equipment • Accuracy of measurement methods • Sensitivity of data analysis	• Constraints imposed by safeguards agreements and facility attachments on safeguards approach, man-days per inspection, use of C&S, etc. • Fatigue of inspectors

[a] Technical and nontechnical factors affecting K also affect Q. The factors listed for Q are those additional factors that may influence differences between Q and K.

A. Average Inspection Coverage, K

For a number of years the IAEA has maintained records that permit estimation of average inspection coverage. Maximum routine inspection effort (MRIE), defined in INFCIRC/153, sets upper limits for man-days of inspection per year as a function of facility type and throughput. In negotiating facility attachments, the IAEA and state authorities set upper limits on the number, duration, and man-days of inspections per year, taking into account details of the facility and state safeguards system. The inspection effort determined in this way is called actual routine inspection effort (ARIE) and is typically somewhat less than MRIE. ARIE is based on full-scale operation of the facility. When the IAEA operations divisions bring into consideration the current operating status of each facility, they usually arrive at a lower maximum inspection effort called PLARIE, or planned actual routine inspection effort. The scope of IAEA inspection coverage is reported annually as a percentage of PLARIE (% PLARIE). The IAEA increased % PLARIE to a yearly average of roughly 55% in 1983, compared with 45% in 1982, and has considered establishing the goal of achieving 100% PLARIE by 1988.

Average inspection coverage K can be closely approximated by % PLARIE provided that 100% PLARIE would generate the number and type of inspection statements necessary to meet IAEA safeguards objectives. For most facilities, this condition appears to be met, so % PLARIE should reflect average coverage with reasonable accuracy. However, for a few facilities, there is concern that a level of PLARIE has been negotiated that would not generate sufficient inspection statements to meet IAEA safeguards objectives. This could result in a value of average coverage K slightly lower than % PLARIE.

Studies are under way at the IAEA to develop guidelines for establishing PLARIE and for determining % PLARIE. These guidelines are needed so that the IAEA can more consistently plan and implement inspection coverage at various types of facilities in all member states. The application of such guidelines could change the estimate of % PLARIE for individual facilities but is not expected to change the overall value significantly.

B. Perceived Credibility of Inspection Statements, C

In principle, data can be gathered and analyzed that would allow empirical determination of the perceived credibility of inspection statements. In practice, the IAEA has the data necessary to determine N_T and N_2 but lacks the data for accurately differentiating between N_1 and N_4. The problem of distinguishing between N_1 and N_4 is exacerbated by the fact that path 4 transactions take a variety of forms and occur over an extended period.

An alternate approach for estimating C would be to develop criteria on which the credibility of inspection statements could be fairly judged. However, because political factors have a strong influence on the perception of credibility (see Table I), the task of determining suitable criteria is by no means easy.

One way to provide a rough estimate of perceived credibility is to consider the response of the world community to IAEA verification activities at different types of facilities. It is clear, for example, that IAEA verification statements regarding light-water reactor facilities, materials testing reactor facilities using low-enriched uranium (LEU) fuel, item storage facilities, and LEU fuel fabrication plants are not seriously questioned today. Similarly, it appears that IAEA safeguards as implemented at most reprocessing and enrichment facilities are questioned. Falling somewhere between these two extremes is the perceived credibility of IAEA inspection statements for most other types of facilities. Estimating the number of inspection statements per year for the different types of facilities provides a value of C between 0.6 and 0.9. A detailed study of perceived credibility should be able to refine this estimate considerably. Such a study should investigate the variation of perceived credibility from one country to another.

C. Critical Inspection Coverage, Q

Critical coverage and detection probability, unlike the other safeguards parameters, cannot be estimated "after the fact" from available data. The IAEA has no way of determining N_T^* and $N_0^* + N_T^*$ from observation; consequently, critical coverage must be indirectly inferred rather than directly observed.

To a first approximation, critical coverage at facilities where there is diversion or facility misuse is equal to average coverage. Because diversion is highly improbable, it would seem to be cost effective, in terms of maximizing E_T for a given safeguards budget, to make critical coverage greater than average coverage. Such an approach could be formalized if there were general agreement that diversion or facility misuse is more likely under certain circumstances. The IAEA appears to be following this philosophy in choosing to make % PLARIE higher at facilities that utilize HEU or separated plutonium. Other formal approaches have been discussed that would consider the total fuel-cycle capability within a country, paying particular attention to any facilities that are not under IAEA safeguards. However, approaches based on total fuel-cycle capability would be difficult for the IAEA to implement without appearing to discriminate against some member states.

Less formal approaches for increasing critical coverage leave matters largely up to IAEA management. For example, the IAEA might choose to increase coverage at a facility following a transaction along path 3 in Fig. 1. Similarly, coverage might be increased at certain facilities because of information received from outside the safeguards regime. Although the IAEA has some flexibility in applying coverage on a discretionary basis, this flexibility must be used sparingly. States that continually receive higher than average inspection coverage may complain to the IAEA and demand equal treatment.

In summary, the IAEA appears to be using both formal and informal approaches to increase critical coverage Q. In opposition to this, a country planning to divert material may take steps to limit or reduce Q. For example, a country can limit inspection coverage by adhering to outmoded safeguards agreements and facility attachments. Similarly, a country can use legal, administrative, or technical means to delay inspections beyond a critical time. Without further study, it is impossible to conclude whether critical coverage is larger or smaller than average coverage, but it is not unreasonable to assume that they are roughly equal.

D. Detection Probability, D

As discussed in Sec. III.C, detection probability cannot be accurately estimated from available data because the IAEA has no way of determining N_T^* from observation. As a result, estimates of detection probability are based on theory, which makes use of experimentally determined constants such as measurement uncertainties.

Detection probability is largely controlled by technical factors and for this reason has received considerable attention from the technical community. In implementing statistical sampling as part of inventory verification, the IAEA aims for 90 to 95% probability of detecting diversion of a significant quantity of nuclear material.[7] The theory of materials control and accountability (MC&A) is well developed, but the theory does not consider many of the typical problems of implementation. Engineering approaches are being developed to estimate the effectiveness of containment and surveillance (C&S) measures for detecting diversion. However, estimates of detection probability based on either MC&A or C&S suffer because the estimates depend in large measure on assumptions regarding diversion concealment methods. The result is that detection probability is one of the more difficult to estimate of the safeguards parameters. It is generally agreed that because of technical problems in implementing MC&A and C&S and because of the nontechnical factors listed in Table I, detection probability is significantly less than 0.9. Typical estimates for D and other safeguards parameters are given in Sec. IV.

E. Coupling Between Safeguards Parameters

Some of the safeguards parameters are directly coupled—meaning that if one parameter changes, it may influence another parameter to change in the same direction. For example, a significant increase in average coverage is likely to increase critical coverage and may also increase perceived credibility. Similarly, an increase in detection probability would tend to increase perceived credibility.

Other safeguards parameters are inversely coupled—meaning that with existing constraints, an increase in one parameter may force the reduction of another parameter. For example, an increase in average coverage, with no change in manpower or technology, might force a reduction in detection probability. Likewise, the use of limited resources to increase detection probability could result in a decrease in average coverage.

Based on the factors listed in Table I, only two of the parameters appear to be closely coupled; critical coverage is largely determined by average coverage. However, as the IAEA continues to increase average coverage (along with perceived credibility and detection probability), critical coverage Q is expected to fall behind and gradually become decoupled from average coverage K. This possible decoupling of Q from K is discussed further in Sec. IV.

IV. RESULTS AND CONCLUSIONS

A. Survey Results for 1983 and Optimistic Projections for 1988

Because of the difficulty in accurately estimating quantitative values of C and D (discussed in Sec. III), a survey of technical experts was used to determine the spectrum of opinion regarding quantitative values of the four safeguards parameters. Eighteen people from Los Alamos who are familiar with IAEA safeguards were given rough drafts of Secs. I to III and asked to provide independent estimates of K, C, Q, and D for calendar year 1983. Table II lists, in random order, responses of the individuals who returned survey questionnaires.† From each complete response, a value of safeguards effectiveness was calculated using the equation $E_T = \sqrt{KCQD}$. Table II also gives the mean value $\bar{X}$, standard deviation S_X, standard error $S_{\bar{X}}$, and estimated bias $B_{\bar{X}}$ for survey estimates of K, C, Q, and D, as well as for the values of E_T calculated from individual responses. The footnote in Table II gives the value of E_T computed from mean values of K, C, Q, and D.

Error in the mean value $\bar{X}$ is due to bias in the survey responses, $B_{\bar{X}}$, and random error in locating the mean value, $S_{\bar{X}}$.

$$S_{\bar{X}} = \frac{S_X}{\sqrt{n}} = \frac{\left(\sum_{i=1}^{n} (X_i - \bar{X})^2/n - 1\right)^{1/2}}{\sqrt{n}} ,$$

where n is the number of survey responses determining $\bar{X}$. Because $S_{\bar{X}}$ is significantly smaller than $B_{\bar{X}}$, errors in the mean survey values of K, C, Q, D, and E_T (compared with their correct values) can be attributed almost entirely to bias. Bias in the present survey is believed to have resulted mainly from unintentional bias of the information in Sec. III (distributed

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†Participants in the 1983 survey were R. Augustson, G. Bosler, E. Dowdy, A. Hakkila, M. Krick, J. Markin, N. Nicholson, D. Reilly, P. Russo, J. Shipley, D. Smith, J. Stewart, R. Strittmatter, and J. Tape.

TABLE II. Summary of Responses to 1983 Survey Questionnaire

Response Number	K, Average Coverage	C, Perceived Credibility	Q, Critical Coverage	D, Detection Probability	E_T, Total Effectiveness
1	0.5	0.6	0.55	0.5	0.287
2	0.45	0.65	0.5	0.75	0.331
3	—	0.8	—	0.8	—
4	0.5	0.85	0.6	0.8	0.452
5	0.5	0.8	0.5	0.6	0.346
6	0.5	0.95	0.6	0.3	0.292
7	0.3	0.8	0.1	0.7	0.130
8	0.6	0.95	0.3	0.5	0.292
9	0.55	0.95	0.4	0.7	0.382
10	0.5	0.5	0.53	0.6	0.282
11	0.5	—	0.5	0.3	—
12	0.5	0.25	0.5	0.6	0.194
13	0.5	0.9	0.65	0.5	0.382
14	0.5	0.99	0.5	0.0	0.0
Mean[a] Value, $\bar{X}$	0.492	0.768	0.479	0.546	0.281
Standard Deviation, S_X	0.067	0.216	0.144	0.224	0.123
Standard Error, $S_{\bar{X}}$	0.019	0.060	0.040	0.060	0.036
Estimated Bias, $B_{\bar{X}}$	±0.05	±0.15	±0.1	±0.2	±0.1

[a] E_T, computed from mean values of K, C, Q, and D, is given by $E_T = 0.314$.

with the survey questionnaire) and bias in the opinions held by survey participants prior to the survey. Less likely sources include possible biases in the proposed model, in design of the questionnaire, and in data analysis and interpretation. The author's estimates of $B_{\bar{X}}$ given in Table II are based primarily on the information in Sec. III.

Several interesting points can be made from a review of the data in Table II. Most of the survey participants indicated that in 1983 average coverage was less than the estimated value of % PLARIE (0.55). Perceived credibility was assigned the highest value of any of the safeguards parameters by 10 of the 14 participants. The participants were split (6, 3, 4) on whether critical coverage Q should be larger than, smaller than, or equal to average coverage K, despite suggestions made in the draft of Sec. III that Q might be slightly larger than K. The two methods for calculating the mean value of E_T yielded results that are in good agreement, $E_T = 0.281$ and $E_T = 0.314$.

In Fig. 2, the survey data are plotted as histograms for K, C, Q, D, and E_T. A histogram interval of 0.1 was used, and survey responses that contain a 5 in the second decimal place were rounded down to the nearest tenth. All of the histograms indicate asymmetric frequency distributions with a longer tail on the low side of the peak. Figure 2 graphically illustrates that among the survey participants there is relatively good agreement on the value of average coverage K, fair agreement on critical coverage Q, and poor agreement on both perceived credibility C and detection probability D. This qualitative interpretation of Fig. 2 is consistent with the values of standard deviation in Table II. It can be inferred from Fig. 2 and Table II that there is also fair agreement among survey participants regarding the value of total effectiveness E_T.

Table III compares the survey results for 1983 with the author's optimistic projections of the safeguards parameters for 1988 and gives per cent increases needed to achieve the optimistic projections. By 1988 the IAEA should be able to attain an average inspection coverage K of approximately 0.85, based on estimated levels of inspector staffing and operational requirements. Further increases in average coverage will be less effective in raising the value of E_T because of reduced coupling between average coverage and critical coverage. Following recent trends, perceived credibility C could reach a value of 0.9 or even 0.95 by 1988, provided that IAEA safeguards suffer no major political setbacks. Critical coverage Q may prove difficult for the IAEA to increase far beyond its present value because states planning to divert nuclear material could avoid negotiations intended to increase inspection coverage at certain facilities. Perhaps it will be possible to increase Q to a value of 0.7 by defining PLARIE more consistently at all facilities and by placing greater overall emphasis on Q. Detection probability D is expected to undergo a substantial increase because of technical advances in safeguards implementation and should reach the IAEA goal of 0.9. The projected values of K, C, Q, and D lead to an optimistic prediction of $E_T = 0.7$ by 1988.

B. General Conclusions

One of the more interesting results of this study is that $E_T = f(E'_r, E^*_r)$; that is, total effectiveness E_T is a function of E'_r (the effectiveness in achieving safeguards objectives at facilities where there is no diversion or facility misuse) and E^*_r (the effectiveness in achieving safeguards objectives at facilities

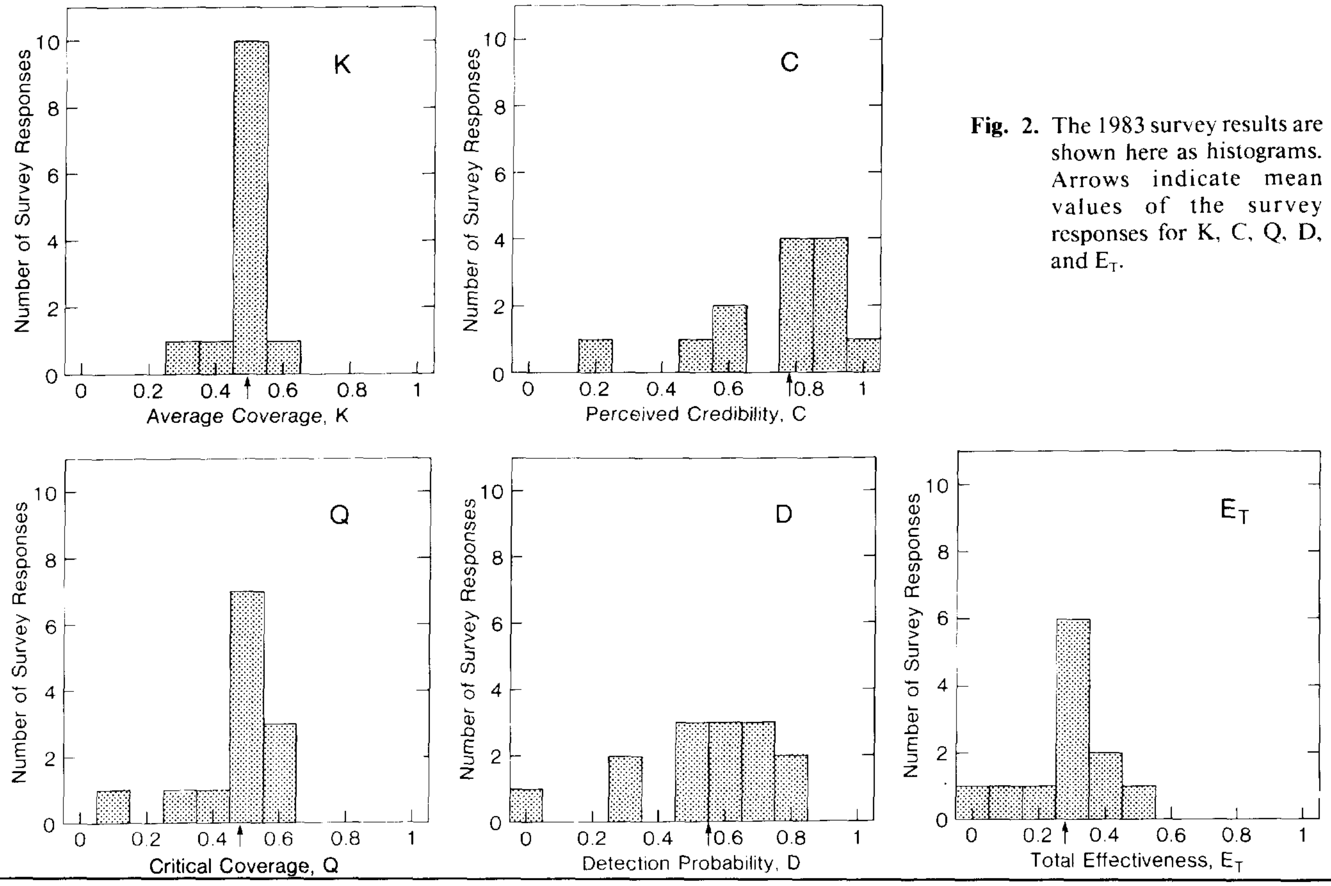

Fig. 2. The 1983 survey results are shown here as histograms. Arrows indicate mean values of the survey responses for K, C, Q, D, and E_T.

TABLE III. Estimated Values of Safeguards Parameters

Safeguards Parameter	Survey Result for 1983	Optimistic Projection for 1988	Per Cent Increase
K, average coverage	0.492	0.85	73
C, perceived credibility	0.768	0.95	24
Q, critical coverage	0.479	0.7	46
D, detection probability	0.546	0.9	65
E_T, total effectiveness	0.314[a]	0.7	127

[a]This value of E_T is quoted in Table III because it can be computed from values of K, C, Q, and D in Table III.

where there is diversion or facility misuse). This equation and the related analysis in Sec. II illustrate the dual nature of IAEA safeguards. The quotations in Sec. I from the IAEA Statute, INFCIRC/66, and INF/3 emphasize the importance of assurance and deterrence, which are closely related to E'_r. INFCIRC/153 emphasizes the importance of timely detection and deterrence by the risk of early detection, which are closely related to E^*_r. But, as the IAEA has recognized, safeguards must emphasize assurance, deterrence, and detection simultaneously in order to be effective. In performing an inspection, the IAEA must not assume either that there has or has not been a diversion, even though the odds greatly favor the latter. Consequently, optimum safeguards design maximizes the product of E'_r and E^*_r, which (in turn) maximizes the product of K, C, Q, and D. Safeguards approaches that would maximize either E'_r or E^*_r while disregarding the remaining factor are certain to have serious deficiencies.

The model shows that effective IAEA safeguards can be attained by implementing a high degree of inspection coverage at all facilities, especially those where there is diversion or facility misuse (K and Q), and by achieving high political and technical quality of the inspections and resulting verification statements (C and D). This conclusion comes as no surprise. Two of the safeguards parameters, average coverage K and detection probability D, have been associated with the concept of IAEA safeguards effectiveness for some time. Critical coverage Q has also been considered previously, but more as a way of distributing overall coverage than as a separate parameter. Both critical coverage Q and perceived credibility C represent newer and more controversial measures of effectiveness. For the purpose of analysis, there are advantages in separating inspection coverage into two types (K and Q) and in having two different measures of the quality of inspection statements (C and D). Within the constraints of future manpower and budgets, trade-offs between the parameters can be used to optimize E_T; however, none of the parameters should be permitted to become significantly smaller than they are today.

Assuming that current trends continue, IAEA safeguards effectiveness is expected to increase dramatically during the next 5 years, as Table III optimistically indicates. Projected increases in average inspection coverage and detection probability are particularly significant. Meeting these projections will not be easy and will require increased financial and technical support by IAEA member states, dedication and innovation on the part of IAEA management and staff, and the cooperation of all parties involved. If the projections are accurate, the one parameter that should receive greater attention is critical coverage at facilities where there is diversion or facility misuse.

The survey of technical experts performed as part of this study illustrates a wide range of opinion regarding values of the parameters that determine IAEA safeguards effectiveness. By revealing privately held opinions, survey techniques can help to identify areas of agreement and disagreement, thereby aiding communication. However, surveys are not a substitute for objective analysis. Even if survey responses are in agreement, they may still be biased.

Developing a methodology for describing IAEA safeguards effectiveness in quantitative terms is a difficult task that involves objectively analyzing and quantifying the key parameters that determine E_T. Work at the IAEA during the past few years has greatly improved the quantitative estimate and general understanding of average inspection coverage. With comparable effort on other parameters, it appears that they also could be quantified, although somewhat less accurately. Given the present level of understanding, it is possible to estimate E_T in quantitative terms, but the error associated with the estimate is fairly large. The main advantage of using a quantitative model is not that it provides an estimate for E_T, but that it helps in systematically analyzing the parameters that determine E_T. It is hoped that this attempt to develop a formalism for IAEA safeguards effectiveness will aid communication and analysis and will bring related problems and their solutions into sharper focus.

Simple models, such as the flow diagram shown in Fig. 1 and the equation for E_T, can help to explain fundamental points that are otherwise difficult to grasp. But there is a danger in taking the models too literally. A simple model obviously cannot describe every possible situation; and as models become more complex, they generally become more difficult to apply. At this stage in the development of international safeguards, it seems appropriate to use models to analyze some of the basic operational features and to trust that people will recognize the models' inherent limitations.

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HUMAN ERRORS IN NUCLEAR MATERIAL ACCOUNTING AND CONTROL DATA*

R. J. BROUNS
B. W. SMITH
R. F. EGGERS**
Pacific Northwest Laboratory***
Richland, Washington

ABSTRACT

Human errors in recording and processing nuclear material accounting and control data can cause false indications of losses or gains of nuclear material. Human errors also cause uncertainty in the statistical prediction of false alarm frequency and power of loss detection. This report reviews the literature on human error rates in handling numerical data, summarizes the frequency and types of errors observed in using process monitoring data for nuclear material accounting, and suggests some methods for reducing human error rates.

SUMMARY

Human errors in recording and processing nuclear material accountability data can contribute to false alarm rates in nuclear material loss detection. The human error rate (HER) is expressed as the ratio of the number of errors to the number of opportunities for error, where the number of opportunities is equal to the number of values recorded or transcribed. Review of the literature on HERs for transcribing or recording three or more numerical digits shows that a range of 0.05% to 0.5% can be expected even in careful work. Transcription errors can be classified into five categories: 1) substitution, 2) illegibility, 3) omission, 4) addition, and 5) interchange. Substitution, omission and addition of characters are generally the most abundant errors. The frequency of errors has been shown to be much more variable than the distribution by type of error. The rates are affected by the number of digits, the mixing of alphabetic and numerical values, the length of strings and the quality of copy. Human factors also contribute to the error rate; these factors include the man-machine interface and the limitations of the human as an information processor.

In two recent nuclear material accounting studies, Smith and Fager (1982) observed that an appreciable fraction of the loss alarms was caused by human errors in collecting and processing the data. The frequency of human error when using process monitoring data for nuclear material loss detection was approximately 1%. In addition to those discussed in the general literature on HERs for recording data, two additional types of transcription errors were observed to contribute to the error rate; namely, 1) failure to transcribe data, and 2) entry space errors where the wrong data were recorded or the right data were recorded in the wrong space. The distributions of the magnitude of the errors were tested for the two cases with a W-test for normality and the results indicate that the error data cannot be treated as normally distributed.

Three general methods for reducing HERs are suggested:

- improve the design of the data collection and processing system
- perform overchecks and verifications
- perform audits to identify system weaknesses.

INTRODUCTION

When nuclear material accounting data are used to detect discrepancies that may indicate a loss of material, the alarm threshold for the loss estimator is usually based on the predicted standard deviation of the estimator. The current practice is to test the estimator, i.e., the inventory difference (ID) of the material

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** Rockwell Hanford Operations, Richland, Washington.
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balance, against the limit of error of the inventory difference (LEID) predicted by a propagation of the measurement error variances. It has been observed that the predicted standard deviation of the estimator (ID) is appreciably lower than the standard deviation indicated by historical ID data (Messinger, Lumb and Tingey 1981). This apparent underestimation of the standard deviation of ID by propagating variances is usually assumed to be caused by the effects of the nonmeasurement variability in the material control and accounting process, such as varying process holdups, incomplete accounting for all of the material in the physical inventory, and human errors in performing measurements and recording and transcribing data. This report discusses some information about the frequency and magnitude of the human errors in handling numerical data and suggests some ways to minimize these errors.

Human error will probably have added importance in material accounting systems designed for prompt loss detection, such as discussed in NRC's proposed Reform Amendments (Federal Register 1984). In these systems, errors in recording the process and material monitoring data will be more likely to cause alarms than would recording errors in current accountability systems that are based on two-month shutdown physical inventories. This increase in the alarm frequency is expected to occur because:

- process control data would not usually be checked or reviewed as closely at the time it is recorded as is current accounting data
- the loss monitoring tests would involve fewer measurement points and data so that averaging effects, i.e., cancellation of positive and negative errors, will be less likely to occur
- process monitoring data are less easily verified against backup information such as source data records or remeasurement of material.

Since dozens of material control tests would be made each week to achieve the goals of the Reform Amendments, an increase in the frequency of false alarms to be resolved can readily become burdensome.

There is a scarcity of objective data on error frequencies, particularly in the case of reading and recording numerical data. Some error frequency data are available in the literature but we have not found any magnitude distribution information. The distribution of the magnitude of errors is particularly important; such errors are superimposed on a distribution of measurement errors and may affect the probability distribution of the resulting loss estimates, thus affecting the predictability of the false alarm frequency and the power of loss detection.

PREVIOUS STUDIES

In developing a prediction method for transcription error rates, Hawley, Melby and McArthur (1967) analyzed sets of data collected in controlled experiments on hand transcriptions of source data for electronic data processing. They found that the factors having the greatest influence on error rates were code length, code content (whether pure numeric, nonadjacent alpha or alphanumeric) transcription method (regular or cross-reference) and repetition or code arrangement (iterative or noniterative). Error rates increased with code length, use of mixed instead of uniform code lengths, and use of alphanumeric codes instead of pure numeric codes. In a study of errors in assigning and recording work unit codes Martin (1971) also observed that error rates were lower for numeric codes than for alphabetic and alphanumeric codes.

Carlson (1963) gives examples of the types of mistakes made in keying cash amounts in a bank office and James and Partridge (1976) cite types of errors made in Fortran texts. A typical breakdown of the errors by type for pure numeric, consecutive transcription of codes is given in Table 1. There is a moderate degree of similarity between these breakdowns. Substitution, omission and addition of characters are generally the most abundant errors.

The frequency of errors has been shown to be much more variable than the distribution by type of error. A common unit for expressing error frequencies is the human error rate (HER) or human error probability (HEP), namely, the ratio of the number of errors divided by the number of opportunities to make the error; e.g., if a person makes five errors in reading and recording 500 numbers from digital displays, the HER is 0.01 or 1%. Table 2 lists error rate estimates for several types of data recording operations. This table was compiled by Swain and Guttmann (1980) from published reports of both laboratory experiments and operating experience. In compiling these data, some adjustments of the reported data were made to ensure comparable circumstances and to allow reasonable tolerances for error in recorded values. For example, if values were read from an analog display (linear scale or dial), a tolerance of several units in the least significant (last)

TABLE 1. Typical Breakdown of Transcription Errors for Numerical Data

	Percentage of All Errors		
Type of Error	Hand Transcription(a)	Keying Cash Amounts(b)	Fortran Text(c)
Character			
Substitution	25	64.5	24
Illegibility	20	--	--
Omissions	29	23.0	58
Additions	10	7.1	18
Interchange	--	1.5	--
Other	3	3.9	--
Code			
Omission	7	--	--
Rejects	3	--	--
Other	3	--	--

(a) Hawley et al 1967.
(b) Carlson 1963.
(c) James and Partridge 1976.

TABLE 2. Human Error Probabilities (HEP) for Errors of Commission in Reading and Recording of Quantitative Information(a)

Reading Task	HEP (%)
Analog meter	0.3 (0.1 TO 1)
Digital readout	0.1 (0.05 to 0.5)
Chart recorder	0.6 (0.2 to 2)
Printing recorder with large number of parameters	5 (1 to 20)
Graphs	1 (0.5 to 5)
Values from indicator lamps that are used as quantitative displays	0.1 (0.05 to 0.5)
Recognize that an instrument being read is jammed, if there are no indicators to alert the user	10 (2 to 20)

Number of Digits to Be Recorded	HEP (%)
<3	Negligible
>3	0.1 (0.05 TO 0.5)

(a) Taken from Swain and Guttmann (1980).

digit was allowed because the accuracy of the analog device is usually only about 3% of the full scale. In addition, the magnitude of an error in the last digit is usually of little consequence in the end function. The values in Table 2 show that error rates are very low for numeric codes of three or fewer digits.

Other published information indicates that error rates are often greater than those indicated in Table 2. One investigator stated that data gathered from a variety of engineering, physical sciences and economics sources showed that the error rate per record averaged about 5% (Terry 1963). A study by Hull and Brown (1975) of copying errors from lists of alphanumeric combinations showed error rates from approximately 0.3% to 1.5% for simple, four-letter combinations and 2% to 10% for 24-letter combinations. The rate also depended very much on the quality of the copy, e.g., copying from manuscript was less accurate than from typescript, and on the confusibility of the letter combinations. It was also observed that errors in numbers were much less frequent than in letters and the error rate increased with the number of digits or characters to be recorded.

Martin (1971) observed overall error rates of 8% to 10% in assigning codes to work units, but for simple numeric codes of three digits the rates ranged from 1% to 5.5%. Since he had observed that transcription errors accounted for only 7% of the total errors, the error rate due to transcription only would range from 0.07% to 0.4% for the favorable case of three-digit, numeric codes.

MATERIAL ACCOUNTING DATA

Anderson et al. (1976) found in an audit of the nuclear material inventory records of one establishment an error rate of 1.28% of incorrect copying of the item identification number and 1.03% for incorrect copying or calculation of the nuclear material content. They propose that errors of omission, calculation and transcription in nuclear material accounts should not exceed 3% of the ledger entries.

Smith and Fager (1982) recently published an account of an in-plant test of alarm resolution procedures for prompt loss detection for nuclear material. The test, which was conducted at a uranium scrap recovery facility, was a study of ways to resolve anomalies in material loss indicators that were tested daily for each of six units of process operations. The loss indicators, which were based primarily on process monitoring data, were subject to process variability, measurement errors, and human errors in recording or transcribing the data. In the first of two two-month campaigns, mistakes in recording and transcribing data had a frequency of nearly one in every hundred measurements, which caused 4% of the indicators to alarm, i.e., to exceed their control limit. In the second campaign, the frequency of process, measurement and recording errors identified in the resolution of alarms was substantially reduced as the operators became more familiar with the procedures and forms being used. The frequency of mistakes in recording and transcribing the accountability data was 0.4% for data evaluated as part of resolution of alarms, and caused 2% of the loss indicators to exceed their control limit. Following completion of the two month campaign, the records were audited by comparison to source documents and measurement logs to provide a more complete tabulation of human errors.

In another test of a similar type (publication pending), Smith and others evaluated loss estimator data for nine (9) process units in a small fuel fabrication plant. A total of 125 alarms out of nearly 2700 loss estimates were evaluated and 23 occurrences of human errors were found. Of these, 12 were the principal cause of the alarm.

The number of items of data recorded or transcribed in these tests has been estimated to be 4200 for the first case, i.e., the second campaign in the first plant, and 5300 for the second case. These lead to the observation that human errors were made in 1.7% of the data entries in the first case and 0.4% in the second case. These rates are greater than those summarized in Table 2, which show a range of 0.05% to 0.5% for recording numerical data, but are in the range observed by several other investigators (Terry 1963, Hull and Brown 1975, and Anderson 1976).

A summary of the types of errors in the data of the second campaign at the first plant and all of the data from the second plant is shown in Table 3. In these data, two prominent types of errors that do not occur in the simple data or code transcription situations discussed above are recording data in the wrong place on the accountability form and failure to record a value at all. However, the most frequent error was substitution of one digit for another.

Figures 1 and 2 show the frequency distribution of the errors by error magnitude in grams of uranium and percent difference from the "correct" value,

TABLE 3. Human Errors in Reading, Recording or Transcribing Quantitative Data

Type of Error in Recorded Data	Case 1: Scrap Recovery Facility Number of Occurrences	Case 1: Scrap Recovery Facility Percentage of Errors	Case 2: Fuel Fabrication Facility Number of Occurrences	Case 2: Fuel Fabrication Facility Percentage of Errors
Substitution	27	38	12	52
Transposition	2	3	1	4
Omission	2	3	2	9
Insertion	1	1	0	0
Decimal point error	1	1	0	0
Recorded in wrong space on the form	20	28	5	22
Failed to transcribe[a]	13	18	3	13
Transcription proceure error[b]	5	7	0	0
TOTAL	71[c]		23	

(a) Not transcribed to the accountability form or into the computer.
(b) Errors such as transcribing uncorrected data or using the wrong units.
(c) Six values were in records of liquid levels in tanks (three-digit numbers), 47 values were in counting data (six-digit numbers) and five values misidentified the detector number/sample size identification code.

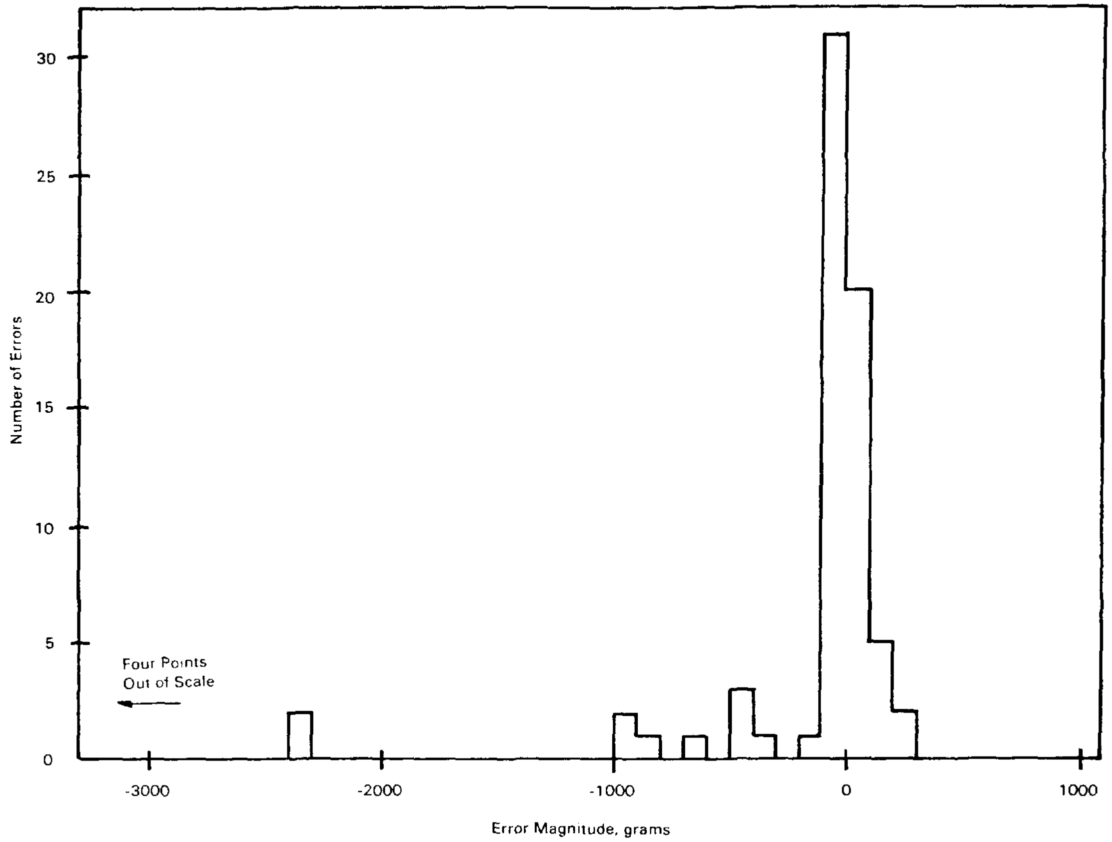

FIGURE 1. Facility 1 Frequency of Errors by Magnitude

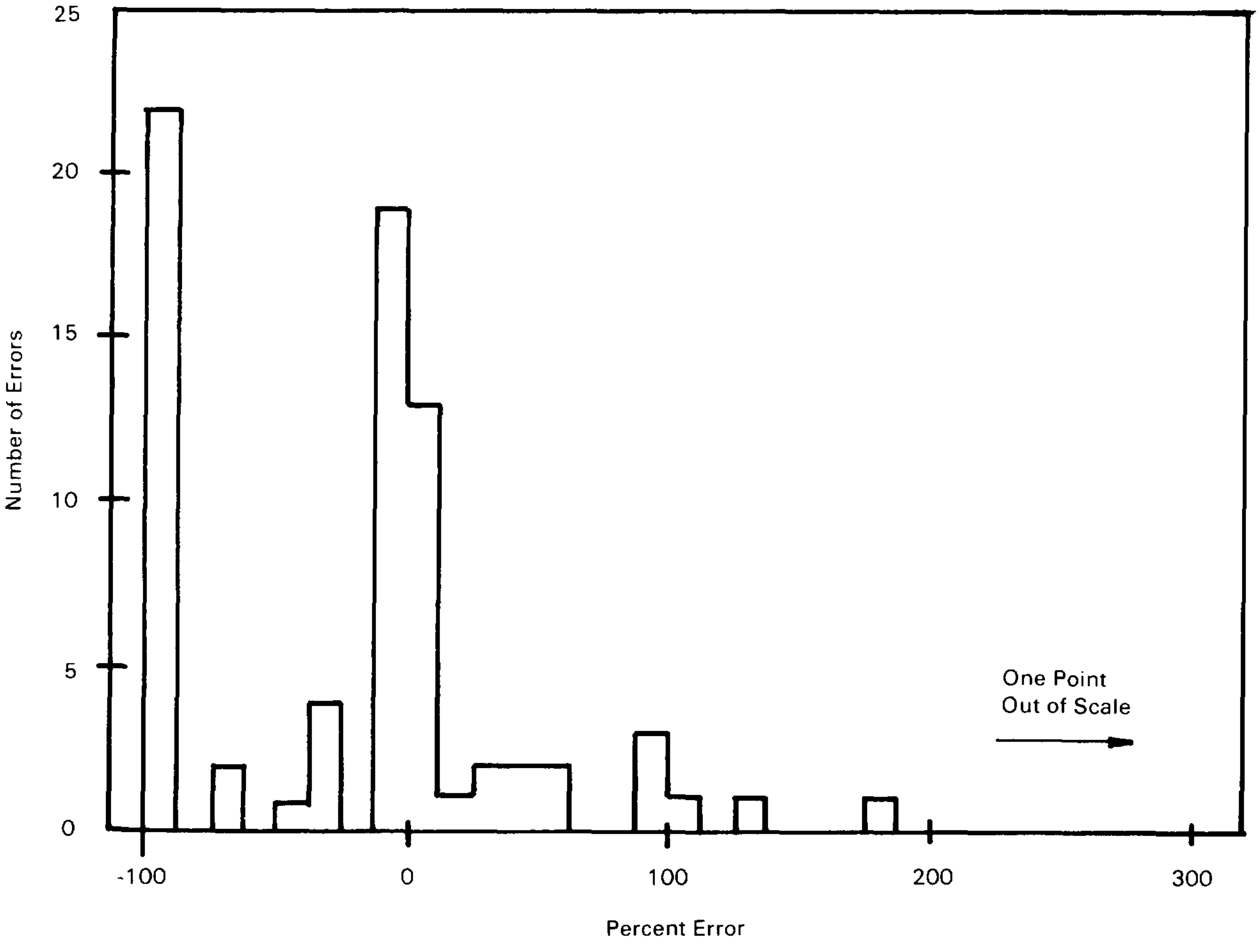

FIGURE 2. Facility 1 Frequency of Errors as Fraction of "Correct Value"

respectively, for the data from the first plant. Figures 3 and 4 show similar information from the second plant. The frequency distribution is of interest because the errors in accountability data will be superimposed on the errors due to measurement and process variability. Since the latter are usually considered to be normally distributed, a distribution of human errors that is different from normal may cause the probability distribution of the loss indicators to be non-normal. Figures 1 and 3 show that the distribution of errors has a single peak near zero, but the long tail on the negative side is clearly a departure from normality. A W-test confirmed that the data were not normally distributed.

Whether a non-normal distribution is a general characteristic of human errors in numerical data cannot be inferred from this small set of data. The degree of departure from normality indicated by these results does not appear to be sufficient to affect the probability distribution of the loss estimator. However, if the rate of false alarms caused solely by the randomness of the measurement processes were of the order of 1% or less, human errors will probably increase the false alarm rate appreciably. The distribution of their magnitudes will not be predictable from the small data base of these two studies. To obtain significantly more confidence about the distribution of recording error magnitudes would require about 100,000 data entries when the HER is about 1%.

REDUCING HUMAN ERROR RATES

An approach for reducing the impact of human error rates in material accounting data is to focus on those types of error that are most likely to cause a material loss indicator to exceed its alarm threshold. The general methodology to reduce the frequency of human error consists of: 1) a systems study to identify the types of errors which occur and their impact on the material control and accounting, 2) development of measures for controlling human error rates, and 3) implementation of the specific measures.

The primary error classes identified by Smith and Fager (1982) that had the most impact were omission of a digit, failure to transcribe data and entry space

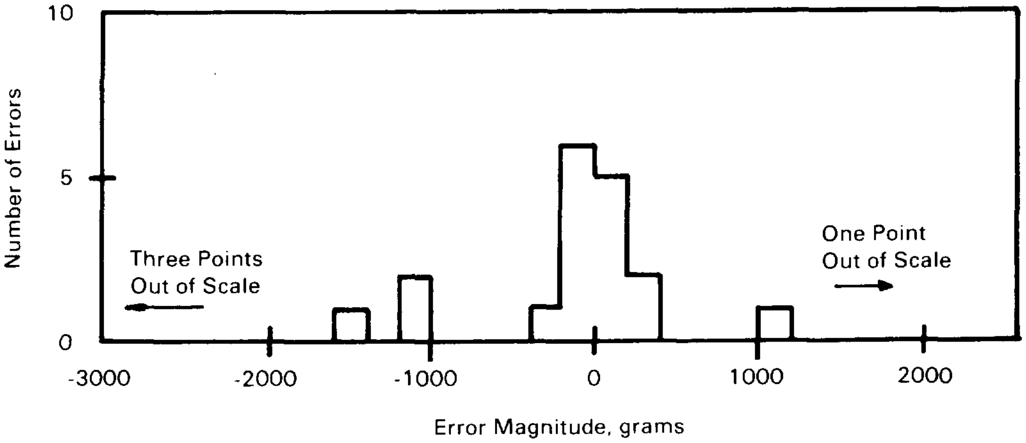

FIGURE 3. Facility 2 Frequency of Errors by Magnitude

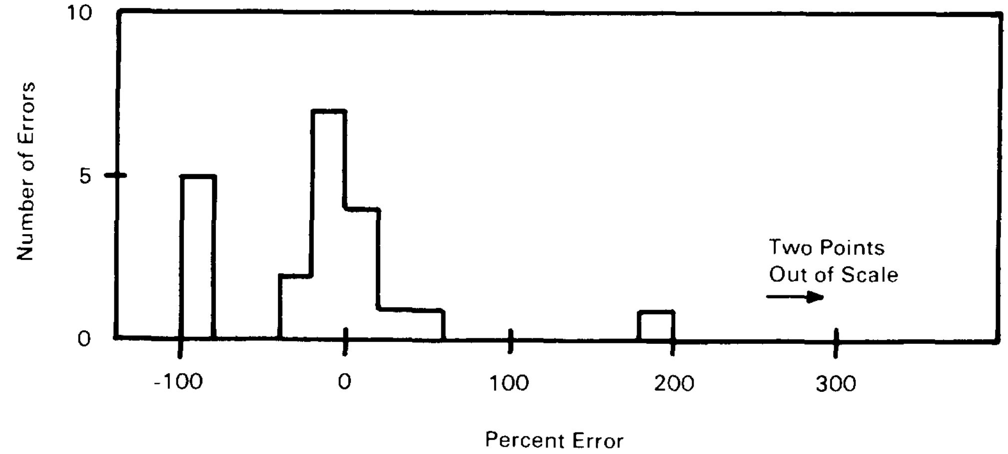

FIGURE 4. Facility 2 Frequency of Errors as Fraction of "Correct Value"

errors. Rudy et al., (1982) in a similar study identified three classes of data errors: missing data, improper or erroneous data and phasing errors. They identified phasing errors where material movement did not agree with inventory records as a major source of variability.

Three general measures for controlling the frequency of human error rates are suggested: system design, overchecks and verification, and audits.

The overall system design for collecting and processing nuclear material accounting data should be reviewed to identify those attributes of various systems that increase the probability of human error. An important consideration in developing the system is to adjust it to perform within the limitations of the personnel, i.e., identify the human limitations and capabilities and how they are affected by external factors. Some elements of the system's design for reducing human errors are integrated and cannot be added as a modification after the system has been constructed. As such, the designers should start with a systems approach that recognizes the necessity of integrating the human's interaction with the system.

When the data are manually recorded and transcribed the designer should provide for:

- unambiguous labeling for each entry space
- clearly written procedures
- preprinted forms which identify all routine transactions
- sufficient space on forms to record data and work space near the data generation location for completing the forms
- commonality of data units
- internal relationships in the data which create pairs that can be compared to ensure that all data are entered and to provide a means of cross checking and reconciling discrepancies

- use of programable calculators or computers to automate calculations.

Another approach to the systems design would be to provide sufficient automation to reduce the human link in handling data. Measurement data could be automatically recorded and processed into accountability files. Dedicated computers can cue the operator when other than measurement data is required, notify the operator of unusual characteristics in the data, perform calculations, and process data to forms for each user of the data. The computer could then perform checks of completeness of the information, authorization and internal consistency. These could include tests of whether an attempted transfer of a particular material to a proposed location is in accordance with the process model and schedule and is allowable with respect to health and safety guidelines. Checks of internal consistency include comparison to historical values, comparison of coding to material types and locations, internal consistency of measurement data (e.g., uranium to uranium-235, gross and net weights, and concentration to specific gravity), and comparison to container or vessel maximum volumes. Redundant entry of data, possibly by two people, may also be used to verify key elements of the data.

Despite good design of the data collecting system, human errors will still occur. The error rate should be monitored and reasonable efforts made to minimize it and to detect gross errors so they can be corrected. This is where overchecks, verification, and audits play an important role.

Overchecking and verification is the process of confirming data entered into the accounting system. Supervisors should verify records generated by operators to ensure that the records are complete, that all data appear reasonable, and that calculations are correct. Safeguards personnel also may review transfer records and compare them to logbooks and source documents. Verification may also include comparing data to 1) historical values to determine whether the data are within an expected range and 2) independent records generated for purposes such as quality control.

Audits would be performed after closing the records to provide independent assurance that the records are representative of the physical activities. An audit would consist of reviewing internal controls, testing records and following audit trails to ensure that the values are traceable to original measurements and observations. One purpose of an audit is to determine whether the system of controls is sufficient to ensure that human errors do not affect the decisions based on those records.

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