Fall 2002 | Winter 2003 | Spring 2003 | Summer 2003 | Volume XXXI, Number 4

JNMM Journal of Nuclear Materials Management

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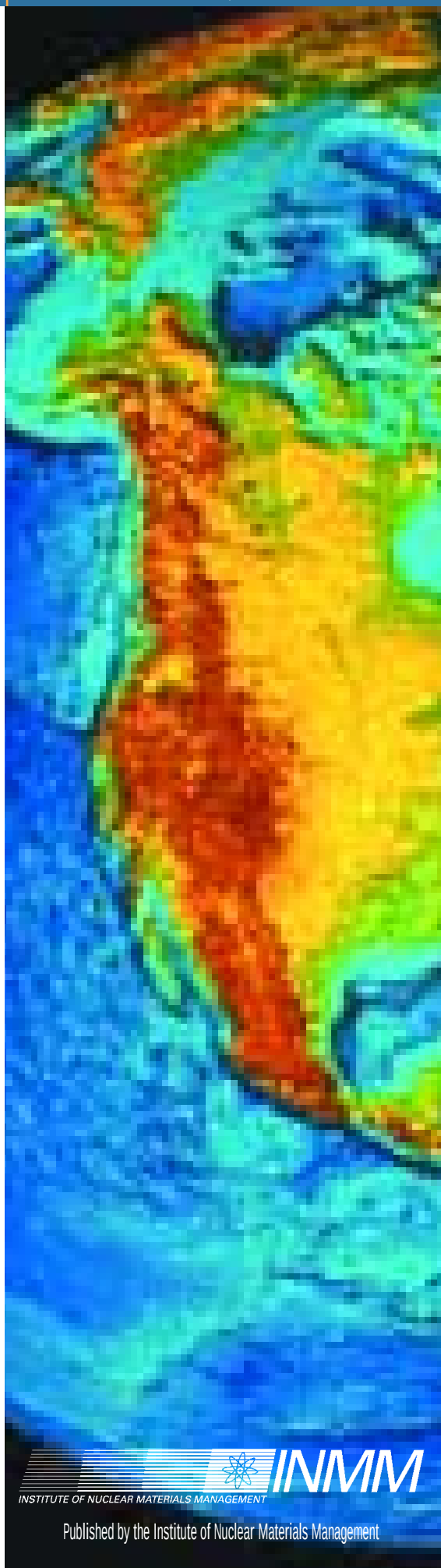

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT
Published by the Institute of Nuclear Materials Management

JNMM Journal of Nuclear Materials Management

JNMM (ISSN 0893-6188) is published four times a year by the Institute of Nuclear Materials Management Inc., a not-for-profit membership organization with the purpose of advancing and promoting efficient management of nuclear materials.

SUBSCRIPTION RATES: Annual (United States, Canada, and Mexico) $100.00; annual (other countries) $135.00 (shipped via air mail printed matter); single copy regular issues (United States and other countries) $25.00; single copy of the proceedings of the Annual Meeting (United States and other countries) $175.00. Mail subscription requests to *JNMM*, 60 Revere Drive, Suite 500, Northbrook, IL 60062 U.S.A. Make checks payable to INMM.

ADVERTISING, distribution, and delivery inquiries should be directed to *JNMM*, 60 Revere Drive, Suite 500, Northbrook, IL 60062 U.S.A., or contact Jill Hronek at 847/480-9573; fax, 847/480-9282; or E-mail, inmm@inmm.org. Allow eight weeks for a change of address to be implemented.

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Building Our Organization

By John C. Matter
INMM President

Welcome to the 44th INMM Annual Meeting and the new J.W. Marriott Desert Ridge Resort & Spa. The Executive Committee chose this venue two years age when it existed only on paper. We were very pleased–and relieved–in March when we met here for the Technical Program Committee and Executive Committee meetings and found it exceeded our expectations.

We are frequently asked how the Executive Committee picks annual meeting sites. It's a matter of priorities and tradeoffs. We stay in the United States because most of our members live there and many would be unable to get their employers' approval for foreign travel to attend a conference. For our international members we select locations easily accessible by international air carriers. We pick properties that can accommodate our needs for both guest rooms and concurrent sessions. We recognize that many attendees travel on government funds and must abide by government per diem rates. Premium facilities at government per diem generally equate with off-season rates–thus summer in southern climes. We are making renewed efforts to move future meetings further north–after returning to Orlando in 2004 and Phoenix in 2005. We hope this will be abetted by a buyer's market due to the current economic downturn and by the more recent two-tier government per diem rate structure that recognizes seasonal rates.

Elections

Every two years INMM members elect a president, vice president, secretary, treasurer, and two members-at-large for their officers and Executive Committee. The election results are presented to the members at the Annual Business Meeting and published in the Annual Report to the Membership. We are frequently asked how candidates are nominated. The process is described in our Constitution and Bylaws. This year the Executive Committee appointed the officers as the Nominating Committee and designated the past president as its chair. The Nominating Committee selects candidates for each position from among INMM members. INMM membership is the only formal qualification for office, but in practice the Nominating Committee follows several unwritten guidelines. These include a demonstrated commitment to INMM, demonstrated leadership qualities, diverse representation, and employer support. This year the Nominating Committee chair solicited names to consider as candidates. We received several and discussed all before selecting the nominees. The Bylaws also prescribe that candidates can be nominated by petition signed by fifteen members.

Volunteers

I would guess that all past presidents have written about volunteerism because volunteers are critical to the success of INMM. We are often asked the best way to get involved with INMM. Let me give you my perspective. Show up, help figure out what needs to be done, then volunteer to do it. I firmly believe that no matter where you live and work you can contribute time and effort to some INMM activity. If you attend the Annual Meeting, you'll find a wealth of opportunities. Each year at the Annual Meeting, all technical divisions, most standing committees, and several chapters hold meetings and actively seek volunteers. All regular meetings of the Executive Committee in November, March, and July are open and provide additional opportunities to get involved. This is especially true with our ongoing strategic planning activities. If you are unable to travel to meetings, then participate in your chapter. The chapters are always seeking more volunteers too. If you can neither travel to distant meetings nor live in the vicinity of a chapter, you can still make an individual contribution. Write articles or review books for the *Journal*, contribute to the *INMM Communicator* or INNM eGroup, make presentations to local schools and universities, recruit new members and student members, or form a new chapter. I am sure you can think of more ideas and I solicit your active participation.

Students

Last year at this time some of us had high expectations for significant increases in student participation in INMM. The Annual Meeting attracted eight student papers and we presented two student paper awards. One chapter sponsored a student and faculty member at the Annual Meeting. Other chapters were engaging universities in their regions. Two universities were considering forming the first INMM student chapters. This year the picture is not as rosy. There is a paucity of student papers and the first student chapter has yet to be established. We must redouble our efforts to attract students to our profession and professional society. I will lead a meeting Wednesday evening during the Annual Meeting to activate a student activities committee, brainstorm ideas to attract students, and support our strategic planning for this vital area. Check the meeting Addendum for the time and location.

INMM President John C. Matter may be reached by e-mail at jcmatter@Sandia.gov.

By Dennis Mangan
Technical Editor

Reducing the Threat... Canberra Safeguards Systems — A World of Support

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Portal Monitors installed at access control and cargo handling facilities and other transit points detect the illicit movement of special nuclear materials and industrial radioisotopes.

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Electronic seals such as the VACOSS and the Cobra Seal are fixed on equipment for the U.S. Program of Technical Assistance to IAEA Safeguards (POTAS) to prevent otherwise undetected tampering. Seals are also used at nuclear material storage areas to safeguard the contents.

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Safeguards inspectors use the InSpector 2000 for a wide range of portable gamma spectrometry measurements with NaI, HPGe and CZT detectors.

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A number of surveillance systems such as GEMINI, GEMINI-N, and DCM-14-based systems are used to continuously record activity at dry storage facilities around the world.

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Performing material accountability and waste assay measurements at over 100 locations across the globe.

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Hybrid K-Edge System

Where fuel reprocessing is performed, this system is used to measure concentrations of plutonium and uranium in process material.

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A battery-operated hand-held gamma-ray spectrometer for identifying special nuclear material. An NaI detector coupled with digital electronics and the Genie2K software enable a broad spectrum of programmable functionality.

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Statistical Analysis of Nondestructive Radioassay System Measurements of Transuranic Waste

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Greg K. Becker
Custom Surrogate Matrices, Idaho Falls, Idaho, U.S.A.

Abstract

A statistical analysis of the measurement performance of five nondestructive assay (NDA) systems currently in use for radioassay of nuclear waste was performed. Relative bias, precision, and reported vs. actual measurement uncertainty were assessed based on measurements of twenty-one real transuranic waste drums. The analysis found significant differences between the systems in the reported mass values for both total plutonium and ^{241}Am. Significant differences in the precision of measurements was evident as well for total plutonium, but not for ^{241}Am. Reported measurement error values often underestimated actual values for certain waste configurations.

Introduction

A number of different types of NDA systems are used to characterize transuranic waste for shipment to the U.S. Department of Energy's (DOE) Waste Experiment Pilot Plant (WIPP) in Carlsbad, New Mexico, U.S.A. To acquire data on these systems' relative measurement performance capabilities, a study of five of these systems was conducted at the Idaho National Engineering and Environmental Laboratory (INEEL). During the study, the NDA systems were presented with a suite of both real and surrogate waste drums for assay. An initial summary report of the findings was released shortly following the study.[1] A later report presented a more detailed analysis of the surrogate drum measurement results.[2] The purpose of this report is to present the results of a statistical analysis of the real waste-drum measurement results.

Participants

Five NDA systems were evaluated during the tests. The test location and its temporary nature required that the systems be mobile. However, the systems are quite similar to others permanently located around the country. With the exception of passive-active neutron systems, virtually all commonly used NDA methods were represented. The evaluated systems were provided and operated by Canberra Industries, Inc., (three systems), Los Alamos National Laboratory (one system), and Bio-Imaging Research, Inc. (one system). A list of the systems and associated software configurations is given in Table 1.

All systems except the waste-inspection technology (WIT) obtained measurements on a majority of the test drums in the study. Due to a long data acquisition time, only a few test drums were evaluated by the WIT system.

It is important to note that the results obtained from these tests apply only to the stated NDA configuration. Suppliers of NDA-characterization services continually refine their techniques. Therefore the hardware configuration and software versions used to develop the results in this report may be different in the future or may have already been modified in an attempt improve performance or address a wider range of waste form configurations. Still, the results given should provide at least a starting point for determining the suitability of the current versions of these systems for a particular application.

Test Methods

The NDA system evaluation was performed by presenting participants with a set of twenty-one well-characterized standard 208-liter drums containing various forms of real transuranic waste. The waste drums were selected from an inventory of drums generated as a byproduct of operations at the DOE's Rocky Flats Plant. The tests were conducted using a blind format. For each drum, participants were only provided the DOE item description code (IDC) of the contents and the net weight. Participants processed each test drum through their routine NDA procedure per a pre-declared hardware configuration and software version. Participants were required to keep the same configuration through the duration of testing. Participants each had six weeks to process as many of the test drums as possible.

To provide data to evaluate of system precision and bias, participants were directed to perform eight replicate measurements of each test drum. Drums were required to be re-indexed or otherwise repositioned between the replicate measurements. On completion of the eight replicate measurements for a test drum, the assay system representative was instructed to transfer a report containing the measurement results to the test monitor. The assay measurement data reports were then logged and transmitted to the project referee. Most reports provided mass quantities of each

Table 1. Participant system descriptions

System and owner/operator	System specification and/or software utilized
High-Efficiency Neutron Counter (HENC) Canberra Industries, Inc.	Canberra Neutron Assay Software (NAS), Version 2.0A MGA V9.5a isotopics software MGAU uranium isotopics software Isotopic values obtained using IQ3 data
IQ3 Gamma-Assay System (IQ3) Canberra Industries, Inc.	Genie-PC Waste Assay Software, Version 2.1 MGA V9.5 isotopics software MGAU uranium isotopics software IQ3_Rev. 3 TMU Report Excel spreadsheet
Segmented-Gamma Scanner (SGS) Canberra Industries, Inc.	Canberra WM2210T SGS Canberra Gamma Waste Assay Software, Version 2.2 MGA V9.5a isotopics software MGAU uranium isotopics software Canberra SGS_REV4.xls spreadsheet (for differential peak correction and determination of derived quantities such as total alpha activity)
Tomographic-Gamma Scanner (TGS) Los Alamos National Laboratory	WIN_TGS, Version 2.20 (data acquisition) TGS_ARC, Version 1.1 (data reduction) FRAM isotopics system
Waste-Inspection Tomography (WIT) Bio-Imaging Research	WIT single detector hardware configuration A&PCT Revision 1.3 software

radioisotope and radionuclide identified. In cases where masses were not explicitly listed, they were calculated for use in this report from the reported activity using known specific activity values.

After the original measurement results were submitted, they were scored per the test plan.[3] Participants were then informed whether their measurement of each drum was inside or outside of a particular parameter evaluation range. Participants were then allowed to adjust their analysis methodology and resubmit results if they wished. This was done to prevent any easily rectifiable gross calculational errors from invalidating an entire set of results. The results after possible recalculation are presented in this paper.

Description of the Test Drums

The selection of test drums was directed toward waste types that represent significant fractions of the DOE waste inventory. The waste types and associated IDCs included were graphite (300), combustibles (330, 336), filters/insulation (376), inorganic sludge (001), organic sludge (003), MSE salts (409, 411), glass (440), raschig rings (442), and mixed metals (480, 481). These waste types cover a broad range of waste attributes including total transuranic alpha activity, radioactive source distribution, and radionuclide/isotopic composition, as well as waste matrix elemental composition, density (average and distributed), and packaging configuration. Multiple test drums were specified for each waste category, resulting in either two or three waste drums for each category.

To aid in selecting appropriate waste drums for the tests, candidate drums were assayed in detail (e.g., using long count times or multiple measurements) using the INEEL's passive-active neutron (PAN) radioassay system. Furthermore, radiochemistry results were available for some of the sludge drums. These measurement results are used below in describing the special characteristics of individual waste drums. However, since even the extensive PAN data does not necessarily state the true radionuclide content of the drums with complete accuracy, they are not used in any way as true or reference results in evaluating participant system performance. A summary of the waste-drum characteristics as estimated using the PAN system data is given in Table 2.

Special Drum Characteristics

Several of the waste drums had characteristics addressing specific NDA performance issues. The combustibles waste drum (RF3) is a good drum for evaluating the ability of a system to properly identify and quantify a radionuclide composition other than standard weapons-grade plutonium. This drum contains ^{235}U in addition to weapons-grade plutonium at a weight fraction of approximately 12 percent. The mass of ^{235}U is in excess of 0.5 grams and should be readily detected. The combustible matrix is generally considered not to pose a significant complication to existing waste NDA technologies. Failure of a given system to at a minimum identify the presence of ^{235}U would thus be indicative of poor or nonexistent ability to accommodate waste forms that have radionuclide distributions other than that of typical weapons-grade plutonium.

The other combustibles waste drum (RF4) clearly falls in the low-level vs. transuranic-waste segregation category at an estimated alpha activity concentration of 56 nCi/g. In addition, this drum also has a small quantity of ^{235}U, which also necessitates identification and quantification.

Table 2. Actual Rocky Flats waste-drum best estimate radioactive material loadings

Actual Rocky Flats waste drum	Total TRU α activity[a] (Ci) {α nCi/g}	^{239}Pu mass (g)	^{240}Pu mass (g)	^{241}Am mass (g)	^{235}U mass (g)	^{238}U mass (g)
graphite (RF1)	0.502 {1.4e4}	5.879	0.367	0.011	———	———
graphite (RF2)	0.799 {1.2e4}	9.270	0.579	0.020	———	———
combustibles (RF3)	0.431 {1.3e4}	4.877	0.305	0.014	0.542	———
combustibles (RF4)	0.002 {56}	0.020	0.001	6.240e-05	0.006	———
filters/ insulation (RF5)	0.285 {4,825}	3.295	0.206	0.007	0.015	———
filters/ insulation (RF6)	11.998 {4.0e5}	143.687	8.090	0.249	———	———
inorganic sludge (RF7)[b]	2.564 {1.7e4}	0.572	0.036	0.735	0.846	———
inorganic sludge (RF7)[c]	1.790 {1.2e4}	0.481	0.030	0.511	0.846	———
inorganic sludge (RF8)[b]	0.353 {1782}	2.348	0.147	0.049	0.633	295.358
inorganic sludge (RF8)[c]	0.364 {1838}	2.650	0.166	0.046	0.633	———
inorganic sludge (RF9)[b]	0.949 {6683}	1.050	0.691	0.022	———	———
organic sludge (RF10)[a]	0.085 {607}	0.980	0.061	0.002	0.018	———
organic sludge (RF11)[b]	0.148 {643}	1.712	0.107	0.004	0.018	———
organic sludge (RF11)[b]	0.114 {496}	1.350	0.085	0.002	0.177	———
MSE (RF12)	15.019 {4.8e5}	161.332	9.612	0.686	———	———
MSE salts (RF13)	73.765 {9.9e5}	277.731	17.355	15.126	2.086	———
glass (RF14)	0.182 {2141}	2.027	0.127	0.006	0.450	———
glass (RF15)	0.238 {4091}	2.722	0.170	0.007	0.056	———
glass (RF16)	7.783 {2.0e5}	76.417	4.775	0.510	2.420	———
raschig ring (RF17)	0.087 {1323}	0.961	0.060	0.003	———	———
raschig ring (RF18)	0.615 {1.3e4}	7.045	0.440	0.017	———	———
mixed metals (RF19)[d]	———	———	———	———	———	———
mixed metals (RF20)	0.437 {3624}	3.969	0.248	0.036	0.099	190.000
mixed metals (RF21)	1.575 {2.4e4}	17.968	1.123	0.047	———	———

a. Based on the PAN passive mode measurement unless otherwise indicated
b. PAN active mass measurement
c. Radiochemistry measurement
d. Blank sample, no activity

The glass waste drum (RF14) is similar to RF3 in that the sample contains an enhanced ^{235}U to weapons-grade plutonium weight fraction. (In excess of 20 percent in this case.) The glass matrix, although more dense than combustibles, should be accommodated by most waste NDA techniques. Thus this sample provides an indication of the ability to detect and quantify radionuclide distributions other than that of standard weapons-grade plutonium in a slightly more difficult matrix configuration.

Some of the sludge drums also have high ^{235}U weight fractions. Due to the density of the sludge materials, detection of ^{235}U in these drums will be the most difficult. Also, one sludge drum (RF8) and one mixed metals drum (RF20) have large ^{238}U quantities.

Data Analysis Methods

The analyses for this report focused on assessing relative bias and precision of measurements and on the adequacy of stated error values. The basic quantities analyzed were the measured mass values for total plutonium mass and the specific isotopes ^{235}U, ^{238}U, and ^{241}Am. (Total plutonium mass quantities were not reported by all participants. In those cases, the total plutonium mass was obtained by summing the individual plutonium isotope quantities. In these cases the total plutonium mass measurement error was calculated as the square root of the sum of the squares of the errors for the individual isotopic quantities.)

Precision is stated in terms of standard deviations of replicate mass measurements. All measures of precision are stated in this report as one standard deviation values. (Participants were required to report two standard deviation measurement errors in the CEP, but these numbers were divided by two for use in this report.)

To formally assess the overall relative performance of the systems tested, a series of statistical comparisons of the mean response values and standard deviation values across drums was performed using analysis of variance (ANOVA) techniques. These analyses did not include the WIT system because it only assayed two of the waste drums. For the other four systems, the ANOVA analyses cover only the thirteen waste drums measured by all four systems. These drums were RF1-RF5, RF8-RF11, RF13-RF15, and RF19. This is a wide enough range of waste types to give a good overall view of the relative performance of the systems.

Because there were considerable differences in the variance of the replicate measurements for the various waste drums, standard ANOVA techniques were not appropriate. (Equality of variance is an important assumption for the validity of significance tests in standard ANOVA). Hence, nonparametric analysis of variance techniques were employed.[4] In particular, the nonparametric Friedman test (equivalent to ANOVA performed on ranks) was used to test for significant differences in values of mean measured mass, and the standard deviations of replicate values between the four systems. In each of these analyses, the value of interest from each system's measurements of a particular drum was ranked in order of magnitude from 1 to 4. Then the average rank for each system across the thirteen waste drums was calculated. The Friedman test was then calculated by means of ANOVA on the ranks. The results indicate whether there are significant differences among the drums in the overall ranking. If so, then multiple comparison tests can be used to determine which systems are significantly different from one another. Unless otherwise indicated, all tests in this report were considered to be statistically significant if the p-value for the test was 0.05 or less.

Results

Because the true contents of the waste drum are not known, the analysis of the waste-drum measurements focuses on the relative performance among the systems. Again, it is important to note that some of the waste drums contained matrix material characteristics and/or nuclide quantities that were outside the capability envelope of a particular participant's technology, but participants were encouraged to attempt all measurements anyway. Thus in interpreting the results, it is important to realize that, in production waste measurement operations, some of these data would never occur because drums with characteristics outside a system's known capabilities would be rejected from the measurement process.

Mean Measurement Values for Individual Isotopes

Mean measurement values and 95 percent confidence bounds for each of the measurement systems for the waste drums are plotted in figures 1 through 4 for total plutonium and the isotopes ^{241}Am, ^{235}U, and ^{238}U. Results for the uranium isotopes are shown only for those drums for which these isotopes were indicated as present in Table 2. When a drum was not assayed, no data appear in the plots. To distinguish between cases were a system did not assay a drum and cases where it assayed a drum but did not detect or report any values for a particular isotope, a value of zero is plotted in the later case.

Analysis of Variance for Mean Differences, Total Plutonium and ^{241}Am

The comparison of the measured values across the measurement systems using ANOVA provides a measure of relative bias among the systems. This is a useful measurement but it should be kept in mind that while it will indicate if a system is performing differently from other systems in terms of the measured mass values, it does not identify which system is most correct (since the true values are not known).

The nonparametric ANOVA tests were performed separately for the two measures total plutonium and ^{241}Am. In both cases, the Friedman test indicated there were significant differences between the measurement systems. The p-value for the overall significance test was less than 0.01 in both cases. The mean ranking of each system for the measurements of each isotope and results of the multiple comparisons tests to determine which systems were producing the significant results are presented in tables 3 and 4.

Table 3. Mean ranks and significance test results for differences in total plutonium measurements of thirteen waste drums (Significant p-values indicated by asterisks.)

System	Mean rank	p-value for difference in mean rank from: HENC	IQ3	SGS	TGS
HENC	2.8	___	0.11	0.06	0.24
IQ3	2.0	0.11	___	0.73	0.01*
SGS	1.9	0.06	0.73	___	0.00*
TGS	3.3	0.24	0.01*	0.00*	___

Table 4. Mean ranks and significance test results for differences in 241Am measurements of thirteen waste drums. (Significant p-values indicated by asterisks.)

System	Mean rank	p-value for difference in mean rank from: HENC	IQ3	SGS	TGS
HENC	2.6	___	0.31	0.10	0.10
IQ3	2.2	0.31	___	0.50	0.01*
SGS	1.8	0.10	0.50	___	0.00*
TGS	3.4	0.10	0.01*	0.00*	___

The tomographic-gamma system (TGS) produced the highest total plutonium measurements overall with a mean rank of 3.3. (A system that produced the highest measurement on every drum would have a mean ranking of 4.0. If it always produced the lowest measurement, the mean ranking would be 1.0.) The differences between the mean value for the TGS system and the IQ3 and SGS systems were statistically significant. The smaller difference between it and the high-efficiency neutron-counter (HENC) system was not. The difference between the segmented-gamma scanner (SGS) system (which at 1.9 had the lowest mean ranking) and the HENC system was nearly significant ($p = 0.06$).

As might be expected, the results for ^{241}Am parallel those for total plutonium. There were only slight differences in the mean rankings and the significance test results. This similarity is generally due to the use of standard isotopic mass ratios applied to base plutonium measurements to obtain the ^{241}Am value. Typically, with both neutron and gamma systems operating on this type of waste, standard weapons-grade plutonium isotopic values are used unless evidence suggests there are significant departures. See the discussion below for ^{235}U for the systems' capabilities to recognize the presence of other isotopes in nonweapons-grade source configurations.

The WIT system only assayed two of the waste drums (RF11 organic sludge and RF20 mixed metals). In both cases it reported noticeably higher quantities of total plutonium than the other systems. A consistent relative bias in the WIT system measurements does not apply to the ^{241}Am results for these two drums. It reported the lowest ^{241}Am value for the mixed metals waste drum but fell in the middle of the other systems values on the organic sludge drum measurements.

Uranium Isotope Results

Among the twelve drums in Figure 3 (those with reported ^{235}U quantities in Table 2), none of the evaluated systems reported detectable quantities in the filters drum, the MSE salts drum, or three of the four sludge drums. Only the HENC and the IQ3 systems reported quantities in the combustible drum RF4. The HENC system did not report ^{235}U quantities for the glass drums RF14 and RF16, but it did for RF15. The SGS system did not report measured values for the glass drum RF15 but did for RF14. (The SGS system did not assay the RF16 glass drum.) The WIT system did not report measurable ^{235}U on the mixed metals drum RF20, the only drum of the twelve it assayed.

Relative agreement of the mean values between the measurement systems varied from drum to drum. Maximum mean values exceeded minimum non-zero mean values by as little as 10 percent (mixed metals RF20) and as much as 300 percent (glass RF15). For drums for which it reported non-zero measured values, the TGS system always reported the highest ^{235}U mass.

The HENC, IQ3, and SGS systems all detected ^{238}U in the inorganic sludge drums RF8 and the mixed metals drum RF20 (Figure 4), reporting at least 250g in each case. The TGS system did not report any ^{238}U in RF8 and did not assay RF20. Of these two drums, the WIT system assayed only RF20 and did not report any ^{238}U.

Precision of Isotopic Mass Values

Although the confidence bounds plotted in figures 1 through 4 are based on standard errors, they are proportional to the standard deviation of the replicate measurements because (except for a few cases of missing replicate measurements) they are all based on eight replicate measurements. Thus they serve as graphical representations of the precision of the measurements. (The length of the error bars are equal to 0.85*s, where s is the standard deviation of the replicate measurements and 0.85 is the two-sided 95 percent student's t-value divided by the square root of 8.)

Analysis of Variance for Replicate Standard Deviation of Total Plutonium and ^{241}Am Measurements

The standard deviations of the replicate measurements were compared across the HENC, IQ3, SGS, and TGS systems using nonparametric ANOVA techniques in the same manner as reported above for the mean values. (As with the means analysis, only the thirteen waste drums assayed by all four systems were included, and the WIT system was not included because it assayed only two drums.) The results of the ANOVA tests for precision were performed for total plutonium and ^{241}Am. The results provide measures of significant differences in the replicate standard deviations of the four systems.

The Friedman test indicated no significant differences exist between the measurement systems in the ^{241}Am standard deviations ($p = 0.15$). For the total plutonium quantities, the Friedman test was statistically significant ($p < 0.01$). The mean ranking of each system for the standard deviation of total plutonium values and results of multiple comparison tests to determine which systems were producing the significant results are presented in Table 5.

Table 5. Mean ranks and significance test results for differences in total plutonium replicate standard deviations of thirteen waste drums (Significant p-values indicated by asterisks.)

System	Mean rank	p-value for difference in mean rank from: HENC	IQ3	SGS	TGS
HENC	3.0	___	0.00*	0.04*	0.33
IQ3	1.4	0.00*	___	0.05*	0.00*
SGS	2.2	0.04*	0.05*	___	0.00*
TGS	3.4	0.33	0.00*	0.00*	___

All the comparisons between systems in the mean ranked standard deviation values for total plutonium were statistically significant except for the difference between the HENC and TGS systems. These two systems showed the largest mean ranks on the replicate standard deviations, hence the poorer precision values. The IQ3 system showed the lowest rank (best precision).

Reported Error vs. Replicate Standard Deviation

It is of interest to compare the replicate standard deviation values to the average reported error value. In general the reported error should be larger than the replicate standard deviation because it is suppose to be a total uncertainty value. As such, it should include all sources of measurement error including bias (which can be quite large) as well as other precision error effects not reflected in replicate measurements. Total uncertainty is generally calculated by combining precision error with bias error in quadrature. Hence the approximate degree to which other error sources have been considered in deriving the stated measurement error values is calculable by taking the square root of the difference between the squared average reported error and the squared replicate standard deviation. These values, expressed as a percent of the mean total mass quantity, are reported in tables 6 through 9 for each of the four systems that reported error values. When the average reported error value for a particular drum was less than the replicate standard deviation, a value of zero is listed. Thus a zero value indicates a tendency to underestimate the true value to some degree.

In terms of percent of the mean mass value, some measurements showed extremely large excess variability in the reported vs. replicate standard deviation values. This was usually due to the

Table 6. Comparison of stated error values to replicate standard deviations, HENC system

Drum	Excess variability in the mean stated error over replicate standard deviation (expressed as a percent of mean measured mass value) Total plutonium	^{241}Am	^{235}U	^{238}U
RF1	5	5		
RF2	5	5		
RF3	9	11	8	
RF4	14	17	102	
RF5	0	15		
RF6	11	0		
RF7	0	0		
RF8	59	60	69	39,514
RF9	0	24		
RF10	46	47		
RF11	64	64		
RF12	17	18		
RF13	0	0		
RF14	10	10		
RF15	2	6	13	
RF16	8	6		
RF17	6	3		
RF18	5	5		
RF19	162	163		
RF20	0	4	29	25,745
RF21	6	6		

Table 7. Comparison of stated error values to replicate standard deviations, IQ3 system

Drum	Excess variability in the mean stated error over replicate standard deviation (expressed as a percent of mean measured mass value) Total plutonium	^{241}Am	^{235}U	^{238}U
RF1	18	19		
RF2	18	19		
RF3	12	11	10	
RF4	16	9	96	
RF5	22	15		
RF6				
RF7				
RF8	35	36	48	39
RF9	32	35		
RF10	28	28		
RF11	38	40		
RF12				
RF13	18	22		
RF14	19	12	22	
RF15	15	16	21	
RF16				
RF17	16	17		
RF18	15	16		
RF19				
RF20	24	25	36	26
RF21	16	17		

Table 8. Comparison of stated error values to replicate standard deviations, SGS system

Drum	Excess variability in the mean stated error over replicate standard deviation (expressed as a percent of mean measured mass value)			
	Total plutonium	^{241}Am	^{235}U	^{238}U
RF1	32	34		
RF2	15	16		
RF3	10	12	14	
RF4		0		
RF5	14	15		
RF6	13	14		
RF7		0		
RF8	43	46	47	15
RF9	11	12		
RF10	12	0		
RF11	31	27		
RF12	20	22		
RF13	30	35		
RF14	18	18	21	
RF15	14	15		
RF16	16	18	22	
RF17	13	14		
RF18	13	14		
RF19				
RF20	15	16		
RF21	14	15		

Table 9. Comparison of stated error values to replicate standard deviations, TGS system

Drum	Excess variability in the mean stated error over replicate standard deviation (expressed as a percent of mean measured mass value)			
	Total plutonium	^{241}Am	^{235}U	^{238}U
RF1	9	10		
RF2	9	10		
RF3	9	9	8	
RF4	897	1,117		
RF5	9	10		
RF6	9	10		
RF7	186	218		
RF8	19	22	0	
RF9	6	0		
RF10	60	71		
RF11	24	32		
RF12	9	10		
RF13	9	10		
RF14	17	19	9	
RF15	12	13	14	
RF16				
RF17				
RF18				
RF19	1,395	1,535		
RF20				
RF21				

measured quantity being quite small (thus inflating values expressed as a percentage of the measured quantity). Several differences between the systems in regard to reported errors can be seen by comparing the results for total plutonium and ^{241}Am between systems.

Overall, the HENC system's reported uncertainty showed the least amount of error in excess of replicate standard deviation. The median value for total plutonium and ^{241}Am was 6 percent. The IQ3 system exhibited the largest median excess error values; 18 percent for both total plutonium and ^{241}Am. The median values were approximately 11 percent for the TGS system and 15 percent for the SGS system (for both total plutonium and ^{241}Am).

The HENC system reported error was less than the replicate standard deviation for five of the twenty-one drums measured for total plutonium and for three of the twenty-one drums for ^{241}Am, suggesting a tendency to underestimate total error. The TGS and IQ3 systems showed no drums for which the reported error was less than the replicate standard deviation. For the SGS system, the reported value was less than the replicate value for one of nineteen drums for total plutonium and three of twenty drums for ^{241}Am.

In a previous report on surrogate waste-drum measurements for these same systems where the true isotopic mass quantities were known, significant bias values in excess of 20 percent (i.e., recovery values less than 80 percent or greater than 120 percent) for plutonium isotopes and ^{241}Am were common for all the measurement systems.2 However, due to the balancing of the over and under 100 percent recovery values, the median bias values in the surrogate waste drums were much closer to zero in most cases. For example, for ^{239}Pu the median surrogate waste-drum bias values were 6 percent for the HENC and IQ3 systems, 8 percent for the SGS system, and 5 percent for the TGS system. For ^{241}Am, the values were 7 percent for the HENC system, 0 percent for the IQ3 system, 9 percent for the SGS system, and 49 percent for the TGS system. Hence, except for the case of the TGS system ^{241}Am measurements, the median of the allowed excess uncertainty in the waste-drum measurements seems to be large enough to include expected bias effects. However, for specific waste types (such as those where no excess in the reported uncertainty vs. replicate standard deviation), there can still be considerable differences between the allowed excess and the bias exhibited in the surrogate waste drums of the same waste type.

Summary

The tests presented NDA systems with a broad range of real transuranic waste configurations and included many complicating factors that challenged their measurement capabilities. No clear *winner* among the systems tested in that no one system consistently outperformed the others. Each system had configurations where it performed well and those where it did not.

Results on the waste drums were quite variable. The WIT system only assayed two drums, so its results are not complete. However, the WIT system reported the largest total plutonium

mass values for the two drums it measured. It also showed the lowest ^{241}Am mass on one drum. It did not detect uranium in the mixed metals drum RF20 while the other systems measuring that drum did. This suggests that the WIT system behavior is quite different than the other systems.

The ANOVA analyses performed on the ranked waste-drum data for systems besides the WIT system showed significant differences between systems both in terms of bias and precision. The TGS system tended to record higher mass values for both total plutonium and ^{241}Am than did the other systems. (This is a measure of relative bias only; there is no way of knowing whether the TGS system or any of the others is more correct.) Precision results for the waste drums showed the TGS system had the highest replicate standard deviation rank results for total plutonium measurements compared to the other systems, although the difference between the TGS and the HENC (with the second highest rank) was not statistically significant. The IQ3 system provided the best overall precision results on total plutonium in the waste drums. There were no significant differences however, between any of the four systems in regard to overall precision of ^{241}Am measurements.

A noted weak point in the NDA system performance brought out in some of the tests is related to the reporting of errors in measurements. The results indicate that measurement error was often underestimated for certain waste configurations. Assuming that such underestimation exists in actual production waste measurements as well, the confidence that certain waste-drum characteristics derived from isotopic mass measurements are meeting shipping and storage requirements may be less than what is currently assumed.

Discussion

This study has shown that although there is considerable performance overlap among the various waste NDA systems, no two have identical capability envelopes. System performance differs between systems due to a convolution of the waste-form attributes, the measurement method, and the associated data acquisition/reduction techniques. Although the effects of ancillary characteristics of the measured material (e.g., matrix effects) on measurement system results are not unique to NDA of transuranic waste, the degree of these effects in this application is arguably greater than is generally encountered in most scientific and engineering applications. As a result, developers of radioassay systems for transuranic waste have been somewhat unprepared for and slow in adequately resolving these issues to the degree necessary to produce truly robust measurement results.

Not all of the poor measurement results on the more-challenging waste drums in this study were a surprise to the participants. To get a complete picture of the performance of each system, operators were asked to perform and report measurements on all drums, even when it was determined that a particular drum was outside the system's normal operating limits. In some cases however, the waste-drum characteristics appeared to be within the known operating envelope of the system and what looked like reasonable measurement results were obtained. But, when the results were compared to the true radioisotope quantities, it became obvious that the system did not respond properly or that the uncertainty in the measurement was much larger than anticipated and was not properly quantified.

It is clear from this analysis that most systems will at least occasionally perform inadequately when presented with new waste form configurations for the first time. Given this situation, it is not surprising that facilities sometimes find that acquiring a system that has been working acceptably in another application at another facility does not guarantee that it will be easily adapted to their specific setting. In most cases, thorough test measurements and a detailed technical evaluation of the proposed measurement system relative to the waste forms to which it will be applied should be performed before a system is accepted and placed into operation.

The bottom line is that the wide variety of performance results found in this study underscores the need for both system improvements and constant monitoring and evaluation of system performance. Detector and hardware enhancements of systems may offer some potential for mitigating the effects of waste-form heterogeneity on the measurement results. However, more immediate and potentially larger and less expensive gains are to be expected by improving data reduction and analysis techniques for the current systems. Examples include more accurate waste-type and waste-container specific attenuation corrections and/or calibration equations. These types of changes have the potential to not only improve accuracy but to also extend a system's operating envelope.

Until more robust NDA systems are made available, independent monitoring of measurements will remain necessary to insure that systems are only being used in applications appropriate for their performance envelope, and that the system continues to work well in that environment. Currently, the primary official means for ongoing quality-assurance testing is the NDA portion of the WIPP Performance Demonstration Program (PDP). The PDP periodically tests all measurement facilities shipping waste to WIPP using controlled blind measurement tests. This program has been refined over the years to provide test samples to each facility that are representative of the waste forms being processed at that facility. These periodic independent performance assessment tests provide ongoing objective evidence on the general capability of all NDA systems generating data for WIPP.

The PDP process is capable of identifying NDA systems significantly out of control or improperly applied. But it has a low probability of identifying systems with bias or precision problems that are variable over time and the waste inventory. Furthermore, the PDP tests involve only mainstream or average waste-drum configurations that generally do not test the boundaries of the system capabilities. Mainstream tests validate the system per-

formance on typical drums but do not address the extent to which adequate measurements will be obtained when significant deviations in waste parameters exist. Until more robust systems are developed and put in place, the PDP program or other test programs should begin to address defining the boundaries of the acceptable performance limits of systems rather than (or in addition to) the average. This is of particular importance at facilities where systems have been effectively calibrated to the PDP drum configurations (by test measurements using the PDP drums or identically constructed surrogate drums).

In addition to expanding the scope and role of the PDP tests in the quality assessment of NDA systems, more use could be made of the existing PDP data. PDP data are currently only formally used to evaluate a single system at a single point in time. While some efforts have been made to glean information from the combined PDP test results (e.g., Reference 5), the totality of PDP data collected over many years and many measurement systems has never been thoroughly exploited and analyzed to present an overall picture of the quality of data measurements on WIPP-destined waste. A detailed analysis of the PDP data for time trends in bias values, the ability of systems to provide repeatable measurement over time, and overall WIPP waste-data quality would be of great value to directing improvements in systems as well as contributing to a better understanding of the data quality (in particular the uncertainty bounds) of the WIPP inventory.

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Acknowledgements

This work was performed under U. S. Department of Energy Idaho Operations Office Contract DE-AC07-99ID13727.

Figure 1. Reported total plutonium mass

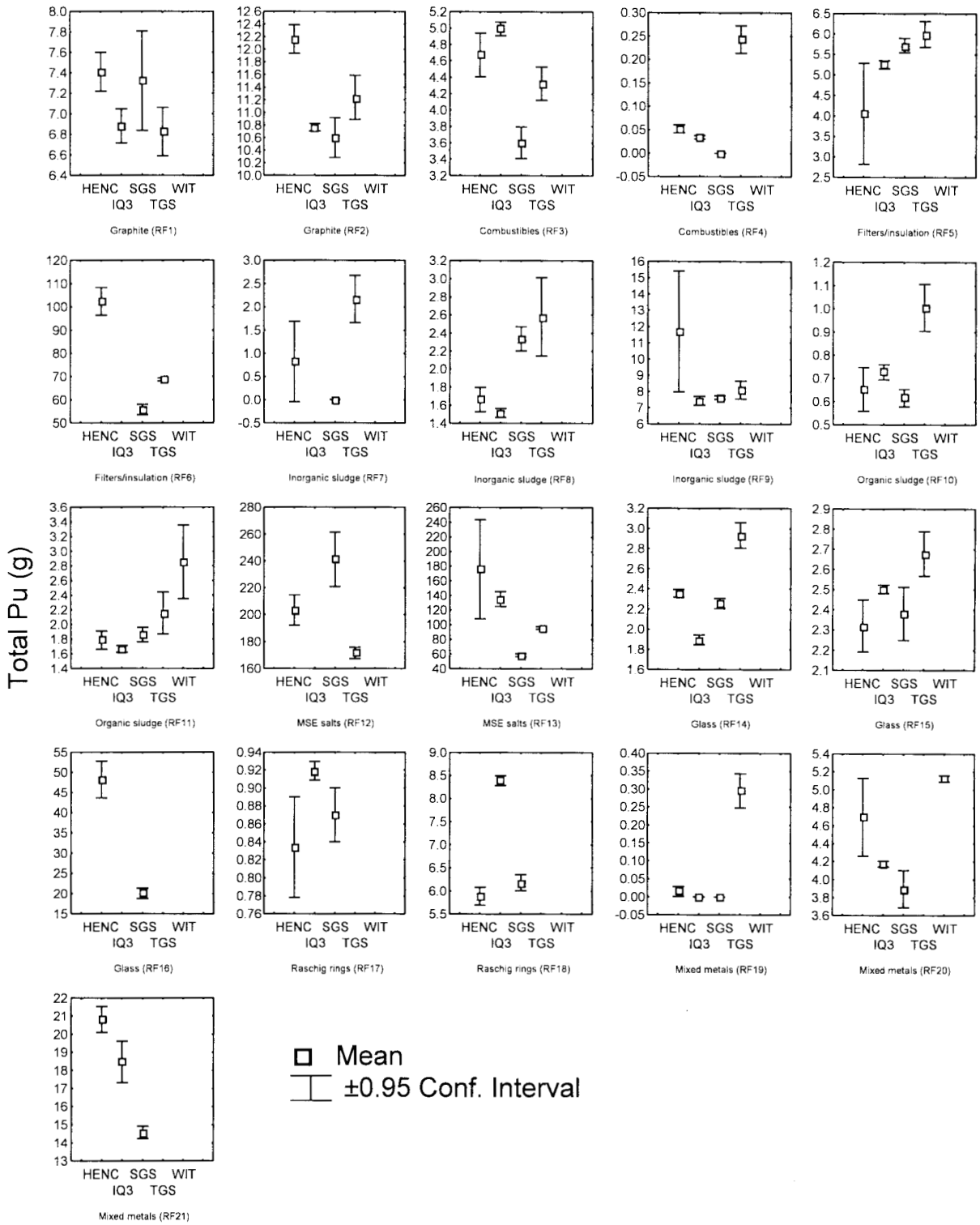


Figure 2. Reported ^{241}Am mass

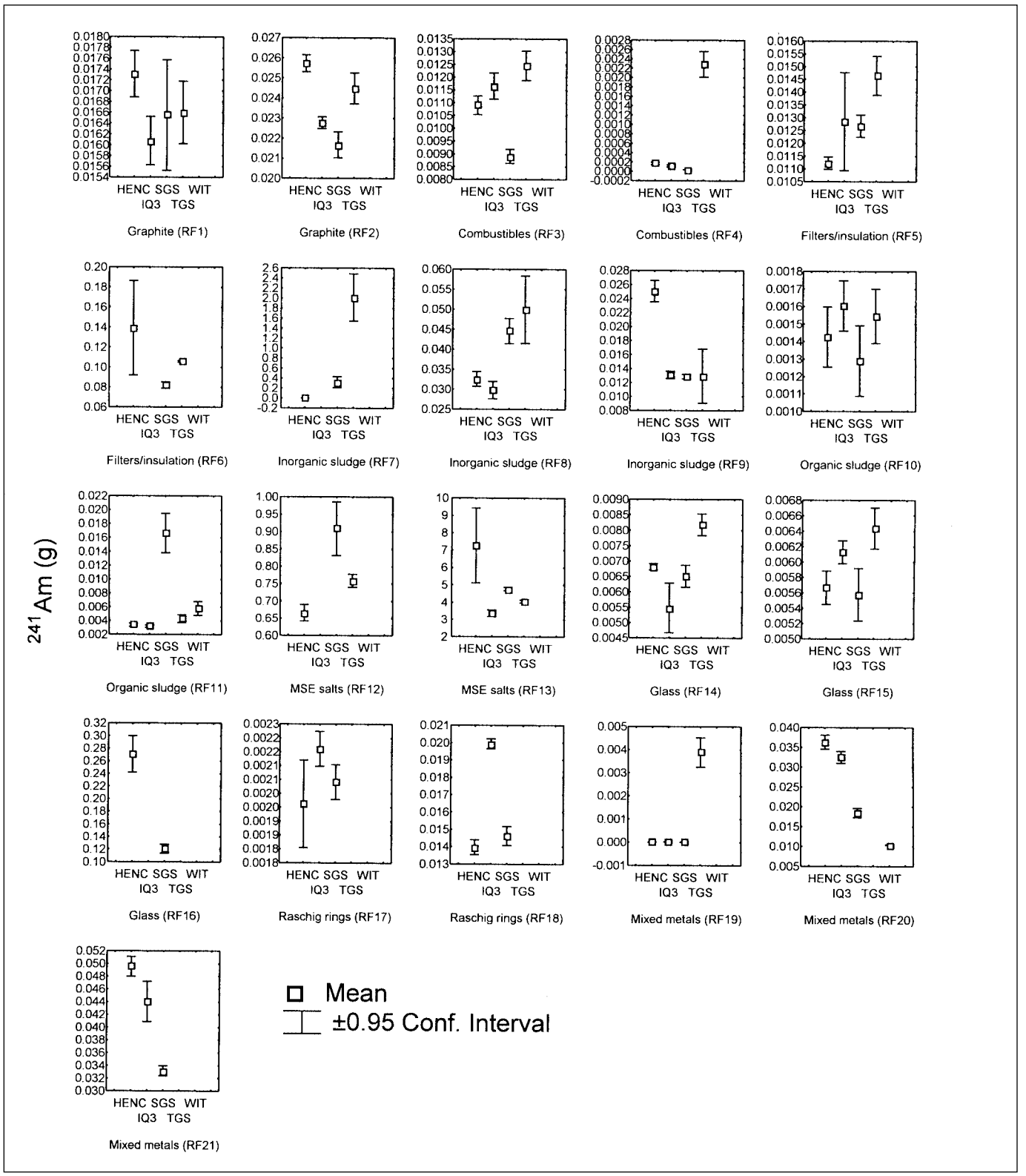


Figure 3. Reported ^{235}U mass

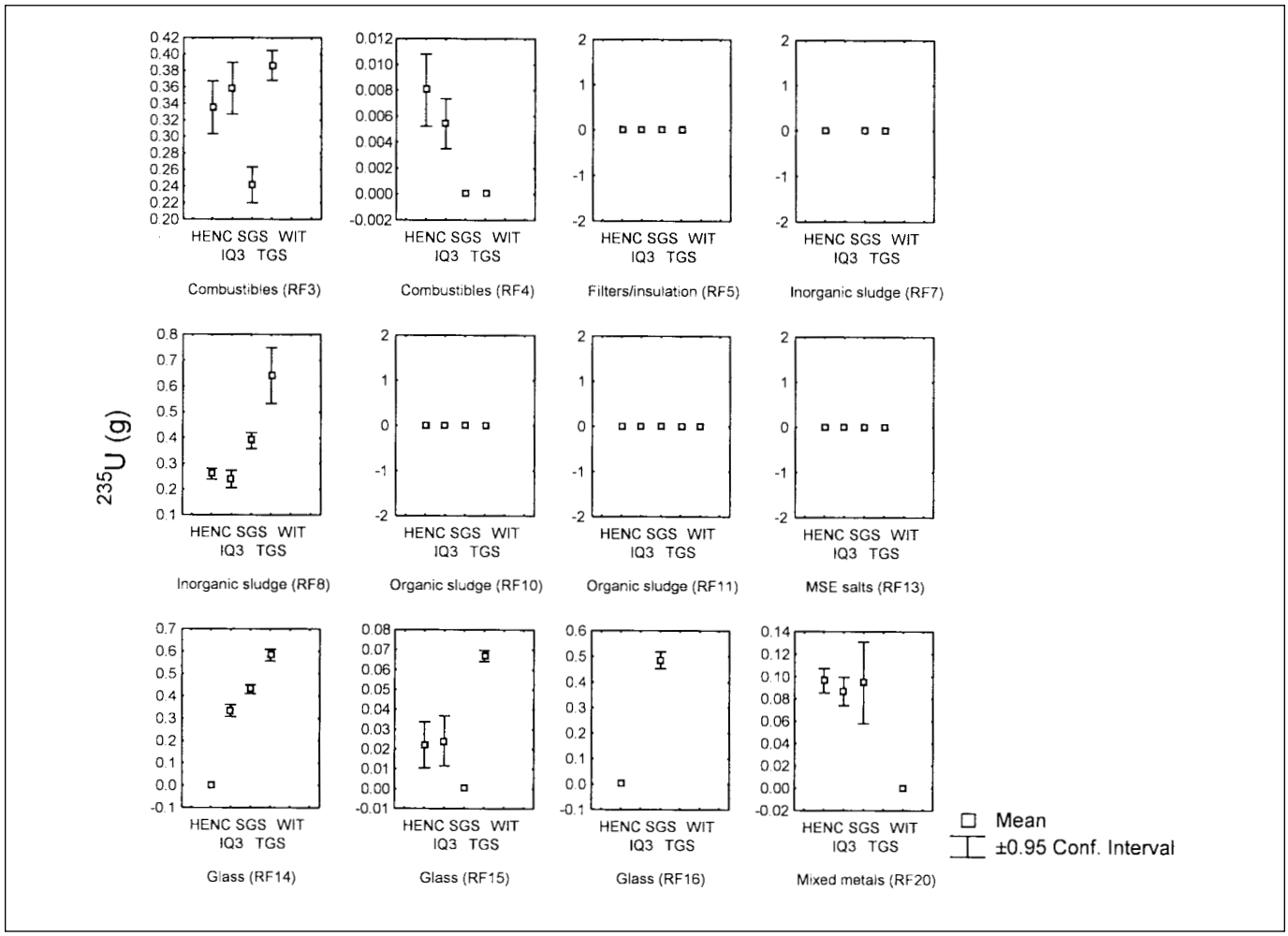
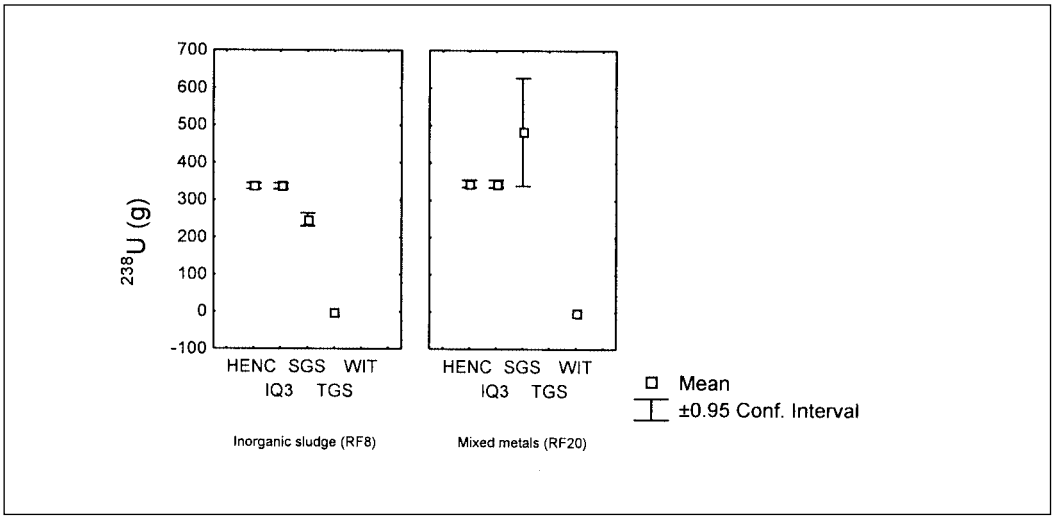


Figure 4. Reported ^{238}U mass



Timely Options for Increased Transparency and Nonintrusive Verification on Fresh Highly Enriched Uranium Naval Fuel

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Abstract

Fresh highly enriched uranium naval fuel constitutes a significant part of global HEU stocks. However, no bilateral or multilateral verification or transparency measures have been envisioned on these sensitive and proliferation-attractive fuel cycles. This might be detrimental to sound nonproliferation and disarmament practices. This article argues in favor of increased transparency on unirradiated naval fuel and discusses a range of technical options for nonintrusive verification. A set of fairly simple and technically available verification measures that do not compromise national security needs and legislation exists. If implemented, these measures could raise confidence in nondiversion of naval fuel for weapon purposes, and could help establish an international transparency norm for fresh naval fuel cycles.

Introduction

In September 2002, a joint experts group under the auspices of Presidents Bush and Putin presented proposals on near- and long-term bilateral and multilateral means to reduce inventories of highly enriched uranium (HEU) and plutonium. The expert group identified several areas where joint cooperation could lead to a reduction of Russia's HEU stocks.[2]

The proposals for HEU reduction should be implemented as a matter of urgency—not least to substantiate the statements of Bush and Putin that the United States and Russia both recognize their common interest in guaranteeing the irreversibility of nuclear disarmament, in strengthening nonproliferation, and in combating terrorism by accelerating the disposal of excess nuclear weapon materials.[3] Military HEU quantities exceed those of military plutonium stocks by a factor of seven. These quantities constitute obvious security threats to the international community. [4]

A fundamental prerequisite for effective implementation of any reduction proposals is, however, a comprehensive understanding of how much fissile material is available and for what purposes. Today more information about military nuclear stocks is available than only a few years ago, but still—with some noteworthy exceptions—no official figures exist on the military inventories of HEU in the nuclear-weapon states.[5] Unofficial estimates indicate that some 1,750 tons of HEU have been produced since the dawn of the atomic era, the vast majority by the United States and Russia.[6]

In addition to its weapons applications and use in research reactors, HEU is used for the propulsion of submarines and some surface vessels, most notably by the United States and Russia.[7] Estimates indicate that naval fuel represents 10 to 15 percent of all HEU stocks worldwide.[8] Russia alone may hold as much as 80 to 85 metric tons of HEU for naval propulsion.[9] As nuclear-weapon states under the Nonproliferation Treaty, the United States and Russia, like other current nuclear submarine possessors, are exempt from international safeguards.[10]

For sound disarmament and nonproliferation practices, material destined for naval propulsion, which represents a significant part of the global HEU stocks, will also eventually have to be accounted for and some assurances that it is not being diverted to weapons will have to be given.[11] To avoid mutual distrust and to lay the foundation for substantial reductions of all stocks of fissile material, increased transparency and possibly nonintrusive verification on the naval fuel cycle should be explored. Due to technical developments (in the United States) and a declining number of submarine operations (in Russia), naval HEU needs and consumption are likely to decrease in the coming decades.[12]

Transparency could, and most probably will, become an increasingly important tool for addressing both arms control and nonproliferation issues, particularly as less emphasis is put on formalized and mutually verifiable arms control.[13] Taking Russia's naval nuclear program as the point of departure, this article explores the technical options, and potential pitfalls, for increased transparency, and possibly, nonintrusive verification on the highly sensitive naval fuel cycles. Endeavors toward increased transparency and nonintrusive verification could build upon the remarkable progress and solid working relations achieved during the cooperative U.S.-Russian naval MPC&A upgrades.[14]

Before focusing on specific transparency measures to put in place, this article begins with a discussion of why increased transparency and nonintrusive verification of naval fuel are needed. The differences of and links between *transparency* and *nonintrusive verification* are discussed, followed by a general background on highly enriched uranium fuel.

Throughout, the challenges associated with naval nuclear-fuel transparency will be assessed. The relevance of ongoing work and research and development in related areas of technical arms control will be investigated, as technology originally developed for nonintrusive verification of warhead components may be

applicable for naval fuel cycles as well. It will be shown that technical arrangements are available for nonintrusive naval fuel verification, once the necessary political will is generated.

Focus will be on the fresh naval fuel—and thus on the front end of this highly sensitive and proliferation-attractive fuel cycle.[15] When the fuel enters into an operational reactor, the transparency and nonintrusive verification may be terminated, as the highly radioactive fission products generated render any removal of the fuel most challenging and dangerous.

The measures proposed could help establish a norm of naval-fuel transparency and boost confidence that such material is not being diverted for clandestine bomb production. These measures may not, however, permit the identification or verification of the exact quantities and qualities of HEU destined for naval propulsion.

This article is of an exploratory nature. Further studies in this highly unexplored area are desirable.

Why Transparency and Nonintrusive Verification of Naval Fuel?

States possessing naval reactors all have nuclear weapons—and, of course, domestic systems of material protection, control, and accountability (MPC&A) in place to safeguard and protect the fuel. Why then bother with increased transparency and nonintrusive verification of highly enriched uranium naval fuel cycles? We note six main reasons.

First of all, the high enrichment levels and low radiation levels of fresh naval fuel could make the material attractive for nuclear-weapon production. HEU is the only material that allows the easy manufacture of a crude and reliable nuclear explosive device.[16] As to the threat of nuclear terrorism, opinions differ among scholars and security experts. However, it seems clear that educated terrorists could turn weapons-grade uranium into a workable gun-type nuclear device.[17] With highly enriched naval fuel, it has been suggested that as few as ten fuel assemblies would suffice to supply enough highly enriched uranium for a bomb.[18] It should also be borne in mind that naval fuel has been exposed to thefts in the past.[19]

Due to the proliferation risks, HEU for land-based reactors is being phased out.[20] Important efforts have been launched to reduce the danger of nuclear proliferation by developing alternative low-enriched uranium (LEU) fuel for research reactors—and possibly naval reactors.[21] Pending such technological fixes and a ban on naval HEU uses, however, options for transparency and nonintrusive verification should be pursued in parallel.

Secondly, fissile material stockpile accountability is essential. To optimize nuclear nonproliferation and disarmament, there is a need to know the total quantities of HEU produced, the quantities destined for weapons or reactor consumption, and finally, the quantities, if any, declared as excess and slated for elimination. Throughout the 1990s, the considerable uncertainties in fissile materials inventories were deemed to be the largest obstacle for verifying nuclear disarmament.[22] As the number of deployed warheads continues to decrease, the uncertainties associated with stocks of fissile material will loom correspondingly higher.[23] This is neither beneficial to nuclear nonproliferation nor to nuclear disarmament.

Thirdly, as highly enriched uranium enrichment has ceased in both the United States and Russia, the navies now draw their uranium fuel directly from existing HEU weapon stocks. The needs of the navies determine the stocks of HEU declared in excess by the states. In the United States for example, the low fraction of higher enrichment levels in HEU declared excess to national security needs stems from the insistence of the U.S. Navy that such material be reserved for its potential needs.[24] Unambiguous stockpile knowledge is thus essential to ensure optimal excess fissile material declarations by states.

Fourthly, increased naval transparency and nonintrusive verification serve to limit new HEU markets outside international control. Such markets could prevail due to an unfortunate loophole in existing safeguards agreements for HEU for military naval propulsion.[25] States may thus withdraw naval HEU from international control.[26] Russian plans to boost its domestic nuclear industries through exports of floating power plants—built with naval reactor technology and HEU fuel. Moreover, Russia has recently agreed to lease nuclear bombers and a nuclear-propelled submarine to India—a state that remains outside the Nonproliferation Treaty.[27] This could increase global naval HEU use and trade. International naval fuel transparency norms are thus highly desirable.

Fifthly, norms of increased naval fuel transparency and nonintrusive verification are also beneficial in terms of establishing a fissile material cut-off treaty (FMCT). Current schemes for such a treaty, if implemented, envision a cut-off that would prohibit the production of HEU and plutonium for weapons, but at the same time allow HEU production for nonexplosive military uses like naval reactors. Such an exception, however, could render the treaty inconclusive, possibly opening the way for clandestine weapons-usable material production through a naval cover. Ways to deal with transparency in the naval fuel cycle and nonintrusive verification under a future FMCT should therefore be explored.

Finally, states may themselves have an interest in promoting transparency, so as to assure other states and possible opponents that they are in fact dealing with sensitive and proliferation-attractive material satisfactorily. This could increase international recognition, as well as improve nuclear security through information sharing with regard to security practices. As mentioned, the highly successful implementation of U.S.-assisted security upgrades at Russian naval facilities hosting fresh fuel and nuclear weapons could serve as a springboard for enhanced cooperation in related areas.[28] The U.S.-Russian naval MPC&A teams have succeeded in overcoming many of the problems hampering other sectors of cooperative U.S.-Russian threat reduction activities, such as issues of access and accountability.

At Odds With Security?

At first glance, transparency and nonintrusive verification may seem to be at odds with security. It may be argued that any openness is likely to harm the long-term security interests of a nation, due to its loss of control of information. Transparency and verification could introduce the risk that classified, sensitive, or proprietary information might be compromised or released—with adverse impacts on national security and international obligations.[29] Apart from the proliferation risks, this could increase vulnerability and lessen the (political) strength of the nation, as sensitive technical information and possible weaknesses could be revealed.

Moreover, increased openness could make it easier for criminals and subnational groups to divert fissile material unlawfully, if government details of the physical protection systems and quantities and qualities of fissile material at facilities were to be made available. Thus, it is clear that transparency measures should not release information that could be damaging to the very nonproliferation interests they are to promote. Detailed information concerning sensitive nuclear technology and/or physical protection and control of the material should be protected, and not released.

However, within the jurisdiction of domestic laws and international agreements there is probably room for more openness with regards to fresh HEU naval nuclear fuel. In fact, the ability to detect HEU in weapons and their dismantled components is now viewed by the U.S. political community as a potentially important transparency measure.[30] Embarking on a path of increased naval nuclear transparency and nonintrusive verification, while protecting proliferation-sensitive information, is thus likely to support global disarmament and nonproliferation efforts, as well as the long-term security interests of the United States, Russia, and other states.

Currently, however, in the political arms-control environments, no bilateral or multilateral verification or transparency measures are envisioned on the sensitive naval fuel cycles. Voluntary alternatives, along the line of those discussed in this article, should be explored.

Naval Fuel Transparency, Nonintrusive Verification—Or Both?

As verification should increase knowledge about the nuclear capabilities of a potential opponent, many scholars and practitioners do not distinguish between verification and transparency.[31] However, any newly and hard-won verification knowledge is not only highly limited in its carefully negotiated scope—it is also an adversarial act, where the inspected (host) party will do its utmost to limit any intrusive revelations of its defensive or offensive capabilities. If sanctions can be expected, states engaged in undesirable behavior will have few incentives to supply accurate information themselves.[32] Moreover, classified and proliferation-sensitive information is, as indicated above, protected by law.

Thus, states often want the level of intrusiveness to be kept as low as possible, though this may conflict with the initial verification goals and expectations. This has resulted in a range of nonintrusive verification options to protect information, while providing meaningful verification outputs for disarmament and nonproliferation purposes. While nonintrusive verification may be a necessary, yet not sufficient, element of contemporary nuclear arms control, it should be supported—and even preceded—by transparency.[33]

Transparency is a process in which information about governmental actions, preferences, intentions, and capabilities is made available, or more properly, allowed to flow, to citizens and the international community.[34] Based on voluntary measures, transparency permits outsiders to accumulate data from a wide range of sources over an extensive period of time to build confidence that the behavior of a country or a collection of countries is consistent with agreements and norms.[35] Typically, transparency does not involve (lengthily) negotiated schemes for inspections or monitoring equipment.[36] Declarations, statements, or interviews with key officials are some important transparency channels.

As transparency becomes more established, it also becomes more self-corroborating because of the increasing number of channels of information that intrinsically crosscheck each other. [37] To date, however, transparency has remained a novel feature of international nuclear arms control. Despite strong international calls for greater openness,[38] most nuclear-weapon states remain quite opaque regarding their military nuclear activities. While this may be (partly) justifiable in terms of security and nonproliferation, the potential for improved global nuclear security associated with increased transparency should be explored.[39]

Russia's Highly Enriched Uranium Naval Fuel: Background

Since 1958, the Soviet Union and/or Russia have constructed 249 nuclear-powered submarines, more than half of the submarines produced worldwide. Two-thirds of these vessels were delivered to the Northern Fleet, the rest were destined for the Pacific Fleet. In addition to the combat submarines, five research and development submarines and several full-size, land-based submarine-training facilities have been produced. Additionally, the eight vessels of the Russian icebreaker fleet are nuclear propelled, each with one or two reactors, accompanied by four (decommissioned) battle cruisers, and a communication ship with twin reactors. The overall number of naval reactors produced by the Soviet Union/Russia is therefore at least 480.

In northwest Russia, military submarines and surface ships are home-ported at the several naval bases on the Kola Peninsula.[40] At all these bases and shipyards spent-nuclear fuel is stored, partly under highly unsatisfactory conditions.[41] Fresh nuclear fuel for pressurized naval reactors is produced at the Elektrostal fuel factory outside Moscow, whereas fuel for liquid-

metal-cooled naval reactors was produced the Ulbinsky Metallurgical Plant in Kazakhstan. The fresh naval fuel is transported by special railroad cars to the Murmansk area.[42] With U.S. assistance, the fresh naval fuel storage has been secured, and the team from the U.S. Department of Energy has moved on to securing the nuclear weapons of the Russian Navy.[43] Security upgrades are planned to be installed at all 4,000 naval nuclear weapons by 2005, and work is ahead of schedule.[44]

Naval reactors and commercial reactors differ in size, number of fuel assemblies, fuel enrichment, power output, and core lifetimes. Very little is officially known about submarine nuclear-fuel designs, production technology, operational data, and naval fuel stocks. Open-source information tells us that today's Russian submarines run on fuel enriched to intermediate levels,[45] most commonly in twin reactors.

The Russian Navy has used fuel varying from slightly less than 20 percent to 90 percent U-235, depending on the specific reactor design.[46] In all, twenty-four of their reactors are believed to have been designed to use uranium enriched to 90 percent U-235.[47] A wide variety of fuel geometries and alloys have been used in naval reactors. Most Russian naval reactors today use uranium-aluminum dispersal fuel in steel or zirconium cladding; some of more the advanced or modern reactors apparently make use of cross-shaped fuel rods.[48]

More information is available on the reactors in the civilian Russian icebreaker fleet than on the military submarine reactors. The icebreaker reactors were developed in parallel with the submarine reactors, with the same reactor designs—and more space available for measurements and testing. The icebreakers were thus used as test beds for the development of submarine reactors. After the Russian icebreaker Vaygach visited the city of Tromsø in northern Norway in 1991, new technical information about the naval reactor cores was released.[49] According to the safety report of the ship, the reactor core contained 150.7 kg of U-235 enriched to 90 percent.

Alternatives for Increased Naval-Fuel Transparency and Nonintrusive Verification

Past experience indicates that an incremental approach is the best way to progress throughout the implementation processes towards bilateral or trilateral verification.[50] One approach is to use small gestures, such as creating bilateral declarations as stepping-stones to more elaborate agreements.

In the following, we will first explore the prospects of increased naval transparency through declarations, succeeded by a discussion of various possible schemes for nonintrusive verification of fresh naval fuel, to raise confidence in the declarations given. In the absence of conflicts—or the desire to create conflicts—states' nuclear activities are likely to be of a nonoffensive nature. This has the potential to make increased nuclear transparency a powerful confidence-building tool.

Transparency Through Declarations

Declarations can have an important confidence-building aspect, as an indication of good will and the revelation of nonmalicious intentions of a state. Moreover, declarations could make diversion of fissile materials for clandestine nuclear-weapon production less probable, as later stockpile discrepancies between the official statements given and independent international estimates then could arise—to the embarrassment of the state in question.

Such declarations could be part of bilateral or multilateral agreements on data exchanges on the aggregate stockpiles of fissile materials, based on existing commitments of transparency, or they could be arranged under special agreements on naval information exchange.[51] As a minimum, voluntary state transparency on fresh naval fuel could include (regular) declarations of:[52]

- Current domestic quantities of fresh HEU dedicated to naval propulsion
- National estimates of future naval HEU needs
- Fresh naval fuel, if any, withdrawn from military stockpiles and put under international control

Declarations along these lines will provide information on the total quantities of fresh HEU dedicated to naval propulsion, while protecting any detailed and possibly sensitive information regarding fuel and reactor operations. States may also be willing to declare quantities of spent naval fuel generated through naval propulsion. If so, this could allow for later comparisons of stocks of fresh and spent fuel, to substantiate the initial declarations.

Confidence in the declarations given could be boosted through nonintrusive verification throughout the naval fuel cycle. To this aspect we now turn.

Nonintrusive Naval-Fuel Verification

Technical communities are now examining a variety of nonintrusive measurements on items with sensitive or classified properties,[53] some of which may be applicable to unirradiated naval fuel. The underlying physics is well understood, but the need to protect and limit the data output while providing enough information to foster sufficient confidence in the results of the measurements raises technical challenges.

HEU measurements are likely to be more challenging than measurements of weapons-grade plutonium.[54] Less penetrating gamma emissions, a low neutron background, a ubiquitous uranium presence in all background radiation, masking weak signals, and a preference for passive measurement techniques (see below) challenge the identification of appropriate HEU verification techniques. Self-shielding of fuel assemblies could further complicate the detection of gamma rays. Moreover, even if U-235 is detected, its presence alone may not mean that the uranium is highly enriched.[55]

All this may explain why nonintrusive verification technologies so far have focused on sealed containers of plutonium in storage. However, as shown in the appendix, various schemes are available for meaningful fresh HEU measurements.

Acceptability of Technical Arms-Control Measures

Before a measurement technique can be accepted for use in an arms control agreement, all parties must agree on its use. Experience has shown that the likelihood that an arms-control technology will be accepted increases if the following points are taken into consideration:[56]

- Measurements cannot reveal classified information.
- Simple technology is preferable to complex technology.
- Familiar technology is preferable to unknown technology.
- Passive measurements are generally preferable to active interrogation measurements.

All measures should be as transparent as possible, thus the call for simplicity and familiarity. In the simplest cases, radiation emitted from the object of interest can be measured directly, through passive measures. Active measurements collect and analyze the resultant radiation after, for example, neutron bombardment. However, such measures may be overly intrusive, which would violate the primary principle of arms control verification: not to reveal any classified information. Current efforts to protect classified information include carrying out the radiation measurements behind information barriers,[57] normally in combination with a set of acceptable attributes—describing, to the extent possible and desirable, the objects in question.

Practical Approaches to Nonintrusive Naval-Fuel Verification

On the basis of the acceptability requirements above, we now turn to the applicability of and the prospects for introducing identifiable naval fuel attributes, naval fuel templates, naval fuel tagging, or tags and seal regimes on the naval fuel cycle. To protect classified information, all measures and measurements are to be performed externally to the fresh-fuel transportation containers, not directly on the fuel. For gamma detection, the signature radiation must thus be sufficiently penetrating to escape through the container wall.[58]

Naval HEU Fuel Attributes

Measurements of relevant attributes are meant to raise confidence that the measured object is what it is claimed to be, without compromising any classified or sensitive information. To be useful for arms control, the identifying criteria/acceptable characteristics should possess a set of general properties. The attribute should be:[59]

- *Relevant:* It should provide some useful distinction between items admissible.
- *Measurable:* It should be quantifiable and identifiable through the use of technology. The needed measurements should also be practicable; they should be achievable under realistic conditions in acceptably short periods of time.
- *Amenable to negotiation:* The properties and presence of the attribute itself must not be classified.
- *Limited*, or more accurately, the means for measuring the attribute should be limited, to minimize the risk that sensitive information might be divulged.

On the basis of this set of requirements, possible attributes for naval HEU fuel signatures, and candidate measurement approaches are suggested in Table 1.[60]

The attributes proposed are all relevant, yet limited in scope, as they should be for sensitive verification schemes. Moreover, the attributes are all amenable to negotiation and practicable. Taken together, they should be able to raise confidence in the presence of unirradiated highly enriched naval fuel inside transportation containers. High-resolution gamma-ray spectroscopy allows for passive measurements, using well-known techniques. To protect

Table 1. Possible attributes for fresh naval fuel

Attribute	Relevance	Signature	Measurement Approach
Presence of HEU	HEU in naval fuel	Weak gamma rays, limited neutron background	High-resolution gamma spectroscopy (HRGS)
Isotopic ratio	Determine enrichment level: Ratio of U-235 to total uranium	Specific gamma lines associated with respective isotopes	With HRGS, measure the intensity of 186 keV (U-235) and 1001 keV (U-238) gamma rays, or use the "Enrichment Meter Method"[61]
Mass (threshold)	Identify more than a trivial HEU quantity in the container	Weight	Scale; weight of transportation container with and without fuel
Presence of uranium metal	Identification of later generation Russian naval fuel with metal alloys	Gamma rays	Possibly through the absence of oxides, as this could make it easier to protect classified information
Shape and size of material	Look for defined physical properties of naval fuel	Spatial gamma rays	E.g. through axial scanning using high-resolution gamma-ray spectroscopy
Presence of radioactive contaminants	Determining unique and strong gamma rays for identification	E.g. gamma rays associated with U-232 decay (see below)	High-resolution gamma-ray spectroscopy

classified and sensitive information, the inspection measurements would have to be compared through a trusted information barrier.

Naval Fuel Templates

In contrast to the attribute approach where the measured characteristics of single items are evaluated, template approach measurements are compared with data for reference items. If the authenticity of the template can be assured, the template approach may provide higher-confidence verification, through the comparison of sensitive characteristics with sufficient precision to detect and thereby deter deception.[62] However, template comparisons require secure storage and possibly certification of a classified database, as well as the use of information barriers to protect classified information and reference data.

Profiles of gamma-ray intensities could be measured at various points along the axis of a transportation container for the naval fuel, and could then be compared directly to the template data through a trusted information barrier. Gamma-ray peaks at a number of energies, or their ratios, could also be compared with the template. However, as discussed, the Russian Navy uses fuel with a wide range of different geometries and different enrichment levels—and even with varying enrichment levels within the reactor cores (with a enrichment gradient of up to 20 percent).[63] The corresponding gamma signatures outside will vary accordingly, and a wide range of templates may be needed.

Naval Fuel Tagging

For any measurements to be meaningful, the gamma signature must be sufficiently penetrating to escape from the interior of the fuel elements and container. The radiation must also be of adequate intensity to allow measurement to be completed in a reasonable period of time. For HEU, the only signature that can meet these criteria is from gamma rays emitted by the radioactive decay of uranium isotopes. Unfortunately, as mentioned above, the signature of U-235 is so weak that simple detection of shielded HEU may be challenging.[64]

One option could be to introduce isotopes that are more easily traceable into the fuel. A wide range of isotopes and techniques may be applied, but limited effect on the fuel performance is an obvious requirement. The isotope U-232, with a highly penetrating gamma-ray decay line (2,614 KeV), is often already present in uranium fuel and is an interesting candidate. With only a 69-year half-life, U-232 does not occur in nature, but is introduced as a result of reactor irradiation of uranium.[65] In any reprocessed uranium, there will be a tiny but traceable fraction of this isotope. U-232 is found in fresh U.S. naval fuel,[66] and is likely to be a trace contaminant in fresh Russian naval fuel as well, given that the fuel originates from reprocessed uranium.

During the enrichment process, the U-232 is preferentially swept into the light isotope fraction that becomes HEU, and minuscule amounts get into the depleted uranium.[67] Therefore, the presence of U-232 in a uranium sample is consistent with that uranium being U-235. But unfortunately, the most distinctive gamma emission associated with its decay series is not unique. U-232 and Th-232 have a common daughter (Th-228), and their decay schemes are identical from that point on. Thorium could thus be placed in the container in sufficient quantities to spoof verification measurements.

However, as the decay of Th-232 involves some prominent gamma rays that are not present in U-232 decay, this problem could be bypassed by performing measurements on the Th-232 decay before Th-228 is reached.[68] With only U-232 present, no gamma rays from Th-232 decay should be detected. Therefore, with an appropriate measurement setup, decay of U-232 can probably be distinguished from decay of Th-232, making it possible to use U-232 tagging with far higher confidence.

Tags and Seals for Transportation Containers

The least intrusive approach in terms of protecting classified information may well be to introduce tags and seals on the transportation containers. Tags are meant to label an object uniquely, so that it can be identified at a later date. A seal is intended to leave unambiguous, nonerasable evidence of unauthorized access or access attempts (e.g. to open a container). It offers, however, little or no protection.[69]

A regime can thus be envisioned that uses tags and seals to ensure what is literally a closed fresh naval fuel cycle—from the transportation containers leaving the naval fuel production facilities to the destination in a naval reactor. This would require validation of the integrity of the tags and seals at designated checkpoints throughout the fuel-transportation cycle. Once the fuel is introduced into the naval reactors, tracking could end, as the radiation levels will make the fuel self-protective after the first chain reactions have been initiated in the submarine or icebreaker reactor cores. Any attempt then to divert the material for nuclear-weapon purposes would not only be very difficult, but also highly dangerous.

Assessing Approaches for Nonintrusive Naval-Fuel Verification

Several options for nonintrusive fresh naval-fuel verification techniques may be available. The pros and cons of the various techniques are discussed in the following, and summarized in Table 2.

The use of gamma spectroscopy allows for the passive identification of radionuclides. The various naval attributes may thus be identified with a set of passive measurement techniques, but this will depend on stringent uses of information barriers as the measurements may be overly intrusive. Gamma spectroscopy is used for both templates and attribute measurements. If the attribute approach is chosen, all parties involved should devise the naval fuel attributes jointly, together with proper measurement and inspection procedures that will have to be negotiated and formalized.

The wide range of enrichment levels and different fuel designs may require a disproportionately huge number of fuel templates to be available. This is likely to complicate compar-

Table 2. Nonintrusive verification techniques for naval fuel

	Pros	Cons	May be used successfully in combination with	Remarks
Attributes	Passive measurements; fairly well-known concept	May be too intrusive. A set of measurable attributes is needed to gain confidence. Hard to measure HEU directly.	Tagging: presence of high-energy isotopes a distinct attribute	Relies on information barriers and high-resolution gamma-ray spectroscopy
Templates	Passive measurements No agreed values for measured characteristics Fairly robust and easily operated system, once installed	A wide variation of fuel-enrichment levels may require multiple templates The need for authentication requires additional schemes for protection of equipment during storage	Tagging: presence of high-energy isotopes eases the identification and comparisons	Relies on information barriers and high-resolution gamma-ray spectroscopy
U-232 tagging	Unique U-235 identifier	Needs to be introduced in HEU sample Resulting and highly penetrating gamma ray is not unique to U-232	Templates and attributes	Isotope does not occur naturally. Traces will be found in all reprocessed uranium fuel.
Tags and Seals	Fairly easy to implement, no need for information barriers	May provide a false sense of security; heavily dependent on procedural solutions	All the above	More a supplement than a stand-alone element

isons; and, as with the attribute approach, a trusted information barrier is required for template comparisons.

Support for any of the above schemes is likely to be boosted through a combination of an additional set of supportive measures. In this context, U-232 tagging appears particularly attractive. As the isotope U-232 is a reliable U-235 indicator, U-232 tagging may boost confidence in both attribute and template measurements. However, the fact that the most-penetrating gamma radiation is not unique to the isotope U-232 complicates measurement setups.

The introduction of tamper-indicating devices on naval fuel transportation containers may support verification and control. A tamper-indicating system on fresh naval-fuel transportation containers is fairly easy to piece together, at least in theory. In practice, however, the limitations and fallibility of tamper-detection tags and seals should be taken into account when designing verification systems.[70] The effectiveness of a tag-and-seal regime will depend heavily upon the appurtenant inspectoral procedures and the degree of surrounding hostility.

In reality, there is no such thing as *tamper-proof* tags and seals,[71] so tags and seals should be viewed as only part of an overall security or verification program. Practical vulnerability assessments should be conducted taking the relevant and specific applications, purposes, environment, economics, personnel, training, adversaries, and defeat consequences into consideration.[72] The integrity of tags and seals could be strengthened by introducing (protected) live video feed at different locations throughout the fuel transfer.

Conclusions

Keeping a massive shroud of secrecy on naval nuclear-fuel stockpiles can only maintain and exacerbate excessive uncertainties in fissile material stockpile accounting and control. This is not likely to be beneficial to the security of any state. Options for increased transparency of and nonintrusive verification on proliferation-attractive naval-fuel stocks should thus be explored.

We have seen that a set of fairly simple and technically available nonintrusive verification measures for naval fuel cycles are possible without compromising national security needs and legislation. If implemented, such measures could raise confidence that naval fuel is not being diverted for weapon purposes, and could help establish an international transparency norm for naval fuel cycles.

Declarations of quantities of HEU destined for naval propulsion could be a starting point for increased transparency and thus more credible and accurate estimates of navies' HEU stocks, consumption, and future needs. Confidence in such declarations could be boosted through a range of techniques for nonintrusive verification of sensitive naval nuclear-fuel cycles. Most promising appears to be the attribute approach, possibly coupled with fuel tagging (U-232).

There might be important synergistic effects between nonintrusive verification of naval fuel and ongoing warhead dismantlement verification. The attribute approach is, for instance, an important part of the trilateral initiative between the United States, Russia, and the International Atomic Energy Agency (IAEA) for control of fissile material declared excess to national

security needs. Experience from naval-fuel transparency and nonintrusive verification may provide important feedback for improved HEU weapons dismantling activities and third-party control of weapons-usable fissile material as well.[73]

To optimize naval transparency and nonintrusive verification, more R&D and increased information sharing are needed in several areas. Firstly, to avoid spoofing—or suspicion of spoofing—measurement procedures and techniques should be developed carefully and jointly by all interested parties. Procedures for the use of HEU detection equipment have been developed under past bilateral nuclear arms control agreements, and the operational experience from these trails could prove valuable.[74] Secondly, more knowledge on fresh Russian naval fuel is required to determine the best attributes and tags for fuel identification and control. Thirdly, more information is needed on the transportation containers used for fresh naval fuel to permit best possible external gamma-ray attenuation estimates and optimal uses of passive detectors in combination with information barriers.[75]

Problems in the practical implementation of the proposed nonintrusive verification schemes should be anticipated. There are several *real-world constraints* to overcome. These include, apart from the obvious issues of classification and sensitivity, possible impact on operational activities at the naval bases and the need for new working procedures. Distrust and cultural differences may require a shift in attitudes and mindsets before any type of transparency can be successfully implemented.[76] Reciprocity and increased openness with regard to the fuel practices of the U.S. Navy may, moreover, be not only desirable but also a prerequisite for genuine Russian openness on their naval fuel cycles.

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Appendix

Nonintrusive, Nondestructive Measurements of Fresh, Shielded HEU

The determination of enrichment of uranium has long been a challenging task. Typically during nondestructive analysis, the 187 keV from the decay of U-235 (4.3x104 (/s/g) and/or the 1,001 keV line from U-238 decay (75 (/s/g) are used. The 187 keV line is weakly penetrating (half thickness of Pb approximately 0.5 mm) and can easily be lost in the background if other strong gamma emitters such as fission products and activation products of higher energy are present. The 1,001 keV line is more penetrating (half thickness of Pb about 9.1 mm) but the specific yield is low so that it can suffer similar problems, particularly in the case of HEU when the ratio of U-238 mass to U-235 mass is low. Because of these characteristics, large errors can be introduced when the detector-sample geometry is altered only slightly, when the performance of the detector changes or when the homogeneity, chemical composition or the filling height of the sample differ from the calibration standard.[77]

In the past, gamma-ray measurement outside transportation containers was feasible with a multiple detector setup and ideal (laboratory) conditions for simultaneous energy measurements.[78] Recent developments in detector and shielding technology and software, however, now allow for reliable and portable single-set gamma-ray spectrometry of shielded uranium samples *in situ*.[79]

Equipment

The Canberra InSpector system could be one option for nonintrusive, nondestructive shielded HEU measurements. Using calibration sources, the resulting energy shape-calibration factors take into account the particular form of uranium used, as well as up to two separate container walls of different density and thickness.[80] For such measurements, the thickness of the attenuators between the source and the detector should be reduced as much as possible to allow good measurement precision. Maximum sample wall thickness for confirmatory measurement on fresh HEU is reported to be between 5 to 15 mm of steel.[81] This appears to be the thickness range of the Russian transportation containers for fresh, unirradiated HEU fuel.[82]

According to manufactures and current users (e.g., the IAEA), the Canberra system provides a gamma spectrometer that is portable, rugged, simple to operate, delivering uranium-enrichment analysis capability with a high degree of automation. All the hardware and software features allow for simplification of the counting procedures, so that the equipment may be operated with a minimum of training for all major international safeguards requirements for years to come.

HEU Weapon Component Measurements

The United States and Russia have already conducted bilateral and joint measurements on classified weapons components. These, and in particular the HEU weapon-component measurements performed at Oak Ridge in November 1996 and August 1997, could provide an important platform for additional HEU transparency measures.[83] The first measurements aimed at demonstrating the receipt of a weapons component, the presence of HEU, and the confirmation that two sealed components are identical. Later measurements conducted in 1997 were designed to demonstrate the conversion of a HEU component into metal shavings behind a metal barrier.

Moreover, ongoing transparency measurements under the U.S.-Russian HEU agreement may provide particularly valuable insights for nonintrusive verification of the fresh naval fuel.[84] The initial detector system using high-purity germanium detectors has been discarded in favor of sodium iodine detectors for enrichment determination because the former may reveal sensitive information. After the initial two years of operation, all measurements under the HEU agreement have been consistent with the declared HEU enrichment levels.[85]

Notes and References

1. Frank von Hippel of Princeton University, Tor Woehni of the Norwegian Radiation Protection Authority, and Eirik Gundersen of Laborel AS provided useful input during the preparation of this article. The comments of an anonymous reviewer helped improve the paper notably. Special thanks also to Dmitri Petrov for directing me to open-source information on Russian HEU transportation containers. Responsibility for any mistakes or inaccuracies rests, of course, with the author. This article builds upon my two papers, "Fresh Look at Highly Enriched Uranium for Naval Propulsion and Associated Proliferation Risks," and "Transparency Technologies and the Naval Nuclear Fuel Cycle," presented at the INMM annual meetings in 2000 and 2001 respectively.
2. The proposals included the creation of a strategic reserve in the United States from Russian HEU down-blended into low-enriched uranium (LEU); an increase in the rate and quantity of HEU converted to LEU under the Nuclear Material Consolidation and Conversion Project; the use of LEU down-blended from Russian HEU to fuel reactors in Western countries; the use of Russian HEU to fuel selected U.S. research reactors, until cores are converted to LEU, and in parallel, work on accelerated development of LEU fuel for both Soviet-designed and U.S.-designed research reactors. See U.S., Russia Identify New Ways to Reduce Excess Nuclear Materials, *The Washington File*, September 16, 2002, http://usinfo.state.gov/topical/pol/ arms/02091703.htm.
3. According to official statements in conjunction with the launching of the September 2002 initiative.
4. Boutwell, J., F. Calogero, and J. Harris. 2002. Nuclear Terrorism: The Danger of Highly Enriched Uranium (HEU). *Pugwash Issue Brief*, vol. 2, no. 1.
5. The United Kingdom is a noteworthy exception, having declared the total size of its stockpiles of uranium (and plutonium) held outside international safeguards.
6. Albright, D., W. Walker, and F. Berkhout. 1997. *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies.* New York: Oxford University Press.
7. All U.S. and British nuclear-powered ships and submarines are fueled with weapons-grade uranium, and all Russian nuclear-propelled submarines today use highly enriched uranium (HEU). France and China use LEU in their submarines. The total HEU naval requirements for the United States and Russia are 1-2 tons a year for each country, and for Britain, 0.1-0.2 tons a year. H.A. Feiveson (ed.). 1999. *The Nuclear Turning Point.* Washington: Brookings Institution Press.
8. Ibid.
9. Hibbs, M. Czech Find May Be Re-Enriched Repu to Naval Fuel or Research Reactors. *Nuclear Fuel*, vol. 20, no.1.
10. Or they, as in the case of India, remain outside the NPT.
11. Feiveson, H. A. (ed.), 1999. *The Nuclear Turning Point*. Washington: Brookings Institution Press.
12. Maerli, M. B. 2002. Components of Naval Nuclear Fuel Transparency. *NATO-EAPC Research Fellowship Report*. June 2001, updated and published by the Norwegian Institute of International Affairs, June 2002. NUPI Report 269, http://www.nato.int/acad/fellow/99-01/maerli.pdf.
13. The 2002 Moscow SORT treaty increases the incentives for assuring that all stocks of fissile material are accounted for. However, the treaty includes no provisions for mutual inspection and verification, nor does it require the actual destruction of a single missile or warhead. Rather, each country may warehouse its weapons and redeploy them later. As Wood et al. therefore correctly point out, due to the controversy of the irreversibility of the reductions under the treaty, "the time is now ripe for increased transparency measures on both sides of the U.S.-Russian relationship." Wood, T. W., B. D. Reid, J. L. Smoot, and J. L. Fuller. 2002. Establishing Confident Accounting for Russian Weapons Plutonium. The *Nonproliferation Review,* vol. 9, no. 2.
14. Maerli, M. B. 2002. U.S.-Russian Naval Security Upgrades: Lessons Learned and Future Steps. *Yaderny Kontrol*, no. 4, June 17.
15. To the extent that nonintrusive verification of spent fuel, e.g. the back end of the fuel cycle, is contemplated, this is done only to support substantiate verification and transparency measures introduced at the front end of the fuel cycle.
16. Boutwell, J., F. Calogero, and J. Harris, 2002. Nuclear Terrorism: The Danger of Highly Enriched Uranium (HEU). *Pugwash Issue Brief*, vol. 2, no. 1.
17. von Hippel, F. 2001. Recommendations for Preventing Nuclear Terrorism. *FAS Public Interest Report*, vol. 4, no. 6, November/December 2001, p. 1; and Maerli, M. B. 2000. Terrorists and Crude Nuclear Devices. Paper presented at the Pugwash Workshop on Tactical Nuclear Weapons, Sigtuna, Sweden, May 24-25.
18. Bukharin, O., and P. William, 1995. Potatoes were guarded better. *The Bulletin of Atomic Scientists*, vol. 51. no. 3, May/June. The authors assume that one would need about 12 kg of weapons-grade uranium to produce an implosion-type nuclear device and that much as 300 kg of U-235 is available in the reactor cores.
19. Maerli, M. B. 2002. U.S.-Russian Naval Security Upgrades: Lessons Learned and Future Steps. *Yaderny Kontrol*, no. 4, June 17.
20. An exception to this rule is the new Forschungsreaktor München-II, FRM-II. See Glaser, A. 2002. Bavaria bucks ban. *The Bulletin of the Atomic Scientists*, March/April.
21. For an informative update on U.S.-Russian efforts to convert research reactors to LEU, see Bukharin, O., C. Fieck, and M. Roston, 2002. U.S.-Russian Reduced Enrichment for Research and Test Reactors (RERTR) Cooperation. *Ransac*

Policy Update (Summer). Chunyan Ma and Frank von Hippel make an interesting case for ending the production of HEU for naval propulsion. See Ma, C., and F. von Hippel. 2001. Ending the Production of Highly Enriched Uranium for Naval Reactors. *The Nonproliferation Review,* vol. 8, no. 1. The authors argue, convincingly, that there is enough HEU available from nuclear-weapons stocks to fuel naval reactors during a transition period of several decades, before new reactor technology is developed. According to Ma and von Hippel, future naval reactors could be fueled with LEU without significantly increasing the size of the nuclear submarines, reducing their power, or giving up the technical advantages of lifetime cores.

22. Fetter, S. 1996. Verifying Nuclear Disarmament, *Occasional Paper,* no. 29. The Henry L. Stimson Center.
23. Fetter, S. 1999. A Comprehensive Transparency Regime For Warheads and Fissile Materials. *Arms Control Today*, January/February 1999.
24. In fact, the U.S. Navy proceeds in an extremely cautious manner, keeping all its fissile material usable for naval propulsion in military reserve. With the exception of the first 10 tons declared excess, all the HEU that the United States has declared as excess failed to meet the specifications for use in naval fuel. Yet, the U.S. Navy maintains a right to withdraw any excess material they may need from international safeguards. Bunn, M. 2000. *The Next Wave: Urgently Needed New Steps to Control Warheads and Fissile Material*, p. 54;and Albright, D., W. Walker, and F. Berkhout, 1997. *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies.* New York: Oxford University Press, p. 93.
25. Maerli, M. B. 2000. Deep Seas and Deep-Seated Secrets: Naval Nuclear Fuel Stockpiles and The Need for Transparency. *Disarmament Diplomacy,* no. 49, August 2000. http://www.acronym.org.uk/dd/dd49/49fuel.htm
26. Ma, C., and F. von Hippel. 2001. Ending the Production of Highly Enriched Uranium for Naval Reactors. *The Nonproliferation Review,* vol. 8, no. 1 (Spring).
27. In addition to the Akula-class submarine, the $3 billion package includes the mothballed 44.5-thousand ton aircraft carrier, Admiral Gorshkov. See Josh, M. 2003. Russia gives nuclear edge to Indian defense. *Times of India,* 18 January. http://timesofindia.indiatimes.com/cms.dll/html/comp/articleshow?artid=34743016&sType=1.
28. Maerli, M. B. 2002. U.S.-Russian Naval Security Upgrades: Lessons Learned and Future Steps. *Yaderny Kontrol*, no. 4, June 17.
29. The Center for Strategic and International Studies. 2000. *Managing the Global Nuclear Materials Threat.* Washington D.C..
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31. This confusion and the differences between transparency and nonintrusive verification are further discussed in Maerli M. B., and R. G. Johnston. 2002. Safeguarding This and Verifying That: Fuzzy Concepts, Confusing Terminology, and Their Detrimental Effects on Nuclear Husbandry. *The Nonproliferation Review,* vol. 9, no. 1 (Spring).
32. Mitchell, R. B. 2000. Sources of Transparency: Information Systems in International Regimes, in B. I. Finel and K. M. Lord (eds). 2000. *Power and Conflict in the Age of Transparency*. New York: Palgrave, p. 189.
33. As verification could give "specific, yet limited knowledge" about selected nuclear facilities and activities, transparency could provide a set of more holistic and "permitted knowledge." See e.g. The Center for Strategic and International Studies. 2000. *Managing the Global Nuclear Materials Threat.* Washington DC. p. 54. As such, verification and transparency play different roles in contemporary nuclear arms control. Put together, they may be mutually reinforcing. Transparency is a prerequisite for verification (as one needs to know what to verify), and verification should clear away some of the opacity often surrounding nuclear activities.
34. Based on Finel B. I. and K. M. Lord (eds). 2000. *Power and Conflict in the Age of Transparency.* New York: Palgrave, p. 3.
35. Senazaki, M. et al. Joint DOE-PNC Research on the Use of Transparency in Support of Nuclear Nonproliferation, pp. 2-3. Thus, transparency is more than a mere description or detailed specification of a nuclear program, specific site, or ongoing activity, and more than merely providing data mandated by treaty or law.
36. There may, however, be exceptions. A state could for instance put up a camera at decommissioned nuclear facilities and publish the pictures on the Internet, to increase international confidence that no nuclear weapons production was clandestinely taking place at the plant.
37. Descriptively, such activities have been denoted "information triangulation" by Ronald Mitchell. See Mitchell, R. B. 2000. Sources of Transparency: Information Systems in International Regimes, in Finel and Lord (eds). 2000. *Power and Conflict in the Age of Transparency,* p. 189.
38. The outcome of the 2000 Nonproliferation Treaty Review Conference may be indicative of a trend towards transparency. For the first time, the final document from a review conference calls upon nuclear-weapon states to "increase the transparency with regard to their nuclear weapons capabilities." NPT/CONF. 2000/28 (vol. I, Part I and II) *Final Document 2000 Review Conference of the Parties to the Treaty on the Nonproliferation of Nuclear Weapons,* Article VI and preambular paragraphs 8 to 12.
39. For an excellent discussion on contemporary nuclear trans-

parency issues, see Zarimpas, N. (ed.). 2003. *Transparency in Nuclear Warheads and Materials. The Political and Technical Dimensions.* SIPRI, Oxford University Press.

40. Nongovernmental organizations, national governmental organizations within and outside of Russia, and international governmental organizations have prepared detailed analyses of the fuel life cycle, locations, and quantities of materials, enrichment estimates, and current state regarding disposal. Relevant examples include the following: Bøhmer, N. et al. 2001. The Arctic Nuclear Challenge. *Bellona Report,* vol. 3, 2001, http://www.bellona.no/en/international/russia/waste-mngment/21133.html. The IAEA Contact Expert Group, 2001. *Working Paper on the Management of Spent Nuclear Fuel in Submarines and Service Vessels,* Vienna; and the Advanced Technology Research Foundation. 2002. *Analysis of Radioecological Site, Development of Concept of the Ecological Monitoring and Creation of an Automated Control System Over the Ecological Safety of Units and Installations Involved in Nuclear Submarine Handling After the Decommissioning in Northwest Region of Russia,* November 2002.
41. Bøhmer, N., et al. 2001. The Arctic Nuclear Challenge. *Bellona Report,* vol. 3, http://www.bellona.no/en/ international/russia/waste-mngment/21133.html.
42. The 90-percent HEU found in Russian spent fuel from liquid-cooled alpha-class submarines is contained within a solidified block of Pb-Bi. This HEU is thus likely to pose a much lesser proliferation threat than the same HEU content being removed from the nuclear icebreakers. Fresh fuel for Russia's nuclear icebreakers is stored onboard the service ship Imandra, which has its homeport at Atomflot. The fresh fuel for the military vessels is stored in a newly-built storage close to Sevromosk. There is also storage of fresh nuclear fuel at the shipyard in Severodvinsk and on the two service ships of the PM 2020 type (one is based in Severodvinsk and on at the shipyard in Polyarny). Bøhmer, N., et al. 2001. The Arctic Nuclear Challenge. *Bellona Report,* no. 3.
43. Maerli, M. B. 2002. U.S.-Russian Naval Security Upgrades: Lessons Learned and Future Steps. *Yaderny Kontrol,* no. 4, June 17.
44. Spencer, A. 2002. Remarks given at the Carnegie International Nonproliferation Conference, Washington, D.C., November 14-15, 2002.
45. For an overview of Russian and other nuclear propelled vessels, see the database of the Center for Nonproliferation Studies, Monterey Institute of International Studies. http://www.nti.org/db/nisprofs/russia/naval/subtable.htm.
46. Sukhoruchkin, V. 1996. United States-Russian Laboratory-to-Laboratory Cooperation on Protection, Control, and Accounting for Naval Nuclear Materials. *Proceedings of the 37th Annual Meeting of the Institute of Nuclear Material Management.* However, the Lenin, the first nuclear-powered icebreaker, was run on fuel enriched to only 5 percent.
47. Bukharin, O. 1996. Analysis of the Size and Qualities of Uranium Inventories in Russia. *Science and Global Security,* vol. 6.
48. Handler, J. 1995. Russian Naval Reactor Characteristics. Unpublished paper. December 29.
49. As a precondition for entering the harbor, the Safety Report of Sevmorput—Information of Safety of Icebreaker—Transport Lighter/Containership with Nuclear Propulsion Plant Sevmorput, approved by the Register of Shipping of the USSR (undated)—was handed over to Norwegian Radiation Protection Authorities.
50. In the ABACC process between Argentina and Brazil, these actions conveyed strong political will and provided assurances to the public. See Kim, B. K., and D. Albright. 2001. Building Nuclear Confidence on the Korean Peninsula. *Proceedings of the July 23-24, 2001 Workshop Sponsored by the Technology Center for Nuclear Control and the Korea Institute for National Unification,* p. 87. http://www.isis-online.org/publications/dprk/wrapup.pdf.
51. Formalized agreements already exist for some fissile material stockpile declarations. One example is the guidelines agreed to by the five declared nuclear-weapon states under the NPT, together with Belgium, Germany, Japan, and Switzerland, to increase transparency in the management of civil plutonium by publishing annual statements of each country's holdings of civilian plutonium. In 1998, the IAEA published its *Guidelines for the Management of Plutonium* (INFCIR/549).
52. For a somewhat related set of recommendations for nuclear disarmament, see Fetter, S. 1996. Verifying Nuclear Disarmament. *Occasional Paper* no. 29. The Henry L. Stimson Center. Moreover, the idea of an agreed amount of HEU that could be produced and safeguarded at (then operational) enrichment plants was proposed by von Hippel, F., and B. G. Levi. 1986. Controlling Nuclear weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons, in Tsipis, et al. (eds.). *Arms Control Verification—Technologies That Make it Possible.* Pergamon-Brassey's International, p. 367.
53. For an overview, see e.g., U.S. Department of Energy. 2001. *Technology R&D for Arms Control. Arms Control and Nonproliferation Technologies.* Office of Nonproliferation Research and Engineering. Spring 2001.
54. Because of their robustness and accuracy (with a low incidence of false results), the fact that they do not require representative standards for calibration and therefore may be authenticated using unclassified sources, and because they are familiar IAEA inspection techniques, high-resolution gamma-ray spectroscopy or neutron-multiplicity counting are attractive passive measurement techniques for nuclear material. From N. J. Nicholas, et al., 2000. Attribute

Verification for Classified Fissile Material. *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Material Management.*

55. The signature of U-235 is so weakly penetrating that simply detecting shielded HEU, let alone quantifying it, can be nearly impossible. Gosnell, T. B. 2001. Determining the Presence of HEU with Passive Detection Methods, in *Technology R&D for Arms Control, Arms Control and Nonproliferation Technologies,* Office of Nonproliferation Research and Engineering. Spring 2001, p. 46.
56. Gosnell, T. B. 2000. Uranium Measurements and Attributes. *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Material Management,* and Preprint UCRL-JC-1394450, Lawrence Livermore National Laboratory, July 2000.
57. Generally, an information barrier must both prevent the release (accidental or intentional) of any classified information, and at the same time provide confidence that the measured systems are functioning correctly and that the unclassified display (output) reflects the true state of the measured item. This is often referred to as the "authentication problem." An attribute measurement system with the successful use of information barriers was shown to a Russian audience by U.S. scientists in August 2000. See MacArthur, D. 2001. Attribute Measurement System with Information Barrier Technology. *Technology R&D for Arms Control. Arms Control and Nonproliferation Technologies,* Spring 2001, p. 15, or Langner, D. G., D. W. MacArthur, N. J. Nicholas, R. Whiteson, T. B. Gosnell, and J. Wolford, 2000. Progress Towards Criteria for A Second-Generation Prototype Inspection System with Information Barrier for the Trilateral Initiative. Los Alamos Report LA-UR-00-3048, and *Proceedings of the 41st Annual Meeting of the Institute of Nuclear Material Management.*
58. Naval fuel with lower enrichment levels is likely to be more detectable, due to the higher presence of the isotope U-238 (with more penetrating gamma rays).
59. Johnson, W. M. 2000. Attributes and Thresholds in Measurements for Transparency Initiatives. *Proceedings of the 41st Annual Meeting of the Institute of Nuclear Material Management.*
60. The scheme is based on equivalent approach proposed for plutonium, by Nicholas, N. J., B. l. Fearey, J. M. Puckett, and J. W. Tape. 1998. Verification of Classified Fissile Material Using Unclassified Attributes. *Proceedings of the 39th Annual Meeting of the Institute of Nuclear Materials Management,* and *Los Alamos National Laboratory Report* LA-UR-98-3036.
61. See e.g., Decman, D. J., J. Glaser, J. M. Hernandez, and S. J. Luke. 1999. Portable NDA Equipment for Enrichment Measures for the HEU Transparency Program. *Proceedings of the 40th Annual Meeting of the Institute of Nuclear Materials Management.*
62. Kane, W. R., J. R. Lemley, P. E. Vanier, P. B. Zuhoski, and L. Forman. 2000. On Attributes and Templates for Identification of Nuclear Weapons in Arms Control. *Proceedings of the 41st Annual Meeting of the Institute of Nuclear Materials Management.*
63. Personal communication with personnel of the Russian icebreaker fleet, February 1996.
64. Gosnell, T. B. 2000. Uranium Measurements and Attributes. *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Material Management,* and Preprint UCRL-JC-1394450, Lawrence Livermore National Laboratory, July 2000.
65. For a description of the decay chains, see e.g., Peurrung, A. J. 1998. *Predicting U-232 Content in Uranium.* Pacific Northwest National Laboratory, December.
66. Personal communication with an anonymous source March 2000.
67. Depleted uranium will typically contain 1,600 to 8,000 times less U-232 than HEU does. From Peurrung, op.cit.
68. I am indebted to an anonymous reviewer for this point.
69. Johnston, R. G. 2001. Tamper Detection for Safeguards and Treaty Monitoring: Fantasies, Realties, and Potentials. *The Nonproliferation Review,* vol. 8. no. 1.
70. Ibid
71. Ibid.
72. Johnston, R. G., and A. R. E. Garcia. 1997. Simple, Low-Cost Ways to Dramatically Improve the Security of Tags and Seals. *IAEA Symposium on International Safeguards, Vienna,* October 1997.
73. The positive effects of looking at different nonintrusive verification schemes in parallel have been underlined by, for instance, Pura, C. 2000. Update on Technology to Support Arms Control and Transparency Initiatives. Talk presented at Sandia National Laboratories, California, December 14, 2000.
74. Radiation detection inspections, e.g. under the INF and START treaties, have shown that the equipment is rugged, transportable, and weather-resistant. Bukharin, O., and J. Doyle, 2002. Transparency and Predictability Measures for U.S. and Russian Strategic Arms Reductions. *The Nonproliferation Review,* vol. 9. no. 2.
75. Relevant nonsensitive information needed includes, for instance, the number of fuel assemblies in each container, and container structure, thickness and materials.
76. The implementation of transparency and nonintrusive verification schemes could build upon the working relations and trust established during the successfully completed U.S.-Russian naval fuel MPC&A upgrades. See Maerli, M. B. 2002. U.S.-Russian Naval Security Upgrades: Lessons Learned and Future Steps. *Yaderny Kontrol,* no. 4, June 17.
77. Canberra. (undated). U-Pu InSpector: A Dedicated

Instrument for Assessing the Isotopic Composition of Uranium and Plutonium. Application Note.

78. See e.g., Spinkle, J. K. and L. A. Stovall. 1989. *HEU Drum Monitor Manual (for Confirmatory Measurements).* Los Alamos National Laboratory, LA-11517-M, UC-15, June.
79. The Inspection Multi-Channel Analyzer is an example. See Gardner, G. H., M. Koskelo, RL Mayer II, B. R McGinnis, M. Moslinger, B. Wishard. 1996. The IMCA: A field Instrument for Uranium Enrichment Measurements. *Proceedings of the 37th Annual INMM Meeting.*
80. Ibid.
81. Canberra. (undated). U-Pu InSpector: A Dedicated Instrument for Assessing the Isotopic Composition of Uranium and Plutonium. Application Note.
82. No information seems to be openly available on fresh naval fuel transportation containers. However, other fresh HEU material is transported in vessels with a hollow cylindrical structure, externally and internally lined with sheets of steel. Reportedly the thickness of a steel sheet is 5 mm. Tokarenko, A., N. S. Tikhonov, V. V. Morozov, V. M. Dubrovsky, and A. L. Lazarev. 1995. Design Nuclear Power Engineering Institute (VNIPIET), St. Petersburg Transportation of Highly Enriched Fissile Materials in Russia, *Third U.S.–Russian Workshop on Non-Reactor Nuclear Safety Proceedings.* Los Alamos National Laboratory, Los Alamos, New Mexico. August 14-19. http://plutonium-erl.actx.edu/thirdusruss.html.
83. Based on Andrew Bieniawski's "Historical Review", as presented in Table 3 in Bukharin, O., and J. Doyle. 2002. Transparency and Predictability Measures for U.S and Russian Strategic Arms Reductions. *Nonproliferation Review,* vol. 9, no. 2, Summer 2002, p. 89.
84. On February 18, 1993, the United States and Russia signed the "Megatons-to-Megawatts" agreement. Spanning twenty years, the $8 billion HEU deal sets out to convert 500 metric tons of highly enriched uranium (HEU) from dismantled Russian nuclear warheads into low-enriched uranium (LEU) suitable for U.S. commercial reactors.
85. Portable instruments determine the level of U-235 enrichment of metal chips that results from the machining of the HEU metal components from the weapons.

An Approach for Depleted and Low-Enriched Uranium Verification by Passive γ- and X-Ray

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Abstract

Tons of depleted uranium (DU) are generated every year as a byproduct of enrichment processes. DU is a safeguarded nuclear material subject to accounting and verification everywhere. Verification of DU and low-enriched uranium (LEU) in a high background and with interferences decreases the reliability and performance of the measurements.

This paper introduces an approach to verify depleted and low-enriched uranium based on γ-γ and x-γ ray ratios. This is to eliminate any interference and contribution to the 185.7 keV of ^{235}U. The results show that the γ-γ- ratios, 185/766,143/1,001 and 205/1,001, can be used for verification of depleted and low-enriched uranium with high accuracy. The suggested 98 keV of U X-ray and the 98/1,001 x-γ ray ratio were also found to be very efficient for the accountancy of the investigated nuclear materials.

Introduction

The products of the enrichment process are the enriched material itself and the depleted uranium, sometimes called enrichment tails.[1] Typically, enrichment tails have in the neighborhood of 0.2 percent to 0.3 percent ^{235}U remaining.[1] DU can also be produced from reprocessing spent-nuclear fuel. The present production of DU is ~ 47,000 metric tons per year, but the combined nuclear and non-nuclear consumption is less than 1,000 metric tons per year.[2] It is used extensively as ballast in ships and aircraft, as armor piercing munitions, and as reinforced tank armor. The Gulf War was the arena for the first battlefield use of armor-piercing munitions and reinforced tank armor incorporating DU.[3] Verification of DU and LEU with high accuracy is a very essential task for nuclear material safeguards. Elimination of all sources of interferences, especially in case of DU and LEU, results in increasing the effectiveness and efficiency of the measurements.

This work was initiated to establish an approach to verify depleted and low-enriched uranium to avoid any interference with the 185.7 keV of ^{235}U. Different γ, x, γ/γ and x/γ ray ratios are suggested to achieve this objective.

The Characteristic Gamma and X-Ray Transitions of Uranium and Its Daughters

The daughters of uranium are generated from the following nuclear decay chain:

$$^{238}\mathrm{U} \xrightarrow{\alpha} {}^{234}\mathrm{Th} \xrightarrow{\beta} {}^{234m}\mathrm{Pa} \xrightarrow{\beta} {}^{234}\mathrm{U}$$

Some steps in processing uranium can upset the decay equilibrium causing the 24.1-day half-life of ^{234}Th to control the growth of the ^{234m,234}Pa activity to equilibrium, which is normally reached in about 160 days (99 percent).[4]

The essential and characteristic gamma-ray lines of uranium and its daughters are given in the Table 1.[4,5]

Table 1. The gamma transitions of uranium and its daughters

Isotope (Half- life)	^{235}U (7.1x 108 yr.)	^{226}Ra (1,600 yr.)	^{234}Pa (6.7 hr.)	^{234m}Pa (1.2 min.)
Energy (keV)	143 (10.96 percent)		143.8 (.00051 percent)	766.4 (.294 percent)
	163 (5.08 percent)		164.9 (.00008 percent)	786 (.0485 percent)
(Intensity percent)	185.7 (57.2 percent)	186 (3.50 percent)	186.2 (0.00282 percent)	1,001 (.837 percent)
	205 (5.01 percent)		203.1 (.00196 percent)	

The characteristic X-rays of uranium that may be correlated with enrichment verification are given in the Table 2.[4,5]

The X-ray peaks (e.g. 98 keV) are due primarily to self-induced fluorescence of the uranium sample.[6] The 98 keV X-ray and 185.7keV gamma ray can be used for total uranium concentration and enrichment determination.[6,7]

Set-Up of the Gamma Spectrometer

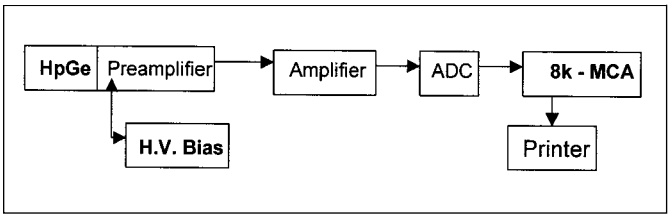
The isotopes of uranium emit α, β, n, and γ radiation. The primary radiation used in passive nondestructive assay (NDA) of

Table 2. The characteristic X-ray of uranium

Assignment	Energy (keV)	Intensity (percent)
U Ka1	98.4	45.1
U Ka2	94.6	28.2
U Ka1	111.3	10.70

uranium samples is gamma radiation, which is usually dominated by emissions from ^{235}U decay. The 185.7 keV gamma ray is the most frequently used signature to measure ^{235}U enrichment.[4] In this work, a nondestructive gamma spectrometer based on a hyper-pure germanium detector with its electronic components was used. The setup of the spectrometer used is given in the Figure 1. The system has a 40 percent efficiency with 0.85 keV FWHM resolution at the gamma transition 122 keV of ^{57}Co. The system was calibrated before measurements by using standard sources. A collimator and 3-cm lead shield were used to fix the geometrical conditions (e.g., the visible volume of the samples) of the measurements and to reduce the external background. A set of nuclear materials from depleted (0.31 percent) to low-enriched uranium (4.46 percent) was used to carry out these analyses. The nuclear materials under investigation are contained in 70-mm diameter cylindrical Al cans with 2 mm bottom wall thickness. Each sample is made up of 200 gram U_3O_8 powder with a density of 5.2 g/cm^3. The counting time was 1,000 seconds.

Figure 1. Set-up of the gamma spectometer



Results and Discussion

The 185.7 keV line of ^{235}U is the most prominent single gamma ray from any uranium sample that is enriched above natural ^{235}U levels.[4] The relationship between the gamma line at 185.7 keV (57 percent intensity) of ^{235}U and enrichment percentage of the investigated nuclear material samples is given in Figure 2. It should be noted that there are several ^{238}U daughters with gamma rays of very low intensity (branching ratio) with energies in the range 185 ± 1 keV (see Table 1). Although these are potentially direct interferences to the 185.7 keV gamma ray of ^{235}U, the intensities are low enough that the interference is negligible for enrichment of ≥ 1 percent.[4,5]

The gamma transition at 163 keV (5 percent) from ^{235}U gives no strong correlation for enrichment verification as an alternative to the 185.7 keV transition. (See Figure 3.) This may be attributed to its low intensity. It was observed that the 143 keV line (10.9 percent) of ^{235}U can be used for enrichment verification of the investigated nuclear materials; from natural (0.71 percent) to low-enriched uranium (4.46 percent). However, it does not give accurate results for depleted uranium (0.31 percent) verification. This may be attributed to attenuation of the less energetic 143 keV gamma line.

As a new approach, it was observed that the ratio of 185.7/766.4 gamma-line intensities from $^{235}U/^{234m}Pa$ can be used for determining the enrichment percentage even in the case of depleted uranium. As given in Table 3, the depleted uranium was accurately verified with 6 percent uncertainty.

Table 3. Results of depleted uranium verification

Material	Certified	Measured	Diff.	Uncertainty
U_3O_8 standard	0.31	0.29	0.02	6 percent

In general, the energy difference between the ^{234m}Pa (^{238}U) gamma rays and the 186 KeV ^{235}U gamma ray necessitates a significant correction for the different relative detection efficiencies.[4] The feasibility to directly extract the information of gamma-ray absorption (self-absorption) of sample for isotopic composition calculation has recently been studied.[8]

The intensity ratios of the 205/1,001 and 143/1,001 gamma lines from $^{235}U/^{234}Pa$ were found to be usefull for enrichment verification of natural and low-enriched uranium only. See figures 5 and 6.

In LEU samples, the X-ray radiation is the most intense component of the emission spectrum.[4] When the ^{235}U enrichment is low, the $K_{\alpha 1}$ and $K_{\alpha 2}$ uranium X-ray will dominate the 100 keV gamma and X-ray region of uranium spectra.[4,9]

A linear correlation between the count rate of the well-resolved 98 keV X-ray of uranium and enrichment (%E) was observed. See Figure 7. The relation is given by:

$$\%E = 1/A \ (CR_{98} - B) \qquad (1)$$

Where %E is the enrichment percentage and
CR_{98} is the count rate in the 98 keV X-ray peak.
A and B are slope and intercept.

The result of depleted uranium verification based on the 98 keV X-ray is found in Table 4.

Table 3. Results of depleted uranium verification

Material	Certified	Measured	Diff.
U_3O_8 standard	0.31	0.35	0.04

The difference between the certified value of depleted uranium and that calculated from Equation 1 is only 0.04. This

means that the 98 keV X-ray energy gives accurate and satisfactory result for verification of depleted uranium.

Use of the 98.4 keV self-fluorescent uranium X-rays as a measure of mass fraction of uranium (MFU) was also observed by other work.[10] Uranium was also determined based on the U $K_{\alpha 2}$ fluorescence peaks at 94.7 keV.[11]

For the first time, the intensity ratio of the 98 / 1,001 gamma lines was studied for enrichment verification (Figure 7). The observed correlation is represented by the following linear function:

$$\%E = 1/a\ (CR_{98}/CR_{1,001} - b) \qquad (2)$$

Where %E is the enrichment percentage, a and b are the slope and intercept of the least square fit, CR_{98} is the count rate in the 98 keV X-ray peak of uranium, and $CR_{1,001}$ is the count rate in the 1,001 keV peak of ^{234m}Pa.

The results obtained are given in Table 5 and depicted in Figure 9.

Table 5. Results of verification by the 98/1,001 gamma-ray ratio

Material	Certified	Calculated	Diff.	Uncertainty
U_3O_8 standard	0.31	0.30	0.01	3.2 percent

The uncertainty in the verified depleted uranium did not exceed 3.2 percent. This means that the 98/1,001 ratio can be accurately used for depleted uranium verification as an alternative to the 185.7 keV of ^{235}U. Based on Equation 2, the %E was also calculated for different U_3O_8 standards and found to be close to the declared enrichment values. The results are given in Table 6 and shown graphically in Figure 9.

Table 6. Results of low-enriched uranium verification

Material	Certified	Calculated	Diff.	Uncertainty
U_3O_8 standard	1.94	2.05	-0.11	5.7 percent
U_3O_8 standard	2.95	2.87	0.08	2.7 percent
U_3O_8 standard	4.46	4.44	0.02	0.4 percent

The 89.9 keV thorium K X-ray from ^{235}U decay and the 92.2 keV gamma-ray doublet from ^{234}Th were used for enrichment verification. The results agreed with standard values to within 1 percent.[4]

Conclusions

The suggested approaches, -γ-γ and x-γ ray ratios, are efficient and reliable to for use for verification of the safeguarded nuclear materials (depleted and low-enriched uranium). Based on the results of the 185/766 and 98/1,001 intensity ratios, depleted uranium was verified with only 6 percent and 3.2 percent error respectively. The approaches might be used for verification of depleted uranium in the presence of other interfering isotopes that emit the similar 185.7 keV gamma transition of ^{235}U.

Acknowledgement

The author thanks his dear colleague Dr. W. El-Gamal for his valuable discussion.

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Figure 2. The relationship between %E and the 185keV count rate

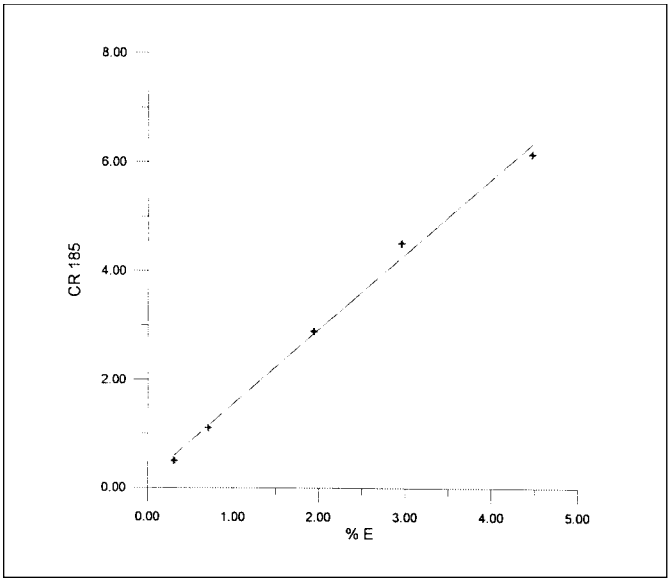


Figure 4. The correlation between %E and the 185/767 gamma-ray ratio

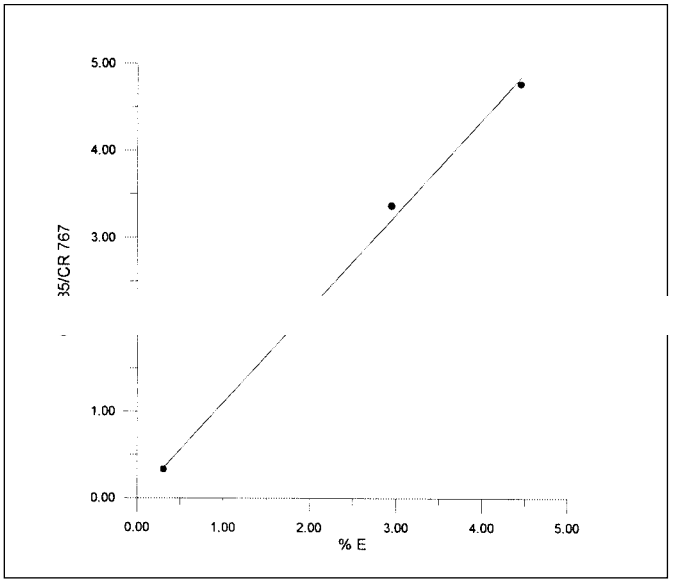


Figure 3. The relationship between %E and the 143,163, and 205 keV count rate

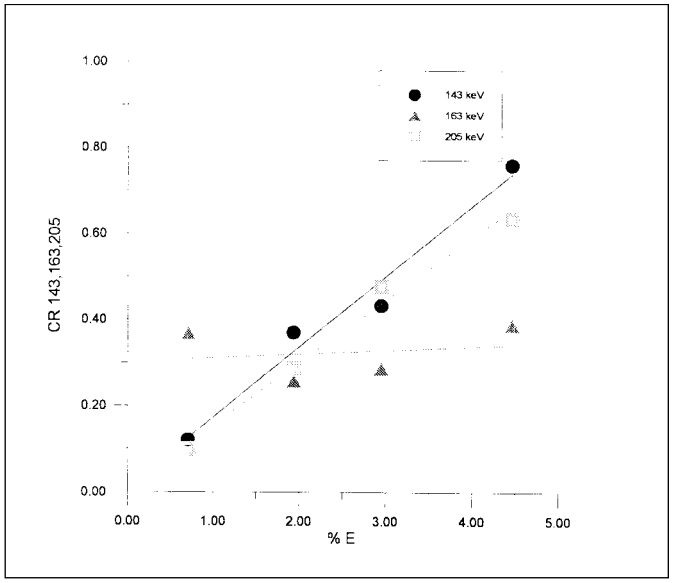


Figure 5. The %E and the 143/1,001 gamma-ray ratio

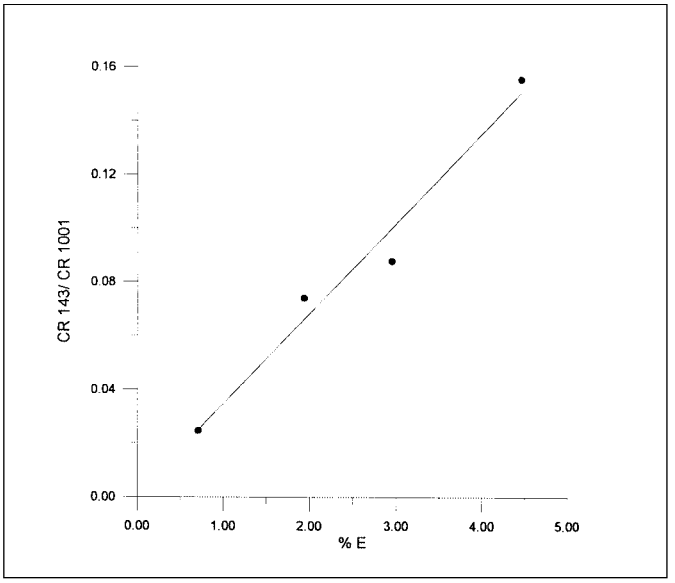


Figure 6. The %E and the 205/1,001 gamma-ray ratio

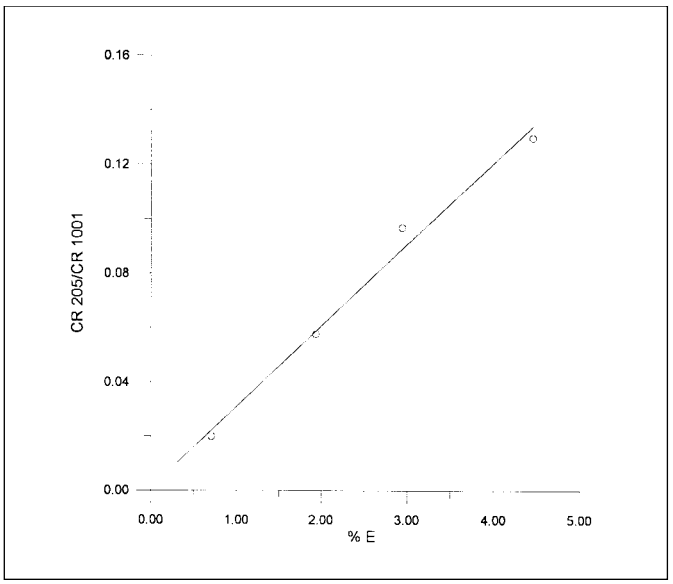


Figure 8. The correlation between %E and the 98/1,001 ratio

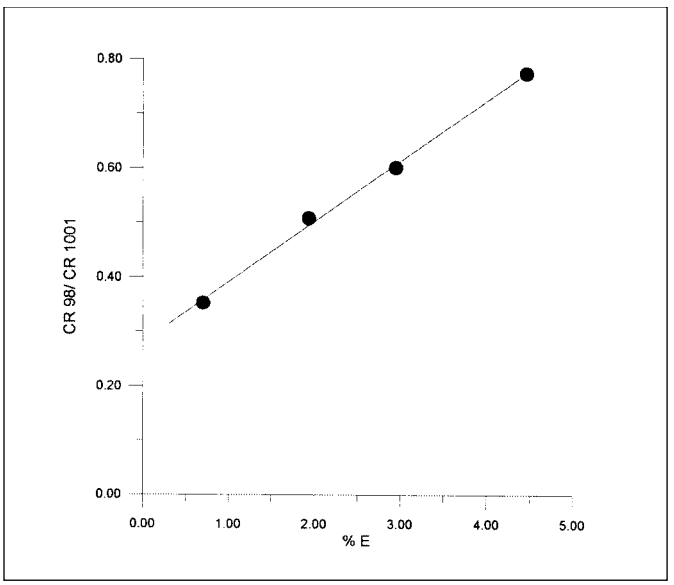


Figure 7. The relationship between %E and the 98 keV X-ray of U $K_{\alpha 1}$

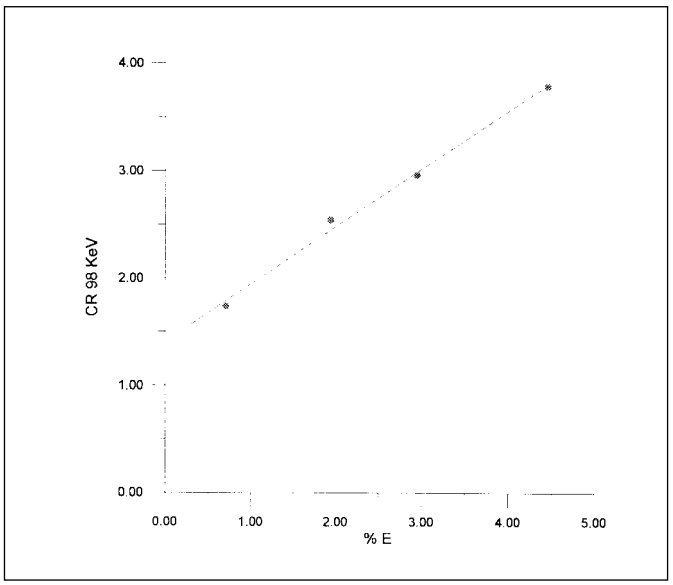
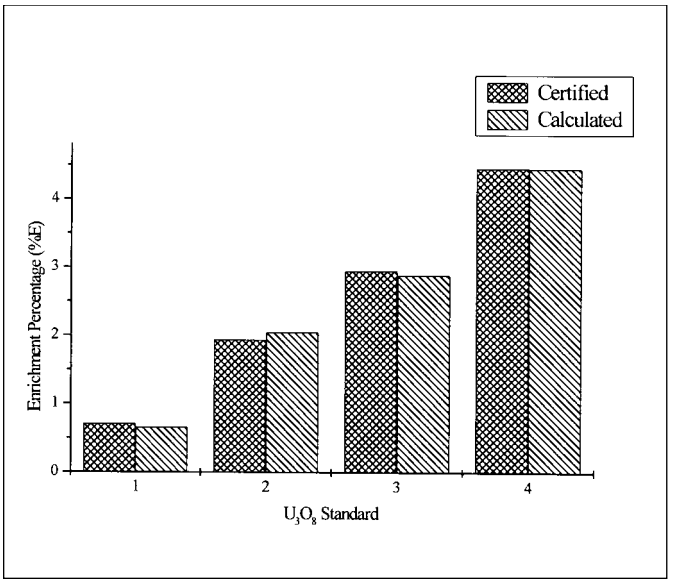


Figure 9. Comparison of the certified and calculated enrichment percentage based on the 98/1,001 x-γ ray ratio



2 U.S. Cities Receive Radiological Detection Equipment from DOE

The U.S. Department of Energy (DOE) formally transferred a shipment of refurbished radiological detection equipment to the Los Angeles Fire Department Hazardous Waste Unit, the Los Angeles Port Authority, and the San Francisco Health Department. The equipment, worth about $60,000, is being provided to first-responder agencies under a DOE and Department of Homeland Security pilot project called the Homeland Defense Equipment Reuse (HDER) Program.

Los Angeles and San Francisco are the sixth and seventh U.S. cities to receive radiological detection equipment from the DOE. The other cities that have received the equipment are Boston, Detroit, New York City, Philadelphia, and Washington, D.C.

The HDER Program provides surplus DOE radiological detection instrumentation and other homeland security-related equipment to state and local emergency first-responder agencies.

U.S., Russia Sign Pact on Reactor Shutdowns

The United States and Russia signed agreements in March that will facilitate the shutdown of three Russian nuclear reactors that currently produce weapons-grade plutonium. These reactors, the last three in Russia producing plutonium for military purposes, also provide heat and electricity to two closed cities in the Russian nuclear-weapons complex. Under the agreements, the United States will provide support to Russia for providing replacement fossil-fuel energy plants.

The United States will provide assistance for the construction and refurbishing of the fossil-fuel plants. In Seversk, an existing fossil-fuel plant will be modernized. In Zheleznogorsk, a new facility will be built. Russia will be responsible for the shutdown and decommissioning of the three existing nuclear reactors.

The new agreements allow for the implementation of the Elimination of Weapons-Grade Plutonium Production Program, a cooperative effort between the U.S. Department of Energy and the Russian Ministry of Atomic Energy. The three reactors are located in the Siberian cities of Seversk and Zheleznogorsk. The reactors have about fifteen years of remaining life and, as a group, could generate an additional 25 metric tons of plutonium per day—the equivalent of about one additional nuclear weapon per day, according to the DOE.

IAEA Conference Urges Stronger Controls to Prevent Dirty Bombs

More than 700 delegates from more than 120 countries gathered in Vienna for the International Conference on Security of Radioactive Sources in March and called for stronger international and national security for radioactive sources, especially those that could be used by terrorists to produce radiological dispersal devices.

"High-risk radioactive sources that are not under secure and regulated control, including so-called 'orphan' sources, raise serious security and safety concerns," the International Conference on Security of Radioactive Sources concluded. "Effective national infrastructures for the safe and secure management of vulnerable and dangerous radioactive sources are essential for ensuring the long-term security and control of such sources."

The conference called for new international initiatives to improve locating, recovering, and securing high-risk radioactive sources throughout the world under the aegis of the International Atomic Energy Agency. The conference also called for a concerted worldwide effort under IAEA leadership to implement the principles in the Code of Conduct on the Safety and Security of Radioactive Sources, which is now being revised to address security concerns, in order to promote adequate radiation safety and security control infrastructures.

The conference offered specific findings for addressing security concerns, identifying high-risk sources, and strengthening government actions to minimize radiological risks. Some of the key recommendations are:

- Implementation by all states of national action plans for locating, searching for, recovering, and securing high-risk radioactive sources
- Strengthening measures to detect, interdict, and respond to illicit trafficking in high-risk radioactive sources
- Public awareness campaigns to foster—among legislators, source users, and the public—a better understanding of real threats and the appropriate responses in the event of a radiological emergency
- Concerted efforts by all states and the IAEA to enhance the current national and international arrangements to respond proactively to the possible malevolent use of high-risk radioactive sources

The International Conference on Security of Radioactive Sources was organized by the IAEA in cooperation with the European Commission, the World Customs Organizations, the International Criminal Police Organization (ICPO-Interpol), and the European Police.

For more information, see the IAEA Web site at www.iaea.org/worldatom.

Low-Level DU Contamination Found in Bosnia and Herzegovina

A report released by the United Nations Environmental Program (UNEP) in March confirmed for the first time that depleted uranium (DU) from weapons used in Bosnia and Herzegovina in 1994 and 1995 contaminated local drinking water supplies and can still be found in dust particles in the air.

The recorded contamination levels, however, are very low and do not present immediate radioactive or toxic risks for the environment or human health. The findings are not a cause for alarm, said UNEP Executive Director Klaus Toepfer, but he also recommended that precautions be taken and in particular that ground and drinking water at and near the sites where the DU has been confirmed be monitored regularly.

The report cites four new and signifi-

cant findings about how DU behaves in the environment. First, ground contamination occurs at DU penetrator impact points at low levels, and is localized to areas typically limited within one to two meters.

Second, DU penetrators buried near the ground surface have corroded, rapidly losing 25 percent of their mass over seven years. The DU penetrators will corrode completely within thirty-five years after impact.

Third, the report records the first instance of DU contamination of groundwater. The previous UNEP assessments of DU in the Balkans were made shortly after the end of the conflict while in Bosnia-Herzegovina the seven years that had passed since the conflict have allowed the corroding DU to penetrate the soil and contaminate the ground water. When contamination is found, UNEP recommends that alternative water sources be used and that water sampling and measurements continue for several years.

Finally, DU contamination of the air was found at two different sites, including inside two buildings. This is due to the re-suspension of DU particles from penetrators or contamination points due to wind or human actions. Some of these buildings are currently in use and UENP recommends a precautionary decontamination of the buildings in order to avoid any unnecessary human exposure.

The UNEP report's recommendations also include collecting the penetrators from the ground, covering contamination points with asphalt of clean soil, handling and disposing of DU material properly, keeping records of DU sites, investigating all health claims, and obtaining the missing coordinates of six confirmed attack sites in Bosnia-Herzegovina.

In Brief

U.S. DOE names New Managers at Idaho and Savannah River Offices

Idaho Operations Office

The U.S. Department of Energy named Elizabeth D. Sellers as the new manager of the Department's Idaho Operations Office effective April 1, 2003. Sellers reports to the Office of Nuclear Energy, Science, and Technology and oversees the activities of 5,900 federal and contractor employees. She is managing the return of the Idaho site to its core mission of nuclear technology development.

Savannah River Operations Office

Jeffrey M. Allison has been appointed to the position of manager of the Savannah River Operations Office in Aiken, South Carolina. He is responsible for the overall leadership, direction, contract management and oversight of all contractor and federal activities associated with the environmental management risk reduction and cleanup at SRS. Allison manages about 400 federal technical and administrative staff and an average annual budget of $1.5 billion. He also has the oversight of the prime contractor, which includes about 13,000 contractor personnel.

New IAEA Web Pages Salute Women in Nuclear Careers

How far women have come and what more can be done to achieve gender equality in the nuclear workplace is the focus of a new feature series on the International Atomic Energy Agency's Web site that was launched in March in support of the UN's annual International Women's Day. The page, located at www.iaea.org/women/2003, aims to encourage young professionals, especially women, to consider how they can contribute to the IAEA's work in nuclear sciences and technology.

The multimedia site showcases the stories of working women from different countries, cultures, and backgrounds. They include top nuclear directors, safety and security regulators, and experts in branches of engineering, science, and technology. Other features highlight past and current contributions of women in nuclear fields, and the IAEA's initiatives to improve gender balance and equal opportunity for its multidisciplinary staff.

DOE/NNSA Cites Los Alamos National Laboratory

The U.S. Department of Energy's National Nuclear Security Administration has issued a Preliminary Notice of Violation (PNOV) to the University of California, the contractor for the Los Alamos National Laboratory (LANL), for violations of nuclear safety rules and procedures involving the inadequate handling of plutonium-contaminated piping, ineffective personnel controls during radiography operations, failure to operate experimental equipment in accordance with safety requirements, and inadequate cleaning of laboratory systems to prevent buildup of potentially hazardous material. The PNOV also documents the failure of LANL to ensure that previously identified work control problems were effectively identified, controlled and corrected. The violations took place in September 2002. No significant consequences to workers, the general public, or the environment resulted from any of the cited operational events. For at least one event, however, worker radiation exposures could have been significant and were not limited by planned work controls.

Germany OKs HEU-powered Reactor

The first large research reactor opened in the past twenty-five years that burns highly enriched uranium was approved by the German government in April. The FRM-II research reactor, located at Garching, near Munich, is likely to become fully operational in 2003.

The reactor is to be converted to use low-enriched uranium by 2010.

In Memoriam

Hastings A. Smith
1943–2003

INMM member Hastings A. Smith, of Los Alamos, New Mexico, U.S.A., died April 17, 2003. He was 59.

At the time of his death, Dr. Smith was the project leader for Russian nuclear programs at Los Alamos National Laboratory. He received his bachelor's degree and Ph.D. in nuclear physics at Purdue University in Indiana. Following a postdoctorate at Los Alamos Scientific Laboratory's Omega Site, Dr. Smith joined the physics faculty at Indiana University in Bloomington, Indiana. He returned to Los Alamos in 1978 to work in nuclear safeguards and nonproliferation.

Dr. Smith became an INMM member in 1979.

He was survived by his wife, Edith Elaine Smith, sons Christopher and Timothy, daughter Angela, and his mother, Elizabeth Rogers Smith.

Katsuyuki Higuchi
1925–2002

INMM member Katsuyuki Higuchi died September 12, 2002. He was 78.

Mr. Katsuyuki Higuchi worked with Power Reactor and Nuclear Fuel Development Corporation (PNC). His major contributions in safeguards and nuclear materials management include the development of a computerized nuclear material accounting system for a plutonium fuel development facility, the practical implementation of thirteen major tasks of the Tokai Advanced Safeguards Technology Exercise for the Tokai Reprocessing Plant, and the initiation of the Japan Support Program for Agency Safeguards (JASPAS) and Hexapartite Safeguards Project (HSP).

Mr. Higuchi received a Distinguished Service Award for Nuclear Material Control from Japan's Ministry of Science and Technology Agency on October 28, 1996.

Author Submission Guidelines

The *Journal of Nuclear Materials Management* is the official journal of the Institute of Nuclear Materials Management. It is a peer-reviewed, multidisciplinary journal that publishes articles on new developments, innovations, and trends in safeguards and management of nuclear materials. Specific areas of interest include physical protection, material control and accounting, waste management, transportation, nuclear nonproliferation/international safeguards, and arms control and verification. *JNMM* also publishes book reviews, letters to the editor, and editorials.

Submission of Manuscripts: *JNMM* reviews papers for publication with the understanding that the work was not previously published and is not being reviewed for publication elsewhere. Papers may be of any length.

Papers should be submitted in *triplicate*, including a copy on computer diskette. Files should be sent as Word or ASCII text files only. Graphic elements must be sent in TIFF format in separate electronic files. Submissions should be directed to:

Dennis Mangan
Technical Editor
Journal of Nuclear Materials Management
60 Revere Drive, Suite 500
Northbrook, IL 60062 USA

Papers are acknowledged upon receipt and are submitted promptly for review and evaluation. Generally, the author(s) is notified within sixty days of submission of the original paper whether the paper is accepted, rejected, or subject to revision.

Format: All papers must include:

- Author(s)' complete name, telephone and fax numbers, and e-mail address
- Name and address of the organization where the work was performed
- Abstract
- Camera-ready tables, figures, and photographs in TIFF format only
- Numbered references in the following format:
  1. Jones, F. T. and L. K. Chang. 1980. Article Title. *Journal* 47(No. 2): 112–118.
  2. Jones, F.T. 1976. *Title of Book*, New York: McMillan Publishing.
- Author(s) biography

Peer Review: Each paper is reviewed by at least one associate editor and by two or more reviewers. Papers are evaluated according to their relevance and significance to nuclear materials safeguards, degree to which they advance knowledge, quality of presentation, soundness of methodology, and appropriateness of conclusions.

Author Review: Accepted manuscripts become the permanent property of INMM and may not be published elsewhere without permission from the managing editor. Authors are responsible for all statements made in their work.

Reprints: Reprints may be ordered at the request and expense of the author. Contact Patricia Sullivan at psullivan@inmm.org or 847/480-9573 to request a reprint.

Calendar

September 1-5, 2003
International Conference on National Infrastructures for Radiation Safety: Towards Effective and Sustainable Systems
Rabat, Morocco
Organizer: International Atomic Energy Agency
Contact:
Cindy Coolbaugh
E-mail: C.Coolbaugh@iaea.org
Web site: www.iaea.org/worldatom/Meetings/2003

October 14-16, 2003
Safeguards Perspectives for a Future Nuclear Environment
Como, Italy
Sponsors: ESARDA and INMM International Safeguards Technical Division
Contact:
ESARDA/INMM Workshop Secretariat
E-mail: 2003.esarda-inmm@jrc.it

October 14-18, 2003
1st International Meeting on Applied Physics—aphys 2003
Badajoz, Spain
Contact:
Web site: www.formatex.org/aphys2003/ aphys2003.htm

July 28-30, 2004
Spent Fuel Management Seminar XXI
Loews L'Enfant Plaza Hotel, Washington, D.C., U.S.A.
Sponsor: Institute of Nuclear Materials Management
Contact:
INMM
60 Revere Drive, Suite 500
Northbrook, IL 60062
Phone: 847/480-9573
Fax: 847/480-9282
E-mail: inmm@inmm.org
Web site: www.inmm.org

February 29-March 4, 2004
7th International Conference on Facility Operations—Safeguards Interface
Francis Marion Hotel, Charleston, South Carolina, U.S.A.
Organizer: American Nuclear Society-Topic
Co-sponsor: INMM Central Region Chapter
Web site: http://ntr.ornl.gov/ANS2004