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The U.S.-Russian HEU Agreement: Internal Safeguards to Prevent Diversion of HEU

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Under the U.S.-Russian HEU agreement,* approximately 500 tons of highly enriched uranium (HEU) from large-scale dismantlement of former Soviet nuclear warheads will be transformed into products not usable in nuclear weapons. According to the agreement, Russian facilities will convert and blend down HEU to low-enriched uranium hexafluoride, which will subsequently be fabricated by U.S. companies into low-enriched uranium (LEU) fuel for nuclear reactors. However, HEU is vulnerable to insider diversion during processing operations. The paper describes the principal HEU diversion vulnerabilities at the plant, and recommends a strong internal preventive safeguards system.

INTRODUCTION

In the near future, many hundred tons of highly enriched uranium will be introduced into the world fuel cycle as a result of the disarmament process. The U.S. and Russia have agreed to reduce their strategic arsenals to 3,000 to 3,500 deployed warheads each. Russia has pledged unilateral reductions of its tactical weapons; and Belarus, Kazakhstan and Ukraine are becoming non-nuclear-weapons states. These actions will slash the nuclear arsenal of the former Soviet Union from 45,000 warheads at its peak size in 1986 to approximately 15,000 warheads (or fewer depending on how many non-deployed nuclear weapons are maintained in storage). Since the dismantlement process started in the former Soviet Union in the second half of the 1980s, the Soviet arsenal has been reduced by about 13,000 warheads.

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* Details on the agreement and its economic aspects are discussed in Oleg Bukharin, "Weapons to Fuel," in this issue.

Today, warhead dismantlement continues at the rate of 1,500 to 2,000 warheads per year. Current disarmament plans will require the elimination of approximately 17,000 nuclear warheads. If each warhead contains 15 to 20 kilograms of highly enriched uranium, then the elimination process in Russia has already released on the order of 200 tons of HEU, and another 300 tons will be released in the coming decade.

At least 500 tons of the weapons-grade HEU in Russia will be blended down to low enriched uranium, as required by the U.S.-Russian HEU agreement. However, large-scale HEU processing operations in Russia will increase opportunities for insiders to steal HEU and sell it on the black market. Strong preventive safeguards systems at processing facilities are therefore essential.

The term "safeguards" in this paper has the U.S. meaning of preventive internal safeguards, as distinguished from international safeguards. The primary functions of internal safeguards are to deter, prevent, detect, and respond to unauthorized possession, use or sabotage of weapons-usable nuclear materials.

Extensive direct access of many workers to HEU during conversion operations will be unavoidable. Therefore, the principal focus of this paper is the need for well designed materials control and accounting (MC&A) systems at processing facilities to prevent insider theft of HEU.

THE U.S.-RUSSIAN HEU AGREEMENT

Thomas Neff, a physicist at M.I.T., originally suggested that the U.S. government could buy uranium from Russian weapons, and thus facilitate dismantlement and disposal of large amounts of weapons-grade materials in an environmentally safe and proliferation-resistant manner.[1] Following this suggestion, the U.S. and Russia began negotiations in the summer of 1992, and on 18 February 1993 both parties signed an umbrella agreement outlining the scope and goals of the HEU agreement: the U.S. will purchase approximately 500 tons of Russian highly enriched uranium, to be converted and blended down to low-enriched uranium. According to present plans, processing of HEU will occur in Russian facilities over a period of 20 years: at least 10 tons per year for the first five years, and subsequently at least 30 tons per year.

The U.S. Department of Energy (DOE) and the Ministry of Atomic Power of the Russian Federation (Minatom) (the U.S. and Russian executive agents) will negotiate an initial implementing contract.[2] The implementing contract shall provide for financial and technical arrangements, including the participation of the U.S. private sector and of Russian enterprises.

In early May 1992, DOE and Minatom agreed on a price for uranium. The U.S. agreed to pay $780 per kilogram of uranium for 4.4 percent enriched uranium in the form of uranium hexafluoride, with adjustments for inflation and changing market conditions. This price is somewhat higher than today's spot market price.[3] It is, however, lower than the price DOE is charging its commercial customers buying enrichment services according to long-term contracts.[4] At the agreed price, Russia's total gross revenues would amount to about $12 billion.

On 2 September 1993, the parties signed a transparency agreement, through which the U.S. seeks assurances that HEU is indeed down-blended to LEU. In its turn, Russia wants assurances that uranium sold to the U.S. is used only for peaceful purposes and is not diverted into the U.S. weapons program.

Also, the parties affirmed their commitment to ensure that controls over the nuclear material "will comply with all applicable non-proliferation, material accounting and control, physical protection and environmental requirements." In particular, the agreement states that the protection of the material "shall, at a minimum, provide protection comparable to the recommendation set forth in International Atomic Energy Agency (IAEA) document INFCIRC/225/REV.2 [Information Circular/225, Revision 2, December 1989]," which classifies the nuclear materials to be protected and specifies basic components of physical security at a facility and in transit. The document serves as a guide to governments on the minimum requirements necessary to protect various types of facilities and materials. It reflects the consensus of experts from countries having most experience in dealing with the problem of physical protection, including experts from the former Soviet Union. Physical protection standards in Russia are generally assumed to be higher than those recommended in INFCIRC/225/REV.2, but adherence to INFCIRC/225 standards alone might not provide sufficient protection.

While physical protection is the principal element of safeguards when protecting the materials from a commando-style attack by outside forces, a coherent system of materials control and accounting is vital to prevent theft of materials by insiders.[5]

In the past, the Soviet Union worried only about espionage activities because there was a lack of economic motivation to divert nuclear materials. A special emphasis was placed on physical barriers and thorough selection of personnel for nuclear programs. The program of material accounting is an instrument developed to facilitate material planning and financial accounting and is inadequate for safeguards purposes.

Economic crisis, wide-spread corruption, and increasing transparency of its borders have opened Russia to black markets for nuclear materials. The recent diversion of tens of kilograms of LEU by insiders from military facilities of the nuclear industry demonstrates both reality of the threat and the inadequacy of the Russian safeguards system.[6]

MATERIAL FLOW AND CONVERSION TECHNOLOGY

Russian weapons are taken apart at four facilities: Nizhnyaya Tura and Uruzan' (a town near Zlatoust) in the Urals, and Penza and Arzamas in Central Russia (see figure 1). Weapons components are placed in special containers and stored at the dismantlement sites or shipped for storage at the facilities where the materials were produced. HEU that is slated for conversion will be fed into a conversion and blending facility in Verkh-Neyvinsk where it will be converted into uranium hexafluoride and blended with 1.5 percent uranium to produce 4.4 percent enriched uranium (see figure 2). Material acceptance tests will assure that uranium hexafluoride meets DOE specifications, "Standard Specification for Uranium Hexafluoride Enriched to Less than Five Percent U-235."[7] The product will be shipped as uranium hexafluoride to St. Petersburgh, and from there to the U.S. In the U.S., the material will be custom-blended at the DOE's gaseous diffusion plant at Portsmouth, Ohio, and sent to U.S. private fuel fabricators.

The bulk of conversion and blending will be carried out at the Ural Electrochemistry plant at Verkh-Neyvinsk near Yekaterinburg.[8] The plant—the first industrial-scale enrichment facility in the Soviet Union—began producing uranium for weapons using the gaseous diffusion enrichment method in 1949. In 1957, it became the first Soviet pilot-scale (and, subsequently, full-scale) centrifuge enrichment plant. The facility features three cascades. In the formerly integrated Soviet enrichment complex, the cascades produced weapons-grade uranium using products of other enrichment facilities as a feed stock. The plant has also produced LEU for export to the West since the 1970s. After the production of HEU was discontinued in 1987, the plant was reconfigured for sole production of LEU. Currently, the plant has a capacity of two to three million separative work units (SWUs) per year, or about 20 percent of the total enrichment capacity in Russia.[9] In addition to enrichment cascades, the Verkh-Neyvinsk production complex incorporates one of the principal Russian facilities producing uranium hexafluoride, which is feed for isotope enrichment cascades.[10]

It is not publicly known which process or processes will be used for conversion of HEU from weapons stocks to uranium hexafluoride. Commercial pro-

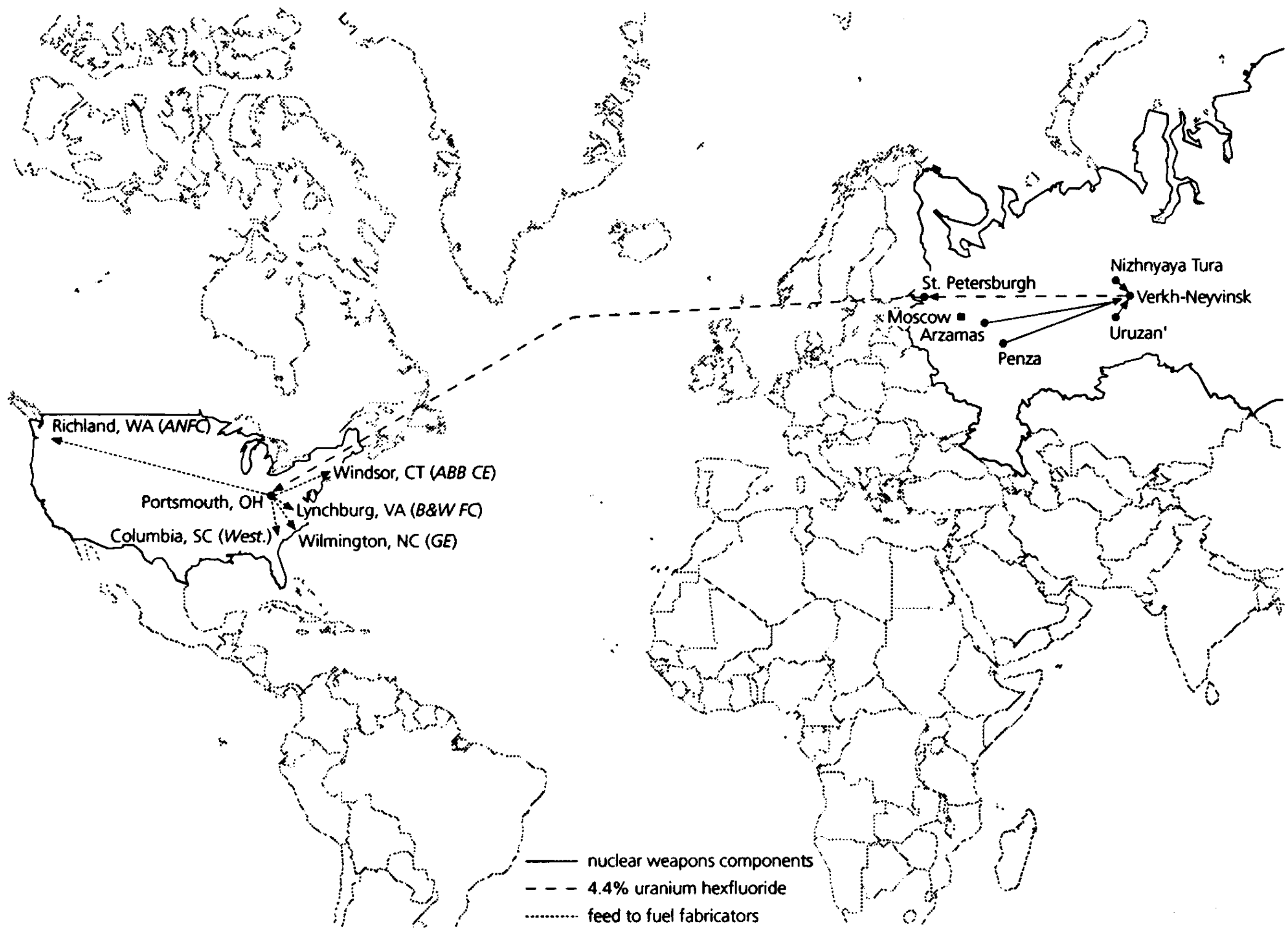

Figure 1: Map of material flow.

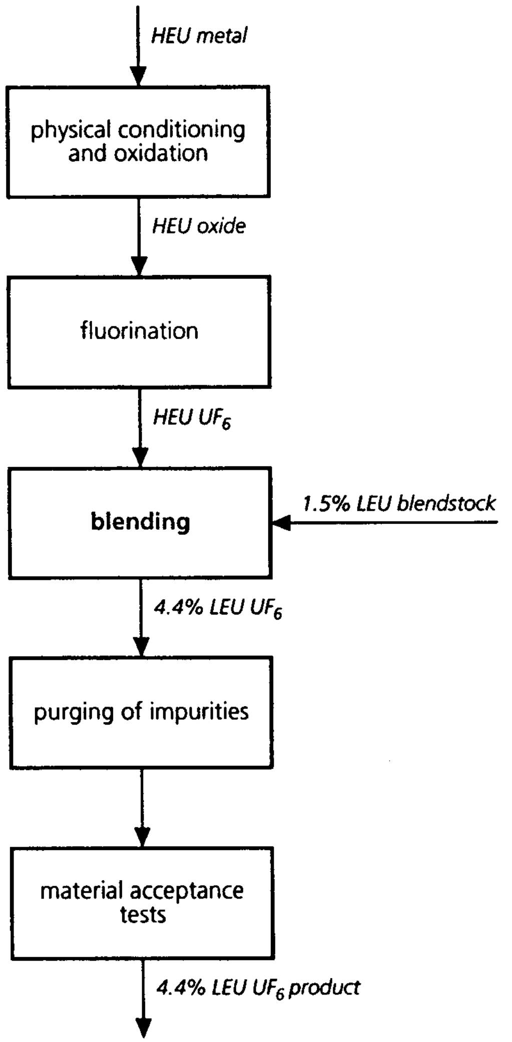

Figure 1: Diagram of conversion and blending.

duction of uranium hexafluoride in Russia is based on fluorination of uranium oxides or tetrafluoride by injecting their fine powder into a fluoride flame in a one-stage flame reactor (fluorination in dust infusion).[11] Direct adaptation of this process to HEU might be difficult because of technical and safety-criticality problems. According to Minatom's officials, the industry has developed a technology of direct fluorination of HEU.[12] Research on direct fluorination of HEU was conducted in the 1970s and 1980s at the pilot-scale installation

"Fregat" (Frigate) at the Research Institute of Nuclear Reactors (NIIAR, Dimitrovgrad).[13] The technology was designed to recover HEU from spent fuel of the BOR-60 fast reactor. It involved direct fluorination of ground material in a reaction with a gas mixture of fluoride and nitrogen, purification of uranium hexafluoride in condensation-evaporation sodium fluoride columns, and desublimation of the uranium hexafluoride gas in a cold condenser.[14] Intermediate fluorides were filtered by a chemical absorber column and returned back to the reactor.

Applied to the weapons uranium, the process will yield HEU hexafluoride, which will be subsequently recondensed into cylinders and transferred to the blending facility. Blending down HEU hexafluoride by mixing it with 1.5 percent enriched uranium, and concurrent purging of chemical impurities from the gas, will reportedly take place in gas centrifuges. The blending material (1.5 percent enriched LEU) might be produced at the facility's operating enrichment cascades via enrichment of previously accumulated uranium tailings. The 4.4 percent enriched product will be withdrawn into standard 2.5-ton shipping cylinders of the 30B type. The Verkh-Neyvinsk facility is capable of converting up to 20 MT HEU a year.[15]

VULNERABILITY OF THE HEU DURING CONVERSION AND BLENDING

A complete vulnerability assessment for the HEU conversion and blending operations is impossible without thorough knowledge of the facility's design and material flows, technological processes, and security practices. However, certain conclusions can be drawn from understanding the general principles of uranium operations at a generic facility processing HEU metal and hexafluoride. This analysis will be applicable only to routine operations and will not account for unusual events caused by criticality, accident, fire, or major equipment malfunction. Special consideration to such possibilities should be given in designing a safeguards system for a specific facility.

Generic problems of safeguarding HEU during conversion and blending stem from the scale of processing activities, multiplicity of material streams, and differences in physical, chemical and isotopic compositions of HEU compounds. Additional difficulties arise from the size of the plant and work force, streams of non-nuclear materials (including decontamination and scrap recovery solutions, fluoride gases and equipment-cleaning gases, chemical trap media, etc.), presence of equipment for processing operations and repairs, and poor detectability of shielded HEU. The points of the process that may present the greatest problem for internal safeguards are associated with less hazardous forms of uranium during the HEU conditioning step, with direct and legitimate access to the material during processing and sampling, and with the multiple waste management operations and their potentially less stringent security and safety requirements.

Below, we describe the processes and HEU vulnerabilities in somewhat more detail.

Conditioning of HEU for the Fluorination Process

HEU from nuclear weapons stocks will be conditioned to be a suitable feed for the conversion process. Conditioning of uranium metal from weapons is likely to involve changes in its physical form (crushing, chopping, and grinding) and conversion of metal to uranium oxide. Generally, uranium-metal operations are carried out in a "dry box" environment. A dry box is similar to a glove box except that it is not completely enclosed; there is an open port through which workers can insert hands to perform operations, including hands-on removal of material.[16] The principal security concern associated with the conditioning operations stems from direct and extended access to the HEU in forms that do not represent a safety or health hazard. Dry box operations are especially difficult to safeguard, because simple, automatic alarms that would be activated upon unauthorized removal of material from a dry box are not feasible,[17] and because presence of equipment commonly obstructs direct personnel surveillance in process areas, especially in back-fitted plants.

Sampling and Mixing HEU with LEU

Uranium hexafluoride—the form in which the material will appear following its conversion—is relatively inaccessible to personnel in the process area, except at sampling ports.[18] Sampling may present a security risk due to personnel's direct access to the material. Regularity and legitimacy of the operation could, in principle, be used to disguise unauthorized activities. Sampling will be conducted immediately following the filling of cylinders at the withdrawal section of the process area.[19] A sampling procedure will involve heating the cylinder in the containment autoclave to liquefy and homogenize uranium hexafluoride, and filling a sample cylinder with liquid UF_6. The sample cylinder will be transferred into the facility's analytical laboratory to determine percent uranium and percent U-235. A principal diversion scenario involves diversion of HEU hexafluoride into an unauthorized cylinder during the operation of sampling, and its subsequent smuggling out of the facility.

There is also a risk of a direct theft of relatively light and small HEU UF_6 cylinders from storage and handling areas before HEU hexafluoride is fed into the blending process.[20]

Waste Treatment

Conversion and blending will generate a substantial amount of uranium-contaminated waste. In Minatom's experiments to develop the HEU conversion process, most unrecoverable uranium losses (waste) occurred in ashes in a fluorination reactor (0.25 percent of the uranium throughput) and in sorption columns (0.2 percent). Major recoverable losses (scrap), about three percent of the throughput, occurred in the condenser. At the conversion rate of 50 kilograms HEU per day, this would correspond to about 0.23 and 1.5 kilograms HEU per day in waste and scrap, respectively; however, U.S. experts expect smaller amount of scrap (about one percent of HEU throughput) in large-scale operations. Additional amounts of uranium will be accumulated over long periods of time in chemical traps (alumina trap media),[21] and will be contained in other waste streams.[22] Uranium-bearing scrap will be sent to the uranium recovery facility, where it will be subjected to nitric-acid leaching and recovery of uranium in the process of solvent extraction. The extract will be calcined to produce uranium oxide, which will be fed back to the process. Filtered solids and unrecovered solid waste will be weighed, assayed for fissile material and shipped off-site for burial.

In waste- and scrap-processing operations, material control and accountancy might be compromised by very large uncertainties associated with assay of heterogeneous and voluminous waste and scrap streams.[23] This might represent a significant safeguards problem for two reasons: (1) assay of waste and scrap containers might grossly underestimate HEU content when HEU is shielded; and (2) substantial poorly measurable uranium streams and inventories cause the accounting uncertainty for the conversion and blending facility to be much larger than other measurement uncertainties would suggest.

Clandestine Removal of the Material from the Facility

Most scenarios for HEU diversion would involve an act of diversion of the HEU from an authorized location within the material process area and its removal from the facility. A particular security risk might be the concealment of substantial quantities of HEU in waste drums. After filled waste drums leave material access areas (MAAs), they will be placed in a lower security environment; waste drums might then be clandestinely opened to permit unauthorized acquisition of HEU concealed within. Thus, waste containers in material access areas constitute a potential route for smuggling HEU out. More generally, containers, bags, and packages of all types which leave material access areas represent potential routes for smuggling out HEU.

In addition, HEU might be concealed in maintenance equipment which must be brought in moderately frequently for necessary repair work while HEU is in locations accessible to workers. Welding machines in particular include many potential hiding places for HEU, but other types of maintenance equipment are also of concern.

Another principal security risk is the potential "walk out" route for smuggling HEU out of the facility. Specifically, personnel might simply walk out of the facility with HEU concealed on their bodies. The risk is magnified by the possibility that HEU so concealed might be encased in lead or other shielding material. Large number of personnel and high frequency of personnel exit make the "walk out" smuggling route a particularly serious security risk.

SAFEGUARDS VULNERABILITIES

The risk of HEU diversion can be moderated by the system of internal accounting and control. Important elements of the system include the following:

- materials accounting and process monitoring;
- visual surveillance;
- portal monitoring; and
- waste screening.

However, effectiveness of individual safeguards measures may be inadequate because of technical limitations and procedural weaknesses. Moreover, economic pressures on plant operations could result in lack of adequate depth in the material protection system. In addition, low wages could cause personnel problems that would increase the risk that insiders would collude to divert HEU to the black market. Below we briefly describe the major areas of safeguards vulnerabilities.

Accounting and Process Monitoring Problems

The conversion and blending plant will have a very large throughput, averaging approximately 50 kilograms per day of HEU during the first five years, and 150 kilograms per day thereafter. Thus, the plant will correspond in "size" to a very large reprocessing plant.[24] For such large plants, "conventional" materials accountancy would likely fail to detect discrepancies of 150 kilograms per year (or even more) of HEU, even when no falsification is involved.[25] Even near real time accountancy (if employed in non-localized fashion as in large reprocessing plants) would, in general, fail to detect a steady "trickle" diversion or loss of this magnitude.[26]

The uncertainties in accounting data, and in conclusions based on accounting data, would be magnified if implementation of the safeguards measurement program were incomplete. Also, accounting uncertainties could be magnified if feed and/or product streams have variable isotopic compositions and clean-out physical inventories are not routinely performed between successive batches.

Process monitoring, which involves frequent collection and analysis of data on various types and aspects of process operations, can partially compensate for material measurement uncertainties. But to be effective the process monitoring system must be particularly well designed and rigorously implemented.

Visual Surveillance Problems

Visual surveillance is an important safeguards measure routinely applied at Russian nuclear facilities. Visual surveillance includes observation of process operations and personnel who perform them, and implementation of a two- or three-man rule. However, personnel observation as an internal safeguards measure has generic weaknesses, including:

- susceptibility to collusion;
- reluctance to report a fellow worker;
- obstruction of view, especially in retro-fitted plants;
- attention to competing task;
- inability to recognize unauthorized activities; and
- insufficient number of observers.

Some of these aspects are functions of the particular task, operational environment, or situation. A U.S. Nuclear Regulatory Commission regulatory guide describes problems of surveillance:[27]

Visual surveillance can be subject to certain inherent problems. The use of pairs of workers to observe each other could be susceptible to collusion. While this susceptibility can be reduced by rotating pair assignments so as not to have set pairs, any surveillance system or procedure that relies on fellow worker surveillance must recognize the reluctance of most workers to report a fellow worker. This type of system may also be of limited effectiveness when workers, in the course of their normal functioning, are located out of view of each other or must place all their attention on a competing task. In addition, a surveillance system that relies extensively on watchmen or remote viewing devices can adversely affect employee morale.

Portal Monitoring Limitations

Portal monitoring is an essential safeguards measure employed at HEU-handling facilities to deter and detect unauthorized removal of HEU from a material access area or facility. A typical walk-through portal monitor at an HEU facility features passive gamma-radiation and metal detectors. Detection capabilities of such portal monitoring equipment are subject to serious limitations (as discussed below). In addition, portal monitoring by use of non-automated detectors is subject to serious human limitations.[28] These technical and human limitations might allow substantial cumulative amounts of HEU to pass principal exit points without detection.

Technical detectability of shielded unreprocessed HEU is low, because of very low rates of neutron emission and low penetrability of emitted gamma rays.[29] Typical gamma-ray portal monitors, under unfavorable conditions, would generally detect no less than about 10 grams of unshielded unreprocessed HEU metal on a person walking through, and no less than about 300 grams of HEU metal that is surrounded by 1.6 millimeters of lead metal shield (about 60 grams of lead). Metal detectors cannot detect lead with good sensitivity: 100 grams of solid lead metal is the effective detection threshold. Moreover, metal detectors cannot detect lead which is in powder form (e.g., lead oxide); this is a severe limitation on detectability of shielding material.[30]

Even in material access areas where all HEU is in the form of uranium hexafluoride, which spontaneously emits fission-spectrum neutrons at rates sufficient for some safeguards applications,[31] portal monitoring devices which detect neutrons would not be practical for detecting HEU concealed on personnel. Indeed, under normal walk-through conditions, a neutron portal monitor would be unlikely to detect an unshielded 90+ percent enriched uranium hexafluoride sample of mass 75 grams (about 50 grams of HEU). Even with a neutron portal monitor that is constructed for optimal detection efficiency, moderate detection probability for a walk-through 90+ percent enriched uranium hexafluoride source would require that the source contain about 130 grams of HEU.[32]

Concealment in Big Containers or Machinery

An HEU warhead component or comparable mass of HEU metal, inside a large-diameter drum which is declared to contain no nuclear material, could be successfully shielded from detection, if the HEU contains virtually no U-232. Inabilitv to detect a hunk of HEU that is surrounded by heavy shielding is a significant weakness, because some large heavy non-nuclear drums are normally admitted into material access areas, and are exempt from surveillance after exiting MAAs.

This vulnerability was partially reported in *Science & Global Security* (volume 3, numbers 3–4) by Fetter et al. in the paper "Detecting Nuclear Warheads," which shows that a three centimeter thick tungsten shield surrounding an HEU weapons component (which contains very little U-232) would not be detectable by practical gamma-ray monitoring means.[33] Equivalent shielding against gamma detection would be provided by eight centimeters of iron or five centimeters of lead. Effective shielding against detection by active neutron interrogation (from a Cf-252 source) would be provided by 20 centimeters of dense borated polyethylene, or 20 centimeters of dense unborated polyethylene with a thin cadmium layer between the polyethylene and the HEU metal.[34]

With only moderate amounts of shielding, large quantities of HEU metal that is essentially free of U-232 could be non-detectable inside standard 200-L drums which are declared to contain waste. Indeed, several kilograms of such HEU metal surrounded by a fraction of the shielding described above would yield the same radiation measurement data as an ordinary waste quantity of HEU.

Similarly, there are detection limitations for HEU concealed in machinery. As indicated above, thick heavy metal surrounding unreprocessed HEU is an effective shield. Accordingly, heavy metal machinery that has internal hiding places could serve as shielding to prevent detection by technical means of large quantities of HEU contained within.

SOME FEASIBLE SAFEGUARDS MEASURES TO PROTECT AGAINST INSIDER SMUGGLING OF HEU OUT OF THE CONVERSION AND BLENDING FACILITY

Eventually, protection of HEU at the conversion and blending facility should be provided by a modern, thoroughly integrated safeguards system. In the U.S., an HEU facility comparable to that in Verkh-Neyvinsk would be required to have an internal control system involving rigorous procedures and techniques, including visual surveillance, materials accounting, process monitoring, and item monitoring, as well as standard physical protection and personnel reliability measures.[35]

According to U.S. experts, there is no such sophisticated safeguards system at the conversion and blending facility at Verkh-Neyvinsk. Its development will require at least 18 to 24 months and will include collection and analysis of the facility information, design, implementation and integration of safeguards components, training of safeguards inspectors, and procurement of equipment.[36] These activities should be carried out as a part of a larger effort directed at the development of a national nuclear safeguards system in Russia.

Adequate protection of HEU at the conversion and blending facility is impossible without these comprehensive, thoroughly integrated and rigorously implemented safeguards elements.[37] However, there are a number of feasible measures which could be put in place relatively quickly and which would be capable of enhancing the HEU protection via substantially blocking some of the routes for smuggling HEU out of material access areas or out of the facility.

Small Control Units

Division of the plant into relatively small control units for safeguards purposes could greatly enhance effectiveness of safeguards. Such division increases the sensitivity and usefulness of materials accounting and of process monitoring. In particular, it improves the ability to detect and localize possible significant diversion if such diversion occurs within a control unit. HEU facilities under U.S. NRC regulation implement this approach; statistical tests for abrupt large losses and for gradual losses are performed on a near-real-time basis.[38]

Exit Search of Personnel for Concealed HEU

To counter insider collusion, screening of objects and personnel at MAA boundaries must be robust, and incorporate substantial redundancy and independence.[39]

U.S. Nuclear Regulatory Commission guidance specifies:[40]

> Prior to exit from an MAA, all individuals, vehicles, packages, and other materials are required to be searched for concealed [HEU]. This search should be conducted using both metal detection and [HEU] detection equipment. The metal detection system used to search for concealed shielded [HEU] should be capable of detecting with at least a 90 percent effective detection rate a minimum of 100 grams of nonferrous metal (shielding) concealed anywhere on an individual . . . Individuals should undergo two separate searches prior to exiting an MAA. An acceptable method of conducting these searches is to require individuals to pass through two separate sets of metal and [HEU] detection equipment, each set monitored by a different member of the security organization.

Change of clothing requirements make it feasible for sensitive metal detection screening (capable of detecting 100 grams of non-granular lead with acceptable false alarm rates) to be routinely applied. Surveillance during required clothing change is an additional safeguards measure that is applied at some facilities. For example, in Japan, "all personnel entering and leaving Japanese nuclear facilities must completely change clothing under the eyes of the guards," according to safeguards experts at Los Alamos National Laboratory.[41]

Screening and Access Restrictions for Non-Nuclear Containers

A general principle is that entry of packages and containers into a material access area (MAA) should be strictly limited. Whenever possible, chemicals should be pumped in through pipes, and the pipes should be equipped with reliable check valves in order to prevent unauthorized flow of material out of the MAA.[42] In particular, gas cylinders should not be admitted into MAAs, because they have thick walls and their interiors cannot be visually inspected by current practical means.[43] Non-nuclear containers admitted into MAAs should, whenever feasible, be configured so that it would not be possible to shield many tens of grams of HEU contained within from detection by available screening instruments.

In general, interiors of containers exiting an MAA should be visually inspected whenever feasible. Questionable containers should be opened, and the contents inspected, before being permitted to cross an MAA boundary. Technical screening can employ X-ray imaging, gamma transmission, passive gamma, and active neutron detection devices.

Waste Container Screening and Restrictions

An immediate essential safeguards measure to protect against use of waste containers as vehicles for smuggling HEU out of material access areas would be strict enforcement of a requirement that all waste containers in material access areas be closed and sealed, except when waste is being loaded into waste containers.[44] Waste-container loading operations should occur under tight surveillance. Whenever feasible, waste that is loaded should be in moderately small transparent bags or pieces, in order to prevent or deter loading of non-detectable concealed HEU. In addition, use of hand-held gamma-detectors for screening waste being loaded into drums could provide some protection against concealment of HEU in waste.

High-density and low-density waste materials should be segregated to improve effectiveness of screening. Immediately after each waste container is packed, it should be tamper-safe sealed, measured by non-destructive assay techniques, and transferred to a controlled access area. Verification of integrity of drums and seals should occur periodically and upon shipment.

A partial technical "fix" would be feasible after a short research and development period. Specifically, it would be possible to prevent the theft of kilogram-size portions of HEU concealed in standard waste containers, if the containers were configured somewhat differently than present standard 200-L waste drums. The new drums could have the same outer dimensions as present drums but be annular rather than cylindrical: each drum would have a full-height cylindrical hole down its center.[45] Fissile uranium waste drum assay via gamma ray or active neutron measurements, utilizing mild upgrades of standard waste assay instruments (i.e., the segmented gamma scanner and the californium shuffler) would be capable of definitively detecting excessive shielding and/or grossly excessive U-235 content.[46] The upgrades would feature use of a detector in the central vertical region and suitable transmission measurements. Assay accuracy for waste could also be greatly improved by this means.[47]

CONCLUSION

By enabling hundreds of tons of highly enriched uranium to be blended down into low-enriched uranium, which is not usable in nuclear weapons, and by speeding up dismantlement of former Soviet nuclear weapons, implementation of the U.S.-Russian HEU agreement will serve an important nonproliferation function. However, to prevent insider diversion of significant quantities of HEU, it is necessary to design and implement a strong preventive safeguards system at the Russian conversion and blending facility.

At the conversion and blending facility, HEU vulnerabilities will arise from large absolute uncertainties in materials accounting data, prolonged direct access of workers to HEU in process, and poor detectability of shielded HEU. Table 1 summarizes principal vulnerabilities.

The safeguards system should protect against all realistic scenarios for unauthorized removal of HEU from the facility. A reasonable nonproliferation objective would be to prevent the unauthorized removal of as much as one bomb quantity of HEU in a single year. Despite limitations of verification by materials accountancy, a well designed robust safeguards system should in principle be capable of providing the desired protection.

Safeguards procedures should be well documented and enforced. In addition to standard physical protection elements, important safeguards measures include: direct visual surveillance, materials accounting, process monitoring, item monitoring, comprehensive application of seals and other tamper indicating devices to containers and equipment, compulsory use of multiple separate portal monitoring stations for personnel exiting material access areas, and effective procedures to prevent undetected smuggling of HEU in containers or maintenance equipment. While thorough organization and integration of the facility safeguards system may take two years to establish, it is essential to implement a well planned combination of safeguards measures, to prevent insider theft of HEU.

Table 1: Some HEU diversion vulnerabilities and safeguards measures for a large HEU conversion and blending facility.

Vulnerability points	Problem	Safeguards measures	Limitations of safeguards effectiveness
HEU conversion process areas	prolonged direct worker access to HEU	surveillance	activities may not be identifiable; collusion possible; human limitations
HEU UF_6 sampling ports	frequent direct worker access to HEU	physical security hardware; surveillance	surveillance limitations
personnel exits at boundaries of MAAs and facility[a]	possible diversion route for HEU	portal monitoring w/ radiation and metal detectors; change of clothing under surveillance	technical limits[b]; human limitations
maintenance equipment admitted to MAAs[a]	shielded hiding places in equipment; possible diversion vehicle for HEU	surveillance	surveillance limitations
non-nuclear containers admitted to MAAs[a]	possible diversion vehicle for HEU	limit entry of containers; technical screening and visual inspection of containers	technical limits[c]; particularly severe if gross shielding exists in container; human limitations
waste containers admitted to MAAs[a]	kilograms of HEU might "look like" a waste quantity; possible diversion vehicle for HEU	limit geometry of waste containers; surveillance; seals; technical screening	technical limits[d] more severe than in non-nuclear container case; surveillance limitations
high-throughput process areas	large uncertainties in materials accounting	subdivide process areas into small control units	uncertainties in materials accounting

a. MAA = material access area.
b. Sensitivities approx. 10 grams unshielded HEU or 300 grams shielded HEU (with shielding below detection level).
c. Kilograms of HEU surrounded by very heavy shielding in a large container might escape detection by non-invasive techniques.
d. Kilograms of shielded HEU in a standard 200-L waste container might escape detection by non-invasive techniques.

NOTES AND REFERENCES

1. *New York Times*, 24 October 1991 (Op Ed).

2. The U.S. has indicated that it may transfer the responsibilities to the newly born U.S. Enrichment Corporation (USEC).

3. About 6.04 SWUs and 9.98 kilograms of hexafluoride of natural uranium are required to produce one kilogram of 4.4 percent enriched uranium. Currently, on the spot market, one kilogram of UF_6 and one kilogram SWU can be purchased for about $25 to 31 per kilogram and $68 to 75 per SWU, respectively. (*NuclearFuel*, 7 June 1993) Thus, production of 4.4 percent enriched uranium costs $660 to 762 per kilogram.

4. DOE's long-term contractual prices are in the range of $90 to 118 per SWU. DOE's gaseous diffusion plants have produced SWUs at a cost of $60 per SWU; however, this cost does not include overhead (administration and management, safeguards, profit margin, etc.)

5. In this paper the term "physical protection" is understood to have the same meaning as in U.S. safeguards usage. Whereas in an international safeguards context, the general European meaning of "physical protection" applied at the facility level includes the entire spectrum of internal facility preventive safeguards measures, the U.S. meaning is more limited; in particular, physical protection (in the U.S.) is only one component of the internal safeguards system, the other principal components being material control, material accounting, and personnel reliability. Although the four components do overlap and the definitions of each are somewhat flexible, physical protection includes general physical security measures such as access and egress controls and physical barriers, technical surveillance and alarm systems, and use of security personnel.

6. About 80 kilograms LEU were stolen from the Minatom facility in Glazov. The material was intercepted during an attempt to smuggle it through Poland (*Kommersant*, 23 February 1993).

7. According to *NuclearFuel* (21 June 1993), HEU from former Soviet weapons may be contaminated with U-234 and U-236. The presence of U-234 creates problems for fuel fabricators because of the increased radioactivity due to (alpha, n) reactions in UF_6; U-236 creates a reactivity problem because it acts as a poison in a reactor core. The ASTM specifications set the levels at 10,000 and 5,000 ppm parts U-235 for U-234 and U-236, respectively. Also, HEU from weapons is likely to be contaminated with chemical impurities (alloying metal, etc.). The material acceptance analysis will probably include gravimetric methods and gas-phase mass spectrometry to determine uranium assay and abundance of U-235, and some method to measure impurities.

8. Interview with an official in the Russian Ministry of Atomic Energy, 12 March 1993.

9. D. Albright, F. Berkhout, W. Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992* (Oxford: Oxford University Press, 1993) p. 55.

10. The other conversion facilities are in Angarsk and Tomsk, (O. Bukharin, "The Structure and the Production Capabilities of the Nuclear Fuel Cycle in the Countries of the Former Soviet Union," Princeton University, Center for Energy and Environmental Studies report no. 274, January 1993.) Uranium and fluorine form very important compounds in nuclear applications. Unlike uranium oxides, uranium hexafluoride is stoichiometric chemically and F-19 is the only isotope of fluorine. Uranium hexafluo-

ride sublimates from solid into gas at 57°C. At slightly increased pressure (1.5 atmosphere) and temperature (65°C) the substance becomes liquid. These properties make uranium hexafluoride uniquely suitable to be a feed for a gas centrifuge or gaseous diffusion uranium enrichment facility. Uranium hexafluoride is also extensively traded on the world's nuclear fuel market and fed into facilities fabricating fuel for power reactors.

11. Nuexco, "Conversion and Enrichment in the U.S.S.R.," *NUEXCO Monthly Report*, No. 272, 1991.

12. E. Mikerin, workshop on nuclear warhead dismantlement in London, 18 June 1992.

13. The discussion is based on the paper "Pilot-Scale Regeneration of Uranium Spent Fuel from the BOR-60 Reactor Using a Fluorination Approach," P-18 (284), NIIAR, Dimitrovgrad, 1976.

14. NaF absorbs UF_6 at 100°C and releases it at 400°C. The after-reactor gases are pumped through an NaF column at 100°C. Pure UF_6 is later released when the column is heated to 400°C.

15. E. Mikerin, "The Uranium Supply Picture through 2010. Russia," International Uranium Seminar 92, USCEA, 20–23 September 1992, Nevada. At the conversion rate of 10 MT HEU per year and plant availability of 200 days per year, the plant will process 50 kilograms HEU per day, which corresponds to the amount of uranium contained in two to three average warheads.

16. Glove boxes may be used in cases when uranium represents an alpha-contamination problem. They also may be used for materials control and accountancy purposes to prevent material spills (also called "process upsets").

17. For glove boxes, automatic alarms to signal unauthorized opening of a glove box door or bag-out port are practical. Opening of a glove box door or port without sounding an alarm would require that a second person simultaneously press an alarm-bypass button. Removal of the glove from the gloved port would result in anomalous pressure increase in the glove box, which should trigger an alarm.

18. Uranium hexafluoride constitutes a significant health hazard affecting lungs, stomach and skin. As a heavy metal uranium damages kidneys. Ions of fluoride cause general poison effects. Of special danger to man and biota is hydrogen fluoride resulting from decomposition of UF_6 in the presence of moisture in the reaction $UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$. Concentrations of HF greater than $1.0 \cdot 10^6$ micrograms per cubic meter ($\mu g\ m^{-3}$) are considered to be lethal (the daily 8-hour occupational exposure limit for HF is $2.5 \cdot 10^3\ \mu g\ m^{-3}$). In addition, uranium hexafluoride is aggressive chemically: it readily reacts with and destroys organic materials; it forms very corrosive acid with water; and the reaction of liquid uranium hexafluoride with hydrogen can lead to explosion. Therefore, the safety rules require monitoring of surfaces and air inside the facility. Typical measures for early detection of UF_6 releases involve control of pressure in the process system, electrical conductivity control (conductivity increases in the presence of UF_6), continuous monitoring of system drains and vent stacks, and air sampling. The process equipment is designed to be airtight and to provide sufficient containment and isolation should any UF_6 leakage occur. Extraction of the product, dust, intermediate fluorides, ashes and other fluoride-contaminated waste are conducted in a vacuum, and equipment is cleaned with inert gases before plant outage or repair.

19. In the U.S., two samples are routinely taken from one cylinder: one is for immediate analysis and one is for possible umpire use. ("Safeguards for Enrichment Plants," Final Report, B&R 50-19-02-03, FIN A3147-6, Brookhaven National Laboratory, December 1978.) A 1S-type cylinder is routinely used for sampling HEU hexafluoride. The 11 inch-long and 1.5 inch-diameter cylinder accommodates up to 0.45 kilograms HEU UF_6. ("Nuclear Material Safeguards for Enrichment Plants. Part 3. Gas Centrifuge Enrichment Plant: Description, Material Control and Accountability Procedures, and IAEA Safeguards," K/ITP-156/P3/R1 [ISPO-284/P3/R1]. Prepared by Martin Marietta Energy Systems Inc. for the safeguards training course, 14–18 November 1988, Vienna, p.75.)

20. A 5A or 5B cylinder is typically used to accommodate HEU UF_6 at U.S. facilities. The 36 inch-long and five inch-diameter cylinder accommodates some 25 kilograms HEU UF_6 and weighs (gross weight) 50 kilograms. ("Nuclear Material Safeguards for Enrichment Plants. Part 3. Gas Centrifuge Enrichment Plant: Description, Material Control and Accountability Procedures, and IAEA Safeguards," p. 79.)

21. Traps are used to remove traces of UF_6 from exhaust gases of vacuum pumps and to contain UF_6 during an accident.

22. Other waste streams will include contaminated lubrication and pump fluids, contaminated combustibles (gloves, paper towels, filter papers, shoe cover, etc.) awaiting incineration, incinerator ash, and wash solutions from decontamination of equipment and removal of sediments from cylinders. The uranium-bearing sediments are formed in the reaction UF_6 + alpha-radiation $\rightarrow UF_x + (6 - x) / 2\ F_2$, where x is an integer from one to five.

23. It is not possible to obtain "representative" samples from heterogeneous waste and scrap. Uncertainty of nondestructive assay measurements for uranium waste and scrap can be large because of geometrical uncertainties in distribution of uranium, and uncertainties due to variation in composition and distribution of the matrix materials which affect detection and/or emission of measured radiation.

24. The THORP reprocessing plant in the UK is designed to process six MT per day of light water reactor fuel. With the plutonium content of eight kilograms per MT of spent fuel, this capacity corresponds to a throughput of 48 kilograms plutonium per day.

25. Indeed, an accounting uncertainty of ± 0.5 percent (for example) translates to about ±50 kilograms per year during the first few years and to about ±150 kilograms per year during subsequent years. Accounting discrepancies of at least three times those figures would be "needed" to trigger suspicion of possible diversion. Thus, within those discrepancy ranges, conventional accounting alone would not raise an alarm. Uncertainties of at least ± 0.5 percent are realistic, particularly if enrichments of input or output streams are somewhat variable. Primary contributors to accounting uncertainties will be material streams and inventories which are poorly measurable, i.e., waste, scrap, and material "hold-up" in process pipes. The volume of waste and scrap might be substantially increased as a result of accidental material spills ("process upsets").

26. This conclusion is based on the assumption that the plant does not have a near-real-time measurement history over an extended period in which diversion definitely did not occur. In general, near-real-time accountancy cannot distinguish between "trickle" diversion, "trickle" loss that does not involve diversion, and measurement bias. Normal "losses" occur (for example) in the form of material hold-up in processing equipment or pipes; its magnitude cannot be accurately measured without cleaning out

the equipment and pipes. Measurement bias involves calibration error.

27. U.S. Nuclear Regulatory Guide 5.14, "Use of Observation (Visual Surveillance) Techniques in Material Access Areas," Revision 1, May 1980, p. 5.14-2.

28. Because of lack of alertness and other human factors, hand search of personnel at busy exit points tends to be unreliable. Typical detection failure rates of 20 percent due to human factors have been reported. See D. Albright, "Portal Monitoring for Detecting Fissile Materials and Chemical Explosives," in *Reversing the Arms Race* (London: Gordon & Breach, 1990) p. 242 and notes 2 and 3 on p. 260.

29. Reprocessed HEU contains U-232, which emits penetrating gamma radiation and is much more detectable.

30. See P.E. Fehlau, "An Applications Guide to Pedestrian SNM [special nuclear material] Monitors," Los Alamos National Laboratory report LA-10633-MS, February 1986. The threshold detection amounts of HEU vary, however, with gamma ray background radiation and with walk-through pace. Attempts to smuggle HEU through portal monitors would logically involve rapid walk-through pace, if possible, to reduce gamma ray detection.

31. The neutrons are produced by reaction of alpha radiation from uranium with fluorine, in so-called (alpha, n) reactions. In enriched uranium, alpha production occurs predominantly by decay of the minor isotope U-234, the concentration of which increases with increasing U-235 enrichment. Hence, rate of fast neutron emission from uranium hexafluoride increases with increasing U-235 enrichment. (In natural uranium, which comprises 99.3 percent U-238, 0.7 percent U-235, and 0.006 percent U-234, rates of alpha production contributed by U-238 and U-234 are about equal and are substantially greater than that contributed by U-235. Enrichment increases the isotopic ratio U-234:U-235, as well as the U-235 concentration.)

32. See Paul E. Fehlau, "A Low-cost Safeguards Pedestrian Portal Monitor Using Chamber Neutron Detectors," Proceedings of the Ninth Annual European Safeguards Research and Development Association (ESARDA) Symoposium on Safeguards and Nuclear Material Management, London, U.K., 12–14 May 1987; J.W. Tape, M.P. Baker, R. Strittmatter, M. Jain, and M.L. Evans (Los Alamos Scientific Laboratory), "Selected Nondestructive Assay Instrumentation for an International Safeguards System at Uranium Enrichment Plants," Proceedings of the 20th Annual Meeting of the Institute of Nuclear Materials Management, Albuquerque, New Mexico, 16–18 July 1979. The first paper describes a neutron portal monitor in which large He-3 detectors are encased in polyethylene chambers to optimize detection efficiency; the monitor detects with about 50 percent probability a walk-through source that emits 1,000 fission-spectrum neutrons per second. In the second paper, figure 2 indicates that a 5-kilogram mass of uranium hexafluoride of 90 percent enrichment emits about $2.5 \cdot 10^4$ neutrons per second. That corresponds to only five neutrons per second per gram of UF_6, or eight neutrons per second per gram of U-235.

33. S. Fetter, V.A. Frolov, M. Miller, R. Mozley, O.F. Prilutsky, S.N. Rodionov and R.Z. Sagdeev, "Detecting Nuclear Warheads," *Science & Global Security* 1 (3–4), 1990.

34. P.M. Rinard, E.L. Adams, H.O. Menlove and J.K. Sprinkle Jr., "The Nondestructive Assay of 55-Gallon Drums Containing Uranium and Transuranic Waste Using Passive-Active Shufflers," Los Alamos National Laboratory report LA-12446-MS, November 1992. See pp. 31, 33 for some concealment results. Although reported experimental results for shielded U-235 pertain specifically to a 100-gram U-235 sample, results would extrapolate to a several-kilogram compact mass of HEU metal and prob-

ably even to HEU weapon components, primarily because of difference in density of material. Indeed, a large mass of compact HEU metal is heavily self-shielding with respect to interrogation by thermalized neutrons, whereas self-shielding effects in the experimental low-density HEU sample were relatively small (smaller by nearly two orders of magnitude). (The experimental sample was 93 percent enriched HEU oxide, of density approximately 2.5 grams per cubic centimeter, with elongated cylindrical geometry. [Private communication from Howard Menlove and Ed Adams, Los Alamos National Laboratory, 9 September 1993.])

35. Safeguards requirements for NRC-licensed facilities are codified in the "U.S. Code of Federal Regulations." (Title 10; Part 70—Domestic Licensing of Special Nuclear Material, 70.58—Fundamental nuclear material controls; Part 73—Physical Protection of Plants and Materials; Part 74—Material Control and Accounting of Special Nuclear Material; Part 74, Subpart E—Formula Quantities of Special Nuclear Material.) 10 C.F.R. 74 Subpart E contains the Nuclear Regulatory Commission material control and accounting regulations specific to HEU plants. U.S. Department of Energy Regulations are similar to NRC regulations and are contained in the DOE Order Series 5633. (DOE5633A—Control and Accountability of Nuclear Materials; DOE5632A—Physical Protection of Special Nuclear Materials. Guide for Implementation of DOE5633.3A, February 1993).

36. Brookhaven National Laboratory internal paper.

37. The system must be integrated so as to compensate for the weakness of its specific components. In particular, the system's integration is required to provide detection capability for "trickle" diversion: small frequent diversions would be detected with reasonable probability by random chance, if the safeguards system is sufficiently "dense" with respect to all feasible diversion scenarios.

38. See 10 C.F.R. Part 74 Subpart E (endnote 35).

39. "Design of a Material Control and Accounting System to Protect Against Concealment of Diversion by Falsification and Collusion," U.S. Nuclear Regulatory Commission guidance document NUREG/CR-5003, October 1987, p. 17.

40. U.S. Nuclear Regulatory Commission Regulatory Guide 5.7, "Entry/Exit Control for Protected Areas, Vital Areas, and Material Access Areas," Revision 1, May 1980, p.5.7-4.

41. E.A. Hakkila and G.W. Eccleston (at Los Alamos National Laboratory), Comment in *Journal of Nuclear Materials Management*, October 1990 to January 1991, p. 8.

42. Proper operation of the check valves should be verified with valve monitors. For a description of check valve monitoring techniques, see H.D. Haynes and W.S. Farmer "Assessment of Diagnostic Methods for Determining Degradation of Check Valves," presented at the U.S. NRC Aging Research Information Conference, 24–27 March 1992, Rockville, MD.

43. This requirement is generally enforced for U.S. HEU plants. Private communication from U.S. safeguards officials, 1993.

44. Wire seals would be suitable for routine application to waste containers.

45. If the radius of the cylindrical drum hole is approximately 12 centimeters, the thickness of the annular drum between inner and outer walls would be about 15 centimeters; the volume of the drum would be about 160 liters. H.M. Hunt, "A New Approach to Waste Monitoring in Material Access Areas," Proceedings of the 34th

Annual Meeting of the Institute of Nuclear Materials Management, Scottsdale, Arizona, 18–22 July 1993, pp. 930–934.

46. Literature describing the segmented gamma scanner and the californium shuffler is available from Los Alamos National Laboratory (LANL) in the form of a multiple-page "Application Note" for each, as well as longer reports. A particular pertinent report on the californium shuffler is P.M. Rinard, E.L. Adams, H.O. Menlove, and J.K. Sprinkle Jr., "The Nondestructive Assay of 55-Gallon Drums Containing Uranium and Transuranic Waste Using Passive-Active Shufflers," LANL report LA-12446-MS, November 1992.

47. Upgrades in waste assay instruments would feature use of a detector within the central vertical drum hole—for both transmission measurements and detection of emissions from drum contents. A principal function of the transmission measurements would be to detect the presence of a localized heavily shielded region; hence transmission measurements would be performed in an automated mode featuring drum rotation, movement of the transmission source vertically in accordance with the height of the drum, and continuous data recording. (With the annular geometry described, there would be no special collimation requirements for neutron transmission measurements intended to detect excessive shielding.) Current neutron and gamma waste assay instruments would be upgraded in this manner. With these changes in drum and instrument design, all pertinent assay techniques would be expected to yield more accurate and reliable assays, as well as definitively detect pertinent anomalies. Assay accuracy and concealment detection for HEU waste, with the californium shuffler, might benefit most dramatically.