CHAPTER 2

U.S. MILITARY NUCLEAR MATERIAL UNACCOUNTED FOR: MISSING IN ACTION OR JUST SLOPPY PRACTICES?

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The standard story is that there is not much to worry about: The United States has the gold standard when it comes to accounting for fissile material, especially in the military sector. Although the U.S. Department of Energy (DOE) has acknowledged that almost six metric tons (MT) of fissile material, including plutonium, highly enriched uranium, and uranium-233—enough for at least several hundred nuclear explosives—is unaccounted for, this discrepancy mostly occurred during the rush to produce fissile material during the first few decades of the Cold War when the emphasis was on fast production rather than accurate accounting. The explanation for the large amount of material unaccounted for (MUF) is that material was sent to scrap, mixed in with other waste, stuck in piping, and otherwise characterized as "normal operating losses." As the Comptroller General of the United States stated in a 1978 report:

> For the most part, MUF is attributed by DOE and NRC [Nuclear Regulatory Commission] to such things as inaccurate measurements and difficult to measure material held up in pipes, filters and machines used in processing special nuclear material.[1]

The other main reason given was "clerical errors."[2] One could infer from that assessment that most, if not close to all, DOE and NRC officials appeared to believe that no material was diverted.

Nonetheless, one should worry about the accounting system and the potential for diversion. In particular, one significant case of alleged insider diversion of highly enriched uranium—that could fuel several nuclear bombs—has been reported and raises concern about conventional wisdom. While one could discount this alleged incident as an anomaly because it took place in the 1960s before the current, more rigorous accounting system was established, many government reports from inspectors general of the DOE and the General Accountability Office have sounded an alarm for more than 30 years that the accounting system is not adequate. As discussed in this volume, the United States is still not meeting its most stringent standards.

If the U.S. nuclear material accounting system is not adequate, then what does that imply about nuclear-armed states that are still manufacturing and remanufacturing warheads more frequently than the United States? According to conventional thinking, if the United States is not producing fissile material and not manufacturing or remanufacturing nearly as many warheads as during the Cold War, then its accuracy in accounting for fissile material should go up. Indeed, this has been the trend. But for a nuclear-armed state still producing fissile material for military purposes such as India and Pakistan or a nuclear-armed state such as Russia, which continually remanufactures its warheads much more frequently than the United States, there may be greater gaps between the material known to be in the inventory and material unaccounted for.

U.S. FISSILE MATERIAL PRODUCTION FOR MILITARY PURPOSES AND INVENTORY DIFFERENCES

The United States was the first nation to make nuclear weapons and subsequently amassed one of the largest stockpiles of weapons and fissile material, only to be surpassed by the Soviet Union's production. For 2 decades from the early-1940s to the mid-1960s, the United States ramped up its fissile material production in response to both external geopolitical and internal political pressures and produced several hundred MT of fissile material.

By the early 1960s, the United States had dozens of facilities, numerous buildings at these sites, and thousands of workers involved in the production and handling of fissile material. Production facilities included plutonium production reactors at Hanford, WA; and the Savannah River Site, SC; and uranium enrichment plants at Oak Ridge, TN; Paducah, KY; and Piketon, OH. Handling and storage facilities were more spread across the country and included facilities located at Los Alamos, NM; Livermore, CA; Amarillo, TX; Rocky Flats, CO; Erwin, TN; and Apollo, PA, to name a few notable sites. As a result of these widespread and numerous activities, the challenge of controlling and accounting for military nuclear materials kept growing.

By the end of 1963, the United States had a surplus of fissile material. This prompted Congress in 1964 to pass the Private Ownership of Special Nuclear Materials Act, which allowed the Atomic Energy Commission (AEC) "to sell, lease, or grant nuclear materials to industry for research and development activities."[3] Such activity could increase the difficulties in accounting for fissile material, especially as the number of commercial firms handling the material increased.

Also, in 1964, President Lyndon Johnson in his State of the Union message declared a reduction in the production of highly enriched uranium and plutonium. Consequently, Oak Ridge stopped highly enriched uranium (HEU) production, and Hanford and Savannah River Site shut down four nuclear production reactors. By the early-1970s, the United States had only four reactors in operation: the N-reactor at Hanford and three at Savannah River. In 1989, the last of the reactors at Savannah River Site was finally shut down due to safety concerns. The uranium gaseous diffusion plants at Paducah and Portsmouth continued to operate beyond 1989, but they were no longer used for HEU production purposes after 1991; the production for weapons had ended in 1964. Instead, they were subsequently used only for production of low enriched uranium for commercial purposes. Thus, by 1991, the United States had stopped producing any fissile material for military purposes but was still using and handling HEU and plutonium in weapons and naval fuel.

During the decades of fissile material production, the amounts of materials generated were shrouded in secrecy. Because these materials were used in nuclear weapons, the Naval Nuclear Propulsion Program, the Army Nuclear Power Program, and other defense-related research and development activities, revealing the exact amounts produced to the public could have jeopardized national security. At least this was the rationale throughout the Cold War.

In 1993, several years after the Cold War ended, President Bill Clinton and his administration's DOE unveiled the "Openness Initiative" to make government more open and accountable to the public. As a result, DOE began to declassify vast amounts of information, as long as it could be assured that such declassification would not harm national security. A major aspect of this initiative was to reveal publicly the total quantities of highly enriched uranium and plutonium produced. A few years after this initiative began, DOE published two unprecedented reports on the HEU and plutonium inventories.

Regarding HEU, DOE reported that as of September 30, 1996, the total inventory was 740.7-MT uranium (MTU) containing 620.3 MTU-235. Importantly, the DOE report did not state the amount of HEU in waste as part of the inventory and that material was thus not included in the overall quantity. (DOE withheld the HEU report for several years.) According to DOE, "Most of the HEU in waste has been removed from the U.S. inventory as 'normal operating losses' because it is technically too difficult or uneconomical to recover."[4] Table 2-1 shows the locations and inventories of HEU as of September 30, 1996.

Note that in Table 2-1, the vast majority of HEU is listed under "Y-12 Plant, Pantex, & DoD" and is aggregated among those sites and DOD facilities for national security purposes. That particular listing does not specify the amounts for the two different HEU assays of less than and greater than 90 percent U-235, the dividing line for **weapons-grade** material, but HEU less than 90 percent U-235 is still weapons-usable; once again, this was done by DOE for national security reasons. Also, note the relatively large amount of material listed under "Miscellaneous." Despite the lack of details for these two categories, the DOE report on HEU was truly path breaking. **This report also described the inventory difference, or material unaccounted for, of HEU from 1945 through September 1996 as 3.2 MTU-235**. Half of this inventory difference is from DOE sites, and the other half is from commercial sites.

Location	20 to <90% U-235		90% U-235		Total	
	MTU	MTU-235	MTU	MTU-235	MTU	MTU-235
Y-12 Plant, Pantex & DoD (Department of Defense)					651.6	557.4
Idaho National Lab	23.1	15.3	4.3	4.0	27.4	19.3
Savannah River Site	21.6	14.1	0.5	0.5	22.2	14.6
Portsmouth Gaseous Diffusion Plant	13.9	6.6	7.8	7.5	21.7	14.1
Rocky Flats Environmental Technology Site			6.0	5.8	6.0	5.6
Los Alamos National Lab	0.4	0.2	3.2	3.0	3.5	3.2
Oak Ridge National Lab	1.6	1.3			1.6	1.3
K-25 Site	1.4	0.7	0.1	0.1	1.5	0.8
Sandia National Lab	0.2	0.1	0.5	0.5	0.7	0.6
Hanford Site	0.5	0.2			0.5	0.2
Brookhaven National Lab	0.3	0.2			0.3	0.2
Miscellaneous	1.8	1.2	1.9	1.8	3.7	3.0
Total					740.7	620.3

Table 2-1. U.S. HEU Inventory at Major Locations, as of September 30, 1996.[5]

Also under the Openness Initiative, in 1996, DOE published *Plutonium: The First 50 Years* in which it described the production, acquisition, and utilization of plutonium from the period of the mid-1940s through 1994. That report identified that:

- The combined DOE and DOD accountable 1994 plutonium inventory was 99.5-MT, which included a pooled 66.1-MT for the Pantex Plant near Amarillo, TX, and the U.S. nuclear weapons stockpile;

- The U.S. plutonium balance included 2.8-MT of inventory differences, equating to 2.5 percent of the total plutonium production;
- A total of 38.2-MT of accountable weapon-grade plutonium was declared surplus to defense needs and would never be used to build nuclear weapons; and,
- The amount of plutonium contained in waste was 3.9-MT located at nine different DOE sites.[6]

In 2012, DOE published an update to that report to factor in changes to data and facilities' decommissioning and opening from the period 1994 through 2009.

> The four most significant changes since 1994 include: (a) the completion of cleanup activities at the Rocky Flats Plant in 2005; (b) material consolidation and disposition activities, especially shipments from Hanford to the Savannah River Site; (c) the 2007 declaration of an additional 9.0-MT of weapons-grade plutonium to be surplus to defense needs in the coming decades; and (d) the opening of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico in 1999. These interrelated factors have not only resulted in decreases to total inventory and inventory differences but also increases in both surplus materials and materials written off the accountable inventory as waste.[7]

The DOE's 2012 report shows that as of September 30, 2009:

- The plutonium inventory, maintained under nuclear material control and accountability, is 95.4-MT, a 4.1-MT (4 percent) decrease to the 1994 inventory. The 95.4-MT total includes a combined Pantex and nuclear weapons stockpile of 67.7-MT. The most important factor for the reduction in inventory was the reclassification of process residues originally set aside for plutonium recovery as waste. Of the 4.1-MT reduction, 3.5-MT (85 percent) came from Rocky Flats residues sent to WIPP [Waste Isolation Pilot Plant] for disposition;

- **The cumulative inventory difference for accountable plutonium is 2.4-MT, a 0.4-MT (14 percent) decrease to the 2.8-MT made public in the 1996 plutonium report**. The 0.4-MT decrease in the cumulative inventory difference is attributed to materials recovered during de-inventorying and closure activities at Rocky Flats (0.3-MT) and Hanford (0.1-MT). Of the current 2.4-MT of inventory difference, 1.1-MT (46 percent) is at Hanford and 0.9-MT (38 percent) at Rocky Flats. **A large portion of the remaining 2.4-MT cumulative inventory difference appears to be explained by understated removals from inventory to waste** [emphasis added];
- Plutonium surplus to defense needs is now 43.4-MT, a 5.2-MT (14 percent) increase to the 1994 declaration; and,
- The plutonium estimated in waste is 9.7-MT, a 5.8-MT (149 percent) increase to the 1994 inventory of 3.9-MT. The 5.8-MT increase is attributed to: 4.4-MT (76 percent) in new discards from the accountable inventory; 0.8-MT (330 percent) increase in Rocky Flats solid waste generated prior to 1970; 0.4-MT (84 percent) increase in Hanford high level waste tank estimates; 0.1-MT in solid waste at a commercial low-level radioactive disposal facility not included in the 1996 report, and 0.1-MT from other sites.[8]

Obviously, the relatively large changes in total inventory, inventory differences, and continuing uncertainties in knowing what is or is not accounted for raises the possibility of diversions of fissile material in the past and perhaps in the future.

In addition to the stockpiles of HEU and plutonium produced for defense purposes, the United States produced uranium-233, a fissile material, for both its military and civilian nuclear programs. Just a few kilograms (kg) of uranium-233 could be used to make a nuclear explosive. In the early-1960s, the United States wanted to test using uranium-233 in nuclear explosives because this material is more stable than plutonium at high temperatures. The stability of plutonium under high temperatures turned out to be not that great of a concern, and the interest in using uranium-233 for weapons purposes stopped by 1966. While the United States made far less uranium-233—about 2-MT with about 1.5-MT being separated from spent fuel—than HEU or weapon-grade plutonium, **a relatively large amount of uranium-233 is unaccounted for—about 123-kg**, or 0.123-MT.[9] On a percentage basis, the portion of uranium-233 unaccounted for is somewhat greater than the inventory differences in the HEU and plutonium stockpiles.

DEFINING MATERIAL UNACCOUNTED FOR AND UNDERSTANDING WHEN IT IS A CONCERN

What exactly is meant by "material unaccounted for"? Nuclear material that cannot be accounted for is officially known as "inventory difference" material. (This name change serves the euphemistic purpose of not reminding the public that material was "unaccounted for.") No measurement system is perfect; there will always be measurement uncertainties. Consequently, to determine if there is a legitimate concern about diversion or theft of nuclear material at a facility, one needs to know how the difference in inventory compares to the limits of errors in measuring the inventory. If the former is greater than the latter, then there may be cause for concern. To calculate the inventory difference or MUF, one needs to know how much material was known to be present at the beginning check of the inventory, how much material was removed, how much was received, and how much was measured at the end check of the inventory. In a formula, one can write this as: MUF = (Beginning Inventory + Receipts) - (Removals + Ending Inventory).

If the two quantities in parentheses balance, the MUF equals zero. But because of measurement uncertainties, the MUF will most likely not equal zero for a given inventory calculation. Every measurement will have an uncertainty; by statistically combining the individual uncertainties, one can determine the limits of error of the material unaccounted for (LEMUF). If the LEMUF is calculated at a 95 percent confidence level, the null hypothesis is that MUF is zero at a 5 percent level of significance; if the LEMUF is calculated at a 99 percent confidence level, the null hypothesis is the MUF is zero at a 1 percent level of significance. The DOE now strives for the latter level of significance. According to Dr. Thomas Cochran:

> The statistical distribution of MUF will have a given one-sigma and two-sigma range. A MUF of zero does not mean that SNM [special nuclear material] is accounted for, but can be the sum of a positive MUF due to measurement error and a diversion of an equal amount of material. The value of the sigma is impor-

> tant not just in a relative sense to the percentage of the overall inventory, but in the absolute sense to the quantity of material needed to construct a nuclear weapon (i.e., kilograms range). This importance of the absolute value of the sigma is what drives requirements for very small sigma and is a challenge for facilities handling SNM in bulk or solution form.[10]

If MUF were just due to random variations in the measurements, one would expect for a series of inventory calculations that the MUF values would sum close to zero. If instead the MUF values show a tendency toward positive values, then one would suspect that there could be biased measurements, recording mistakes, unknown or unrecorded inventory, or losses or thefts of material. If the MUF values tend to be consistently negative, one would suspect biased measurements or recording mistakes.[11] Of course, the biggest concern is statistically significant positive MUF values bigger than the LEMUF because this could indicate diversion, loss, or theft.

The inventory difference also has to reconcile losses of uranium and plutonium through radioactive decay and transmutations of an element to a different element in a nuclear reactor or accelerator. Other losses or consumptions of nuclear material occur in nuclear explosives or reactors via fission. The DOE has tried to take into account these natural and manmade losses and consumptions in its historical assessment of uranium and plutonium stockpiles, which are discussed later.

Each site that contains, handles, or transfers nuclear material has to maintain a ledger to account for inventories, receipts, and removals. A site that has an appreciable amount of material usually is subdivided into more manageable areas with smaller amounts of material. These areas are termed Material Balance Areas (MBAs). An MBA is a well-defined physical area, for example, a storage vault for HEU or plutonium. Ledgers are used to track the material stored or used in an MBA and going into and out of an MBA. In effect, a ledger is like a checkbook. Each ledger for each MBA for a total site is summed periodically to determine whether the inventory balances or has differences. The MBA ledger data are sent to the national nuclear database system.

This explanation, which is the typical description one can find at government websites, for example, in the United States, United Kingdom (UK), and Canada, could not convey the difficulties in making accurate measurements, at the first reading. The uncertainties are much greater than one could imagine if one does not understand the problems in measuring several tons of nuclear material moving through bulk production and processing facilities such as large uranium enrichment and reprocessing plants. These problems have resulted in substantial uncertainties in accounting.

The United States used the gaseous diffusion method to enrich practically all of the uranium for military purposes. (During the Manhattan Project, there was some use of the electromagnetic separation and thermal diffusion methods.) The U.S. gaseous diffusion plants were immense, with thousands of diffusion barriers and miles of labyrinthine networks of pipes, pumps, and other machinery. For example, the Portsmouth Plant being decommissioned in Piketon, OH, takes up about 3,700 acres of land and has almost 200 football fields' worth of floor space in buildings for diffusion and other processing of enriched uranium.[12] During these plants' operations, enriched uranium would easily get stuck in the plants' interiors. Given the history of U.S. production of enriched uranium as discussed earlier, one has to realize that tens of thousands of tons of uranium hexafluoride gas were pumped through these plants to produce the approximately 750-MT of HEU for military purposes. It is not surprising, then, that a few metric tons are considered MUF.

But the accounting problem for tracking HEU was even worse during the decades of massive production. According to the Government Accountability Office (GAO), records were often destroyed due to records disposal instructions, or available recorded data were insufficient to assess how much material could be missing. Concerning the latter issue, the MUF for different enrichment levels was not analyzed for many major facilities during the heyday of production. Thus, one could not say how much material was unaccounted for at the 20 percent enrichment level versus the 90 percent level. (The former is just at the dividing line for HEU, and the latter is weapons-grade material and obviously of grave concern.) According to the GAO, DOE tried to reconstruct data by interviewing contractors who had worked at those sites; consequently, DOE had to rely on the memories of individual workers. At best, DOE could only determine rough estimates of the MUF at those sites. GAO assessed in 1978 that:

> it was extremely difficult for DOE management to routinely analyze the data **from an effective safeguards point of view** without conducting a detailed review of the contractors' inventory records at the facility. The agency recognized this need and in April 1977 began to require contractors to provide the necessary data for such analysis.[13] [Emphasis added.]

From the early-1940s to early-1977, DOE officials and their predecessors in the Manhattan Project and the AEC did not have an effective capability within their accounting systems to know if significant quantities of HEU were being diverted from production facilities.

Plutonium production had a different but equally demanding set of problems in permitting accurate determination of MUF. To make plutonium, reactors convert uranium-238, the very abundant nonfissile isotope of natural uranium, to plutonium-239 by having each uranium-238 nucleus absorb a neutron and then undergo two radioactive decays. Within a few days, a freshly fueled reactor will produce appreciable amounts of plutonium. (Typically, one gram of plutonium is generated for every 1 day of operation at one megawatt (mw) of thermal power. For example, a 1,000-mw thermal power-rating reactor would produce 1,000 grams or 1-kg every day.) To produce weapons-grade plutonium, which contains more than 94 percent plutonium-239, the reactor's irradiated fuel is off-loaded within a relatively short period of a few months. Letting the fuel stay in the reactor longer will result in production of undesirable isotopes such as plutonium-240 and plutonium-241.

With respect to MUF, the important point is that there is relatively rapid loading and unloading of nuclear material from these reactors, and the emphasis was on rushed production during the Cold War. During much of the period of U.S. plutonium production, computer calculations of the reactor's nuclear reactions were done to estimate the amounts of plutonium produced in each reactor rather than measuring the actual amount in each batch off-loaded. These calculations were one of the major sources of error in determining MUF. The MUF estimate was determined by using the following formula:

> MUF = Input (reactor physics calculation) – Output (to Plutonium Finishing Plant) – Waste (rough sample only) – DVessel inventory

According to a Defense Nuclear Facilities Safety Board report from 1993, the input term was the most difficult to determine and was prone to significant errors.[14] Despite the fact that several independent analyses indicated that the reactor calculations were prone to errors that would overstate the plutonium input, these calculations were used until the early-1970s. However, to try to correct for these known problems, there were some corrections made to the codes in 1961 and 1965, but other errors continued to overestimate the amount of plutonium produced. The result was that there were erroneous increases in MUF. Once a more accurate measurement system was instituted, the MUF tended to decrease by almost an order of magnitude.

The other term that was a source of major error was DVessel inventory, which measured the change in the reprocessing plant's plutonium in its vessels before and after a reprocessing campaign. The best way to calculate this value was to do a system flush after a campaign. Of course, that meant that during the campaign itself the system's operators and safeguards inspectors would not have an accurate accounting. As the Defense Nuclear Facilities Safety Board report highlights:

> On at least one occasion, in trying to determine the cause of a MUF in excess of 40-kg in 1969, all of the

> vessels, sumps, and catchbasins were flushed and inspected: total plutonium yield was less than 10 percent of the MUF.[15]

Unfortunately, these were not the only major problems in accurately accounting for nuclear material. As mentioned earlier, discharges of nuclear material in waste streams and the environment were most likely the major reasons why the MUF values were 2.4-MT for plutonium and 3.2-MT for HEU. As also noted earlier, DOE corrected in 2012 its earlier 1996 plutonium inventory report to decrease the plutonium inventory difference by 0.4-MT to account for material determined to be discarded to waste or the environment. In an independent scientific assessment in 1996, Dr. Thomas Cochran investigated plutonium inventory differences at the Rocky Flats Plant and documented numerous instances of significant MUF throughout the decades of operation of the plant. As he underscored, "The very existence of a significant MUF should trigger immediately an investigation as to its cause."[16] He pointed to a declassified study by L. Zodtner and R. Rogers in 1964 that assessed that "losses [of plutonium] have occurred almost every month, and exhibited large variations which may possibly have been due to inventory error."[17] They discussed, for example, a fire in 1957 that most likely resulted in the loss of about 6-kg of MUF. But even much bigger causes of MUF totaled almost 580-kg of "explained" losses. The unexplained losses were still about 84-kg, enough for approximately 20 nuclear bombs depending on the sophistication of the bomb design.[18] (This study was published in early-1964; Cochran details even more losses in his 1996 report.) While more recent studies of Rocky Flats have further explained much of these previously "unexplained" losses (as documented in DOE's 2012 report), there is still more than 2-MT of plutonium MUF associated with the U.S. fissile material inventory.

As the DOE admitted in its 2012 plutonium inventory report, uncertainties remain:

> about how much plutonium was actually produced, processed, and discarded to waste, especially for the period from the mid-1940s to 1970 before advances in nuclear material measurement systems and computer-aided tools to assist in the analysis of nuclear material accounting data. The uncertainties are reflected in the 2.4-MT cumulative inventory difference. This uncertainty applies especially to waste estimates, where quantities will continue to change and evolve as waste processing and characterization are performed as part of environmental cleanup activities.[19]

Similar uncertainties have greatly complicated the ability to ascertain the amounts of HEU and uranium-233 produced, processed, and discarded to waste.

THE EVOLUTION OF U.S. MILITARY NUCLEAR MATERIAL CONTROL AND ACCOUNTING SYSTEMS

Given the problems as outlined, how did the United States act to try to solve them? What are the differences between the material control and accounting systems prior to the early-1970s and today? Have there been significant improvements?

From the early- to mid-1940s, mostly during the Manhattan Project era, records were kept in manual form, and there was no standardization of accounting across facilities. In 1948, the first standard procedures were developed, which served as a prototype for the Nuclear Material Information System (NMIS). NMIS was developed because, in the early-1960s, the AEC hired Stanford Research Institute to perform a feasibility study for an improved system. The authors of the study advised creation of a central database with application of statistical techniques to evaluate shipper-receiver differences, book physical inventory differences, and list unaccounted for materials. NMIS began data collection in 1967.[20]

There is a noticeable improvement in the pre-1968 MUF and the post-1968 MUF for HEU. According to the *Striking a Balance* report, before 1968, there was 269-kg U-235 MUF, and total MUF of all commercial sites was 995-kg. (As discussed later, a large quantity of HEU was unaccounted for at the Nuclear Materials and Equipment Corporation [NUMEC] facility prior to 1968.) In comparison, after 1968, there was 76-kg U-235 MUF, and the total of all commercial sites was 549-kg.[21] Most likely the improvement in accounting systems helped decrease the MUF. But importantly, one needs to recognize that after 1968 the United States had substantively ramped down production of fissile material for military purposes. However, there was still handling of many tons of fissile material for the next couple of decades to the end of the Cold War. Since then, there has been a ramp up on the dismantlement side of handling material as the United States has disassembled thousands of warheads as a result of arms reduction agreements with Russia.

In 1976, NMIS was renamed and became the Nuclear Materials Management & Safeguards System (NMMSS). DOE and the Nuclear Regulatory Commission jointly managed this new system. (These two agencies had shortly before been created from the AEC in order to separate the promotional and regulatory aspects of nuclear power.) NMMSS requires monthly reports per site and semiannual and annual reconciliations. About 250 checks are done in the software to assess the veracity of the data.

In the late-1970s, the NRC identified many potentially serious accounting problems. Sidney Moglewer, an official in NRC's safeguards division, put the matter starkly and provocatively: "Would you rather put your money in a bank with a battalion of guards and a sloppy accounting system, or would you choose a bank with a few guards and good accounting?"[22] He and other NRC staffers reported concerns that the accounting system was ineffective and gave "little confidence . . . that [it] would catch a skillful fuel thief."[23] The NRC's investigation found that the inventory difference exceeded the limits of error about one-third of the time but indicated that was above the business-as-usual rate of 5 percent. The NRC staff's investigation concluded that sloppy accounting was partly to blame, as well as the procedures to measure the limits of error had become inconsistent and "the entire decision structure that's in the current regulations has essentially no statistical basis at all."[24] While the NRC worked on needed upgrades, a couple of commissioners at that time expressed their concern that one of the main culprits for these inventory differences, or MUF, was at one or two facilities that handled naval fuel. In particular, Commissioner Victor Gilinsky said, "You've got some old plants that are not set up to measure things accurately, and they happen to supply fuel for the Navy."[25] Another commissioner on background identified the primary problem facility as the Nuclear Fuel Services Plant in Erwin, TN, which then was the main supplier of fuel for naval submarines. It would routinely have MUF values of about 1-kg per month. Because the Navy needed the fuel, the government's accountants let this facility continue making fuel despite the large values of MUF.[26]

DOE's Office of the Inspector General also performs inspections of DOE facilities to check on the effectiveness of the accounting system. In addition, the GAO conducts its own assessments of aspects of DOE's material control and accounting system. Here is summarized some important findings from past DOE inspector general and GAO reports.

In a 1978 report, GAO noted "the inability of material accountability systems to accurately measure and account for all nuclear materials in a timely manner because of state-of-the-art limitations and the need for tighter physical security requirements" and that these findings were also identified in July 1976 and May 1977.[27] The 1978 report also found:

> Changes in reported MUF data only underscore the imprecision and subjective judgments involved in accounting for MUF. Authorities believe that MUF is attributed to measurement biases and unmeasurable material held up in equipment, nevertheless no one can be certain of the actual location of the unaccounted for materials.[28]

A more recent GAO report from 2011 assessed the U.S. Government's ability to account for, monitor, and evaluate the security of U.S. nuclear material overseas and found that "nuclear cooperation agreement terms . . . do not stipulate systematic reporting of such information, and there is no U.S. policy to pursue or obtain such information." Moreover, "DOE and NRC do not have a comprehensive, detailed, current inventory of U.S. nuclear material . . . overseas that includes the country, facility, and quantity of material." Furthermore:

> [n]uclear cooperation agreements do not contain specific access rights that enable DOE, NRC, or State to monitor and evaluate the physical security of U.S. nuclear material overseas, and the United States relies on its partners to maintain adequate security.

Finally, "[o]f the 55 visits made from 1994 through 2010, U.S. teams found that countries met international security guidelines approximately 50 percent of the time."[29]

The DOE inspector general has issued several reports detailing lapses in accounting for nuclear materials. In an October 2001 report, the inspector general identified that DOE could not fully account for nuclear materials loaned or leased to domestic licensees, at least partly due to inaccurate and/or incomplete NMMSS record keeping.[30] In a February 2009 report, it found:

> For about 37 percent (15 of 40) of the domestic facilities we reviewed, the Department could not accurately account for the quantities and locations of certain nuclear materials. In a number of cases, the Department had also agreed to write-off large quantities without fully understanding the ultimate disposition of these materials. . . . During 2004, a number of domestic licensees reported that their actual holdings of Department-owned nuclear materials were less than the quantities recorded in NMMSS. Based on that information, the Department agreed to write-off over 20,000 grams of special nuclear material . . . without investigating the whereabouts or actual disposition of the material. . . . A 32 gram plutonium-beryllium source on loan to a college and subsequently transferred to another academic institution was not accounted for in NMMSS.[31]

While these problems are serious, the materials in question were not identified as significant amounts of category I nuclear material, which can be directly used in nuclear explosives. Nonetheless, improvements are needed within the management and accounting systems.

Concerning improvements, the 2009 inspector general's report recommended conducting a confirmation of balances of DOE-owned materials and establishing a schedule for periodic confirmations, reconciling this information with NMMSS data, periodically confirming the continuing need for DOE-owned nuclear material at domestic licensees, and improving training. The GAO's 2011 report recommended:

- Determining a baseline inventory of weapon-usable U.S. nuclear material overseas; establishing procedures for annual reconciliations.
- Facilitating visits to sites that U.S. physical protection teams have not visited that are believed to hold category I material.
- Seeking to include physical protection access rights in new or renewed nuclear cooperation agreements. Careful consideration should be given to the impact of any reciprocity clause on U.S. national security.
- Developing an official central repository to maintain data regarding U.S. inventories of nuclear material overseas.
- Developing formal goals for and a systematic process to determine which foreign facilities to visit for future interagency physical protection visits.
- Periodically reviewing performance in meeting programmatic goals.[32]

A very recent DOE inspector general's report raises concerns about the Los Alamos National Laboratory's accounting system that illustrates that even 98.34 percent accuracy is insufficient; the number of errors found showed that the accounting system fell short of its target objective of 99 percent accuracy.[33] This inspector general's report is a follow-up to the September 2007 report on weaknesses found at Los Alamos' accounting system. The July 2013 report found that while the "materials in question were relatively small and the control and accounting issues did not involve materials in sufficient quantity, enrichment and/or configuration to pose a high level of risks," these "issues were, however, worthy of correction and could enhance accounting of higher security category nuclear materials."[34] One of the biggest findings was that "it was standard practice for Los Alamos Materials Control & Accountability (MC&A) Group personnel to conduct inventories in the MBAs we reviewed only on a biennial basis," which raised the concern that "this periodic oversight was not sufficient to ensure MBA inventory control and accounting concerns were identified and addressed in a timely manner."[35]

An independent assessment a couple of years ago by Jonas Siegel of the University of Maryland also highlighted concerns about the effectiveness of the NMMSS. He pointed out that NMMSS:

> relies entirely on facility-level systems to provide detailed, accurate accounting data in a timely fashion . . . varying levels of detail leave significant gaps in what U.S. officials know and can report about U.S. materials; . . . data submitted to NMMSS doesn't always distinguish between what material is in which material balance area within a facility; it doesn't always accurately reflect the location of in-transit materials;

> and changes in inventory aren't always reported in a timely fashion.[36]

INSIDER THREAT

The biggest security concern often comes from those who know nuclear facilities best: employees and management. They have privileged access and, if managers, have authority to coerce subordinates. Thus, insiders have means and opportunities; it will just take motivations to push insiders to exploit vulnerable security systems. According to the National Nuclear Security Administration (NNSA):

> Almost all known cases of theft of nuclear material involved an insider. . . . Even when the insider's illicit activities are observed by coworkers, they often go unreported due to the unwillingness of many workers to recognize the potential for an insider threat and to report on a colleague or especially a boss if a supervisor is the insider thief.[37]

A RAND study from 1990 found that insider/outsider collusion is most relevant to potential crimes targeting nuclear assets. Most of the insiders profiled in the RAND study (focused on conventional crimes given the paucity of data on nuclear crimes) were motivated primarily or solely for financial gain. This finding suggested to the RAND researchers that an outside group "could secure an insider's assistance simply by paying him or her."[38] Perhaps this report's "most important finding" is that success of the criminal operation "seemed to depend less on detailed planning or expert execution than on the exploitation of existing security flaws." The RAND report, however, emphasized, "none of the organizations in our database employed security equivalent to that at a nuclear facility."[39]

The RAND study also found that guard forces pose a "particularly vexing problem"; specifically, guards "were responsible for 41 percent of the crimes committed **against guarded targets"** [emphasis in the original]. Guards obviously know the security routines and can exploit times when supervisors may not be watching or checking up on the guards.

In addition, the RAND report highlights motivations other than financial gain, including "family ties, misplaced altruism, and ideological allegiances." It cautions that:

> security considerations in hiring, guarding, controlling, and checking people can become so cumbersome as to impede the operation of the facility they are meant to protect. Therefore, no organization, no matter how ingeniously protected, can operate without some trust in individuals on all levels. . . . Total security can never be attained, nor can insider crime ever be completely prevented. However, security officials can and must keep all possibilities in mind at all times, to avoid surprises and to be prepared at least to minimize damage.[40]

To protect against thefts of nuclear material, the NNSA recommends and implements a multilayered approach. NNSA categorizes these approaches into two areas: administrative controls and policies, and technical systems. For the former, "human reliability programs help identify at-risk employees before they can become a threat." NNSA also highlights nuclear security culture programs that:

> educate employees on the threat, encourage robust procedural adherence and effective management, and help employees understand their personal responsibility for nuclear material security.[41]

While nuclear security culture is important, it is not sufficient to stop a highly motivated insider; in that respect, personnel reliability programs are essential but may still not be enough. Consequently, to further strengthen the multilayered approach to security, technical systems provide access controls, material controls, and detection and delay features.

> Access control systems and material controls can be used to help enforce administrative controls such as the two person rule, compartmentalization of information, and separation of duties. Detection systems identify when an insider violates access requirements, and delay barriers can impede an insider from accessing a target.[42]

An independent assessment from the late-1980s emphasized the importance of enforcing the two-person rule but pointed out that there has been substantial resistance to implementing it.[43]

THE CASE OF NUMEC AND THE MISSING HEU

Perhaps the greatest alleged incident of insider theft happened in the 1960s at NUMEC, located in Apollo, PA. NUMEC was a nuclear fuel processing plant. In 1965, an AEC inspection at the facility discovered more than 100-kg of unaccounted for HEU. But for several years after this finding, concerns were mounting that the U.S. Government was covering up what happened to the unaccounted for HEU. In part to address these concerns, in 1977, 12 years after the aforementioned inspection, John Dingell, then the Chairman of the House's Subcommittee on Energy Power of the Committee on Interstate and Foreign Commerce, requested that the GAO investigate the so-called NUMEC affair. Specifically, he asked GAO to concentrate primarily on two questions: 1) What information has been developed about the alleged diversion? and 2) Were the investigations done by the federal government adequate?

GAO reported that it was seriously constrained in its review because it "was continually denied necessary reports and documentation on the alleged incident by the Central Intelligence Agency (CIA) and the Federal Bureau of Investigation."[44] The allegations included:

- The material was illegally diverted to Israel by NUMEC's management for use in nuclear weapons.
- The material was diverted to Israel by NUMEC's management with the assistance of the CIA.
- The material was diverted to Israel with the acquiescence of the U.S. Government.
- There has been a cover-up of the NUMEC incident by the U.S. Government.[45]

The GAO did point out that the government investigations had put pressure to improve the U.S. safeguards program. Indeed, there has yet to be an incident of this alleged magnitude since 1965. Regarding GAO's investigation of the relevant documents from previous investigations:

> GAO cannot say whether or not there was a diversion of material from the NUMEC facility. DOE has taken the position that it is aware of no conclusive evidence that a diversion of nuclear material ever occurred at the NUMEC facility, although it recognizes that the possibility cannot be eliminated.[46]

In addressing Chairman Dingell's key questions, the GAO concluded that U.S. Government agencies' investigations were "uncoordinated, limited in scope and timeliness . . . and less than adequate."[47] Another important finding was that the United States:

> needs to improve its efforts for effectively responding to and investigating incidents of missing or unaccounted for weapons-grade nuclear materials. In view of increasing terrorist activities throughout the world, the ability to respond and investigate such incidents should be of concern to national security and the public health and safety.[48]

In a much more recent article on this alleged diversion, Gilinsky and Roger Matson document that by the early-1960s, there were "worrisome signs" that NUMEC's "security and accounting were deficient."[49] They also pointed out concerns about the chief executive officer's connection to the Israeli government and the visits by Israeli officials and technical experts. While, like the GAO, they note that no direct evidence of a diversion was ever uncovered, they believe, based on their extensive assessment, that "the circumstantial evidence supports the conclusion that the HEU ended up in Israel."[50]

CONCLUSION: ADEQUACY OF TIMELY WARNING AND THE WILLINGNESS TO ACT

What are "good enough" accounting procedures? Adequate accounting should, at a minimum, give enough warning of a potential theft or diversion of a bomb's worth of nuclear material. As mentioned several times in this chapter, the United States has had incidents where accounting lapses have occurred or an alleged major insider theft has happened. Assuming that thefts or diversions had occurred, the warning signs would have come too late to prevent someone or some group from making any possibly stolen or diverted nuclear material into nuclear explosives. Effective safeguards should deter diversion by raising the risk of getting caught. But if weeks, months, or even more than 1 year can go by without detection, the accounting system is not adequate because in as little as 1 week, a few kilograms of category I nuclear material could be enough to make a nuclear explosive. Nonetheless, as discussed in this chapter, the United States made significant improvements in its accounting system after the 1960s. But as recent GAO and DOE inspector general reports have indicated, the United States still has improvements to make in its current accounting system because it has yet to meet its own standards.

ENDNOTES - CHAPTER 2

1. Comptroller General of the United States, "Reconciliation of Special Nuclear Material," EMD-78-58; B-157767, Washington, DC: GAO, May 5, 1978.

2. *Ibid*.

3. Office of the Deputy Administrator for Defense Programs, *Highly Enriched Uranium: Striking a Balance: A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, Washington, DC: U.S. DOE, National Nuclear Security Administration, January 2001, p. 11.

4. *Ibid.*, p. 37.

5. *Ibid.*, p. 38.

6. *The United States Plutonium Balance, 1944-2009, An Update of Plutonium: The First 50 Years*, DOE/DP-0137, February 1996, Washington, DC: U.S. DOE, National Nuclear Security Administration, June 2012, p. 1.

7. *Ibid*.

8. *Ibid.*, pp. 2-3.

9. Robert Alvarez, "Managing the Uranium-233 Stockpile in the United States," *Science & Global Security*, Vol. 21, 2013, pp. 53-69.

10. Dr. Thomas Cochran, Communication with the Author, December 17, 2013.

11. Directorate of Regulatory Standards, "Regulatory Guide 5.33: Statistical Evaluation of Material Unaccounted For," Washington, DC: U.S. AEC, June 1974.

12. U.S. DOE, "Portsmouth Gaseous Diffusion Plant Overview," Piketon, OH: Portsmouth/Paducah Project Office, ETS Pre-Solicitation Meeting June 26, 2012.

13. Comptroller General of the United States, "Reconciliation of Special Nuclear Material."

14. Timothy J. Dwyer, Hanford Site Program Manager, "Report on Review of Plutonium Uranium Extraction (PUREX) Facility Material Unaccounted For (MUF)," Memorandum for G. W. Cunningham, Technical Director, Washington, DC: Defense Nuclear Facilities Safety Board, February 22, 1994.

15. Thomas Cochran, "Plutonium Inventory Differences at the Rocky Flats Plant and Their Relationship to Environmental Releases," New York: Natural Resources Defense Council, November 22, 1996.

16. *Ibid*.

17. L. L. Zodtner and R. F. Rogers, "Study of Unaccounted for Plutonium Losses," Golden, CO: Dow Chemical Company, January 6, 1964.

18. Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," New York: Natural Resources Defense Council, Revised April 13, 1995.

19. *The United States Plutonium Balance, 1944-2009*, p. 3.

20. "What is the History of the NMMSS?" Fact Sheet, Washington, DC: National Nuclear Security Administration, available from *nnsa.energy.gov/aboutus/ourprograms/nuclearsecurity/nmmss-home/nmmssinfo/faqs/abouthistorynmmss*.

21. *Highly Enriched Uranium: Striking a Balance*.

22. Eliot Marshall, "Nuclear Fuel Account Books in Bad Shape," *Science*, Vol. 211, No. 4478, January 9, 1981, pp. 147-148, 150.

23. *Ibid*.

24. *Ibid*.

25. *Ibid*.

26. *Ibid*.

27. Report to Rep. John D. Dingell, Chairman, House Committee on Interstate and Foreign Commerce: Energy and Power Subcommittee, "Reconciliation of Special Nuclear Material Unaccounted For," EMD-78-58, Washington, DC: U.S. GAO, May 5, 1978, p. 1.

28. *Ibid.*, p. 5.

29. "U.S. Agencies Have Limited Ability to Account for, Monitor, and Evaluate the Security of U.S. Nuclear Material Overseas," Report to the Committee on Foreign Affairs, House of Representatives, GAO-11-920, Washington, DC: U.S. GAO, September 2011.

30. Office of Inspector General, "Accounting for Nuclear Materials Provided to Non-Departmental Nuclear Facilities," Washington, DC: U.S. DOE, October 2001.

31. Office of Inspector General, "The Department's Management of Nuclear Materials Provided to Domestic Licensees," DOE/IG-0813, Washington, DC: U.S. DOE, February 2009.

32. "U.S. Agencies Have Limited Ability to Account for, Monitor, and Evaluate the Security of U.S. Nuclear Material Overseas," Report to the Committee on Foreign Affairs, House of Representatives, GAO-11-920, Washington, DC: GAO, September 2011.

33. John Fleck, "Plutonium Accounting Falls Short, DOE Finds," *Albuquerque Journal*, July 24, 2013.

34. Office of Inspector General, "Follow-up Inspection on Material Control and Accountability at Los Alamos National Laboratory," INS-O-13-04, Washington, DC: U.S. DOE, July 2013, p. 2.

35. *Ibid.*, p. 2.

36. Jonas Siegel, "Emerging Demands on National Nuclear Material Accounting Systems," Paper presented at Institute for Nuclear Materials Management conference, July 2011, College Park, MD: Center for International and Security Studies, University of Maryland.

37. "Insider Threat to Nuclear and Radiological Materials," Fact Sheet, Washington, DC: National Nuclear Security Administration, March 23, 2012.

38. Bruce Hoffman, Christina Meyer, Benjamin Schwartz, and Jennifer Duncan, *Insider Crime: The Threat to Nuclear Facilities and Programs*, Report Prepared for the U.S. Department of Energy, Santa Monica, CA: RAND, February 1990, p. vi.

39. *Ibid*.

40. *Ibid.*, p. vii.

41. "Insider Threat to Nuclear and Radiological Materials."

42. *Ibid*.

43. Daniel Hirsch, "The Truck Bomb and Insider Threat to Nuclear Facilities," Paper Prepared for the International Task Force on the Prevention of Nuclear Terrorism, Washington, DC: Nuclear Control Institute, 1987.

44. "Nuclear Diversion in the U.S.? 13 Years of Contradiction and Confusion," Report by the Comptroller General of the United States, Washington, DC: U.S. GAO, December 18, 1978, p. ii.

45. *Ibid.*, pp. ii-iii.

46. *Ibid.*, p. v.

47. *Ibid.*, p. vii.

48. *Ibid*.

49. Victor Gilinsky and Roger J. Mattson, "Revisiting the NUMEC Affair," *Bulletin of the Atomic Scientists*, March-April, 2010, p. 62.

50. *Ibid.*, p. 70.