CHAPTER 6

ADEQUACY OF IAEA'S SAFEGUARDS FOR ACHIEVING TIMELY DETECTION

Thomas B. Cochran

INTRODUCTION

The purpose of this chapter is to examine, in light of the A. Q. Kahn network in Pakistan and recent events in Iran and North Korea, the adequacy of the International Atomic Energy Agency's (IAEA) safeguards for achieving timely detection of an effort to acquire nuclear weapons by a non-weapon state. For those less familiar with the obligation of state members of the Treaty on the Non-Proliferation of Nuclear Weapons (Non-Proliferation Treaty, or NPT) and/or states that operate under agreements with the IAEA, the Appendix to this chapter includes relevant excerpts from the NPT, the IAEA's enabling statute, and other IAEA publications.

THE OBJECTIVE OF SAFEGUARDS

As set forth in Article III.1 of the NPT, a primary purpose of IAEA's safeguards system is to prevent "diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices." (See Appendix, Non-Proliferation Treaty).

Since Article III.1 of the NPT stipulates that IAEA safeguards *shall be followed*, any violation of IAEA safeguards is a violation of Article III of the NPT and therefore a violation of the treaty. Thus, when observers point out that the IAEA has no mandate to verify compliance with the NPT but only compliance with IAEA safeguards agreements, this is at best misleading since failure to comply with an applicable IAEA safeguards agreement is a violation of the NPT.

As set forth in the IAEA's enabling statute, IAEA safeguards are "designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose . . ." (see Appendix, IAEA's Enabling Statute).

The IAEA's enabling statute gives the IAEA certain rights. Among them is the right to establish an inspection system that is designed to ensure that the purpose of the safeguards is met. IAEA document INFCIRC/153, which details the safeguards obligations of states that are party to the NPT, provides a technical definition of the object of IAEA safeguards, namely, "the objective of safeguards is the timely detection of diversion of significant quantities of *nuclear material* from peaceful activities to the manufacture of nuclear weapons or of other explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[1]

KEY SAFEGUARDS TERMS

The key terms of the objective of safeguards were not defined in INFCIRC/153; this task was given to the Standing Advisory Group on Safeguards Implementation (SAGSI) of the IAEA, an advisory group of technical safeguards experts.[2]

SAGSI considered the problem of quantifying the safeguards objective for several years. It identified four terms appearing either explicitly or implicitly in the statement of the objective just quoted as in need of quantitative expression. These were: significant quantities, timely detection, risk of detection, and the probability of raising a false alarm. It defined the associated numerical parameters (significant quantity, detection time, detection probability, and false alarm probability) as detection goals.[3]

In 1977, SAGSI submitted numerical estimates for these goals to the Director of Safeguards of the IAEA. The values recommended by SAGSI for the detection goals were carefully described as provisional guidelines for inspection planning and for the evaluation of safeguards implementation, not as requirements, and were so accepted by the Agency.[4] They have since been incorporated in the *IAEA Safeguards Glossary*, excerpts of which are reproduced below and in the Appendix.

Significant Quantity.

Significant quantity (SQ) is the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses.[5] Significant quantity values currently in use by the IAEA are given in Table 1.

In a previous Natural Resources Defense Council (NRDC) report, we argued that the IAEA's SQ values for direct use materials are not technically valid or defensible, and it was proposed that the SQ values for direct use plutonium and HEU be reduced by a factor of about eight.[6] Table 2 gives the approximate plutonium

Material	SQ
Direct Use Nuclear Material	
Pu[a]	8kg Pu
^{233}U	8kg ^{223}U
Highly enriched uranium [HEU] (^{235}U>20%)	25kg ^{235}U
Indirect Use Nuclear Material	
U (^{235}U < 20%)[b]	75kg ^{235}U (or 20t natural U or 20 t depleted U)
Th	20 t Th
a. For Pu containing less than 80 percent ^{238}Pu. b. Including low enriched natural and depleted uranium.	

Table 1. Significant Quantities.[7]

WEAPON-GRADE PLUTONIUM (kg)				HIGHLY-ENRICHED URANIUM (kg)		
Yield	Technical Capability			Technical Capability		
(kt)	Low	Medium	High	Low	Medium	High
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5
Values rounded to the nearest 0.5 kilogram.						

Table 2. NRDC Estimate of the Approximate Fissile Material Requirements for Pure Fission Nuclear Weapons.[8]

and HEU requirements for pure fission weapons as estimated by NRDC. Regarding indirect use material, we note that 375 kilograms (kg) of 20 percent-enriched uranium, which contains one SQ (75kg of ^{235}U), when enriched, using a tails assay of 0.2 to 0.3 percent, yields

79-80kg of 93.5 percent-enriched product, which is three times larger than the SQ for direct use HEU. While it is not the purpose of this chapter to reexamine the validity of the SQ values, we simply note the obvious: if the SQ values are substantially lowered, it could significantly impact estimated conversion times.

Detection Time.

Detection time is the maximum time that may elapse between diversion of a given amount of nuclear material and detection of that diversion by IAEA safeguards activities. Where there is no additional protocol in force or where the IAEA has not drawn a conclusion of the absence of undeclared nuclear material and activities in a state (see *IAEA Safeguards Glossary*, No. 12.25), it is assumed that: (a) all facilities needed to clandestinely convert the diverted material into components of a nuclear explosive device exist in a state; (b) processes have been tested (e.g., by manufacturing dummy components using appropriate surrogate materials); and (c) nonnuclear components of the device have been manufactured, assembled, and tested. Under these circumstances, **detection time should correspond approximately to estimated conversion times** (see *IAEA Safeguards Glossary*, No. 3.13). Longer detection times may be acceptable in a state where the IAEA has drawn and maintained a conclusion of the absence of undeclared nuclear material and activities. Detection time is one factor used to establish the timeliness component of the IAEA inspection goal (see *IAEA Safeguards Glossary*, No. 3.24).[9] [Emphasis added]

Conversion Time.

Conversion time is the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device. Conversion time does not include the time required to transport diverted material to the conversion facility or to assemble the device, or any subsequent period. The diversion activity is assumed to be part of a planned sequence of actions chosen to give a high probability of success in manufacturing one or more nuclear explosive devices with minimal risk of discovery until at least one such device is manufactured.[10] The conversion time estimates applicable at present under these assumptions are provided in Table 3.

Beginning Material Form	Conversion Time
Pu, HEW, or ^{233}U metal	Order of days (7-10)
PuO_2, $PU(NO_3)_4$ or other pure Pu compounds; HEU or ^{233}U oxide or other pure U compounds; MOX or other nonirradiated pure mixtures containing Pu, U (^{233}U+^{235}U>20%); Pu, HEU, and/or ^{233}U in scrap or other miscellaneous impure compounds	
PU, HEU, or ^{233}U in irradiated fuel	Order of months (1-3)
U containing <20% ^{235}U and ^{233}U; Th	Order of months (3-12)
a This range is not determined by any single factor, but the pure Pu and U compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.	

Table 3. Estimated Material Conversion Times for Finished Pu or U Metal Components.[11]

IAEA Timeliness Detection Goal.

The IAEA timeliness detection goal is the target detection times applicable to specific nuclear material categories (see *IAEA Safeguards Glossary*, No. 4.24).

These goals are **used for establishing the frequency of inspections** (see No. 11.16) and safeguards activities at a facility or a location outside facilities during a calendar year to verify that no abrupt diversion (see *IAEA Safeguards Glossary*, No. 3.10) has occurred. Where there is no additional protocol in force or where the IAEA has not drawn and maintained a conclusion of the absence of undeclared nuclear material and activities in a state (see *IAEA Safeguards Glossary*, No. 12.25), **the detection goals are as follows:**

- **One month for unirradiated direct use material,**
- **Three months for irradiated direct use material,** and
- **One year for indirect use material**.

Longer timeliness detection goals may be applied in a state where the IAEA has drawn and maintained a conclusion of the absence of undeclared nuclear material and activities in that state.[12]

With regard to the IAEA's timeliness detection goals, it should be noted that the Agency's resource limitations and resistance of member countries keep the actual inspection frequencies lower than the goals.[13]

ADEQUACY OF CONVERSION TIMES AND DETECTION GOALS

We now turn to the issue of the adequacy of the IAEA's estimated conversion times set forth in Table 3 above, and the timeliness detection goals set forth in paragraph 3.20, of the *IAEA Safeguards Glossary*. We begin with unirradiated direct use material.

Unirradiated Direct Use Material in Metal Form.

As seen in Table 3, the IAEA estimates that it will take a state on the "order of days (7-10)" to manufacture finished nuclear weapon components from plutonium, HEU or ^{233}U metal, where it is assumed that: (a) all facilities needed to clandestinely convert the diverted material into components of a nuclear explosive device exist in a state; (b) processes have been tested (e.g., by manufacturing dummy components using appropriate surrogate materials); and (c) that non-nuclear components of the device have been manufactured, assembled, and tested.

This is not an unreasonable estimate based on the time it took the United States to fabricate finished HEU components for the *Little Boy* device dropped on Hiroshima, Japan, on August 6, 1945. Consistent with the IAEA assumption, the non-nuclear components of *Little Boy* were assembled and tested before the all of the HEU was produced.

The HEU metal was shipped from Oak Ridge, Tennessee, to Los Alamos, New Mexico, in batches over a period of about a year. In the 6-week period from June 16 to July 28, Oak Ridge produced about 22kg of HEU. This was shipped to Los Alamos in batches of a few kilograms each. We estimate that the cumulative Oak Ridge production of HEU through July 14, 1945, was about 67kg, only 3kg in excess of what went into *Little Boy*. Thus, allowing for some losses, it is unlikely that Oak Ridge had produced enough HEU for *Little Boy* before that date.

The shipments of HEU metal from Oak Ridge to Los Alamos by road and rail typically took about 2 days. The shipment of the last six HEU finished components departed in three cargo planes carrying two components each from Kirtland Field, Albuquerque, New Mexico, on the morning of July 26, and, after stopping in San Francisco, arrived at Tinian in the Mariana Islands, South Pacific, on July 28. Thus, allowing for 2 days to transport the HEU metal from Oak Ridge to Los Alamos, Los Alamos must have fabricated the last of the HEU components in 9 days or less.

Little Boy was a gun-assembly type weapon requiring more than one SQ of HEU. The IAEA assumptions are based on an SQ value of 25kg of HEU, which implies an implosion device that would require the casting and machining of only one or two components. Moreover, although it took a relatively long time to enrich the HEU for *Little Boy*, this longer HEU production period is not a factor to be considered here. In sum, if we are correct that it took 9 days or less for Los Alamos to fabricate a few HEU *Little Boy* components in 1945, then 7-10 days is also reasonable assumption for the time it would take today for a state to manufacture finished components for an implosion-type weapon from an SQ amount of HEU.

Although the estimated detection time for direct use material appears reasonable, what is puzzling is that the timeliness detection goal is much longer, namely 1 month according to paragraph 3.20 of the *IAEA Glossary* (reproduced above). Moreover, both the estimated detection time and the timeliness detection goal, in our view, are far too short to allow time for diplomatic pressure to prevent the non-weapon state from fabricating a weapon. In fact, there is insufficient time to the IAEA staff to develop its report to the Board of Governors of the IAEA and for the Board of Governors to report to the UN Security Council.

Unirradiated Direct Use Material in Chemical Compounds and Mixtures.

As seen in Table 3, the IAEA estimates that it will take a state on the "order of weeks (1-3)" to manufacture finished components from unirradiated mixed-oxide (MOX) fuel, or from other compounds or mixtures containing plutonium, HEU or ^{233}U, again assuming that: (a) all facilities needed to clandestinely convert the diverted material into components of a nuclear explosive device exist in a state; (b) processes have been tested (e.g., by manufacturing dummy components using appropriate surrogate materials); and (c) non-nuclear components of the device have been manufactured, assembled, and tested.

Certainly, the lower end of this range—that is, on the order of a week—is a reasonable estimate of the time required in that it assumes that the time to convert the compound to a metal does not add appreciably to the time estimated to convert the metal to a finished component shape.

The upper end of the range—on the order of 3 weeks—seems unnecessarily generous. For example, plutonium metal can be prepared by calcium reduction of plutonium fluorides or oxides in induction-heated MgO crucibles, under an inert atmosphere of helium or argon.[14] Preparation of plutonium metal by reduction of a halide with an alkali or alkaline earth metal in a sealed pressure bomb is the only facet of chemical processing of plutonium that has remained unchanged over the years.[15] Using this technique, a few SQs of plutonium could readily be prepared in a small hot cell in a few days' time.

In any case, whether starting with unirradiated direct use material in metal or compound form, setting a timeless detection goal of 1 month is longer than any conservative estimate of the conversion time and shorter than the time required to bring diplomatic pressure to bear to halt the program.

Pu, HEU or ^{233}U in Irradiated Fuel.

Here the IAEA estimates a conversion time of on the "order of months (1–3)" and the IAEA's timeliness detection goal is 3 months. Assuming the plutonium or HEU is in irradiated fuel, the state must reprocess the fuel, convert the product into metal, and fabricate finished components. With regard to the reprocessing step, there are three diversion cases to consider: 1) the state already operates one or more reprocessing plants, pilot plants, or hot cells under IAEA safeguards; 2) it possesses a clandestine pilot reprocessing plant or hot cell; or 3) the state constructs a small "quick and dirty" reprocessing plant. Another important consideration is the spent fuel cooling time, that is, the time period between the removal of the irradiated fuel from the reactor and commencement of reprocessing.

Due to the high radioactivity levels and high thermal heat output associated with high burnup spent fuel from power reactors, the irradiated fuel is cooled 180 days or longer prior to reprocessing. For low burnup fuel, e.g., fuel elements or target materials removed from plutonium production reactors, the irradiated fuel can be processed after a shorter cooling period. In the United States during the Manhattan Project, the first fuel elements removed from the Hanford production reactors in late-1944 and early-1945 were chemically processed after only about 32-50 days of cooling time. Plutonium product was removed within a week of initiation of the batch processing.

If a state such as Japan already operates a declared reprocessing plant under safeguards, it could divert limited quantities of separated plutonium from plant operations with a low probability of detection by the IAEA, absent an informer. The inventory difference (ID) of reprocessing plants is on the order of 0.5 to 1 percent of the fuel throughput. High burnup, light water reactor (LWR), spent fuel typically contains approximately 1 percent plutonium. Thus, a pilot-scale reprocessing plant, if it processed 80 tons (t) of LWR spent fuel per year, would have an annual cumulative ID of about 0.5 to one SQ of plutonium. Some large-scale commercial reprocessing plants have a capacity that is 10 times greater.

Thus, a state with a large declared reprocessing plant under IAEA safeguards could divert an SQ of plutonium without detection over a period of about 1 month. A state with a pilot–size plant could divert the same quantity over a period of 1 year.

Some advanced reprocessing technologies contemplate not completely separating the plutonium from some actinides and fission products. While this should make it more difficult for an insider to divert plutonium, it would not represent a significant added barrier to a state effort to divert plutonium. Given that the added actinides and fission products would not add significantly to the plutonium mass, the state could divert the spiked plutonium to a small clandestine hot cell for additional processing. The processing time to recover an SQ of plutonium should take only a few days.

If a state does not have an existing declared reprocessing facility, it has the option of developing a clandestine capability, such as the Israeli facility hidden for years below the Dimona reactor. Alternatively, the state could attempt to develop a "quick and dirty" reprocessing capability. The feasibility of clandestine reprocessing of LWR fuel has been addressed by Oak Ridge National Laboratory,[16] Sandia Laboratories,[17] and others, and these studies have been reviewed by Marvin Miller.[18]

"The [Oak Ridge] study concluded the [reprocessing] plant could be in operation 4 to 6 months from the start of construction, with the first 10 kilograms of plutonium metal (about two bomb's worth) produced about 1 week after start of operation. Once in operation, the small plant could process about one PWR [pressurized water reactor] assembly per day, which translates into production of about 5 kilograms of plutonium per day."[19]

The 1966 Sandia study estimated the preparation lead-time for producing the first kilograms of plutonium employing a staff of six technicians was about 8 months.[20]

In sum, if a state has a declared pilot-scale or larger reprocessing plant, the conversion time should be the same as for unirradiated compounds of direct use materials, since the state could divert unirradiated compounds of direct use materials without being detected by the IAEA.

Low Enriched Uranium.

Here the IAEA estimates a conversion time of on the "order of months (3-12)" and the IAEA's timeliness detection goal is 1 year. The enrichment work, measured in kilograms of separative work units (kg SWU, often abbreviated SWU), required to obtain one SQ of HEU is a function of ^{235}U concentration of the uranium feed, product, and tails. Marvin Miller has identified and reviewed the major proliferation risks associated with centrifuge enrichment plants: (1) secret use of a declared, safeguarded low-enriched uranium (LEU) plant to produce HEU or exceeds LEU covertly; (2) construction and operation of a clandestine plant to produce HEU; and (3) conversion of a declared, safeguarded LEU plant to HEU production following breakout.[21]

According to Miller:

(1) The basic "Hexapartite" safeguards approach for centrifuge plants was developed during the early 1980s by a group of six countries—Germany, the United Kingdom, and the Netherlands (the URENCO states), and the United States, Japan, and Australia. It consists of two sets of activities:

(a) verifying the uranium material balance by measuring the amount of uranium as UF6 introduced into the plant as feed material and withdrawn as enriched product and tails; and.

(b) verifying that no material beyond the declared enrichment level, in particular, no HEU is being produced.

While (a) doesn't require inspector access to the cascade halls where the centrifuges are installed, (b) does, and the inspection procedures were designed to provide an element of surprise in order to deter production of HEU between routinely scheduled inspections, while also accounting for the plant operator's concern about the inspector's gaining knowledge of proprietary information relating to the construction and operation of the centrifuges. Various technical difficulties have been encountered over the years in applying (b) at specific plants. But confidence in the IAEA's ability to detect illicit production of HEU has improved dramatically since 1995 with the introduction of sampling and subsequent analysis of particles deposited on surfaces in the cascade area as a standard safeguards tool. Since release of particles to the plant environment is difficult to avoid and the analysis is highly precise, environmental sampling has emerged as a significant deterrent to clandestine HEU production in a declared LEU plant. On the other hand, current safeguards procedures cannot detect the production of LEU in excess of what the plant operator declares to be the normal production rate,[22] and this can significantly increase the difficulty of detecting a clandestine plant, as we discuss next.

(2) The much smaller energy consumption and process area characteristic of centrifuge plants compared to gaseous diffusion plants of the same separative capacity make the former much more difficult to detect. For example, a centrifuge plant with a separative capacity of 5,000 SWU/yr—sufficient to produce 25kg/yr of 90 percent enriched uranium—would likely require less than 100kW of power and have a "footprint" of about 500m^2.[23] Moreover, detection by wide area environmental monitoring is also difficult because emissions from a centrifuge plant normally are very small. The plant operates under high-vacuum conditions so that leaks primarily lead to an inflow of air into the centrifuge equipment, not to a significant release of UF6 from the system into the environment. Finally, as noted above, if excess LEU is used as feed for the clandestine plant instead of natural uranium,

the size of plant required to produce a given amount of HEU product is reduced significantly, especially if the tails concentration is also increased.

(3) There is the possibility of breakout, i.e., takeover by a state of a declared, safeguarded LEU centrifuge plant, and reconfiguration of the plant to produce weapons grade uranium.[24] Because of its high separation factor compared to the gaseous diffusion process, the inventory of a centrifuge plant is much smaller than a diffusion plant, and so is the equilibrium time, i.e., the time required to achieve full production after plant startup or subsequent modification, e.g., from production of LEU to production of HEU by recycling the product material back as feed. Typically, the equilibrium time for LEU centrifuge and diffusion plants are on the order of hours and months, respectively.

As noted by Gilinsky *et al*., the SWU requirements to obtain one SQ of HEU can be reduced substantially if a state already has access to, and can successfully divert fresh LWR fuel.[25] In the examples given in Table 4, using 4 percent-enriched feed (typical of LWR fresh fuel) and operating the enrichment plant at a high tails assay—for example 2 percent ^{235}U—the separative work requirements are reduced by more than 80 percent of that required if natural uranium feed (0.711% ^{235}U) were used.

The enrichment plant capacity (SWU/y) is a product of the number of stages and the capacity of each stage. For a centrifuge enrichment plant, the capacity of a single stage is a function of length of the rotor and its peripheral speed.[26] In Table 4, we also calculate the number of centrifuge stages required to

Product (% ^{235}U)	93.5	93.5	93.5	93.5
Feed (% ^{235}U)	0.711	0.711	4.0	4.0
Tails (% ^{235}U)	0.25	0.5	0.25	2.0
Enrichment Work (kg SWU)	5,422	4,021	1,769	894
U Feed (tons) 1.144	5,057	11.02	0.622	
Centrifuges Required to Obtain 1 SQ/y[27]				
2 kg SWU/y/centrifuge (P1)	2,711	2,011	885	447
5 kg SWU/y/centrifuge (P2)	1,084	804	354	179
10 kg SWU/y/centrifuge (Russia)	542	402	177	89
40 kg SWU/y/centrifuge (URENCO)	136	101	44	22
300kg SWU/y/centrifuge (U.S. R & D)	18	13	6	3

Table 4. Enrichment Requirements to Obtain One SQ of HEU.

obtain one SQ per year of 93.5 percent-enriched HEU. As seen from Table 4, depending primarily on the feed enrichment and the efficiency of each stage, the number of centrifuge stages required to obtain one SQ if HEU per year varies from a few to a few thousand.

We know from events in Iran (and North Korea), a small centrifuge enrichment plant with up to a few hundred centrifuge stages can be readily hidden from the IAEA and from foreign intelligence efforts. A state can acquire the necessary technology and construct and operate a small clandestine centrifuge plant with little risk of detection, and the probability of detection is substantially reduced if the state has a declared centrifuge plant under safeguards.

Assuming a state may have a small clandestine enrichment plant, the conversion time could be on the order of weeks to months, depending on the number of size of the plant and the technology employed.

CONCLUSIONS

IAEA safeguards are inadequate for achieving the objective of timely detection of diversion of significant quantities of *nuclear material* from peaceful activities to the manufacture of nuclear weapons.

The IAEA's SQ values are technically erroneous and excessive.

For unirradiated direct use material in metal form, the IAEA's estimated conversion time (7-10 days) is adequate, but the timeliness detection goal (1 month) is too long, and timely warning cannot be achieved. Nonweapon states should not be permitted to possess an SQ of unirradiated direct use material in metal form.

For unirradiated direct use material in chemical compounds and mixtures, the IAEA's estimated conversion time is on the order of weeks (1-3). The lower end of this range is adequate, but the upper end appears too generous. The timeliness detection goal (1 month) is too long, and the timely detection cannot be achieved. Non-weapon states should not be permitted to possess an SQ of unirradiated direct use material in the form of chemical compounds or mixtures.

For plutonium, HEU or ^{233}U in irradiated fuel, the IAEA's estimated conversion time (1-3 months) is adequate. However, if a state possesses a safeguarded pilot-size or larger reprocessing plant, a state can divert SQs of separated plutonium from plant operations with a low probability of detection by the IAEA absent an informer. If a state has a declared pilot-scale or larger reprocessing plant, the conversion time should be the same as for unirradiated compounds of direct use materials.

Non-weapon states should not be permitted to possess pilot-scale or larger reprocessing plants. When conducted in non-weapon states, research on reprocessing and transmutation related technologies, including those that are unlikely to ever be commercialized, simply train cadres of experts in actinide chemistry and plutonium metallurgy, a proliferation concern in its own right. The hot cells, used for on-hands research, provide readily available facilities for separation of plutonium and fabrication of plutonium components for weapons. Thus, smaller reprocessing activities, and research and development on transmutation related technologies, should not be permitted in non-weapon states.

For indirect use material, such as low-enriched uranium, the IAEA's estimated conversion time is on the order of months (3-12). The lower end of this range is adequate, but the upper end appears too generous. Small gas centrifuge plants can be readily hidden from IAEA inspectors and foreign intelligence forces. If a state is permitted to possess a safeguarded enrichment plant, it can be used as a cover for procuring components and materials needed for a small clandestine plant. A state possessing a safeguarded centrifuge enrichment plant can rapidly reconfigure the plant to produce HEU. Also, a state may have a small clandestine enrichment plant. In either case, the conversion time could be on the order of weeks to months, depending on the number of and size of the plants and the technology employed.

Even if the IAEA's timeliness detection goal of 1 year is met, this is unlikely to provide "timely warning." Consequently, enrichment plants should not be permitted in non-weapon states.

In sum, our recommended conversion times are given in Table 5. The detection goals should be the lower end of the conversion time range in each case.

Beginning Material Form	Conversion Time
Pu, HEW, or ^{233}U metal	Order of days (7-10)
PuO_2 $PU(NO_3)_4$ or other pure Pu compounds; HEU or ^{233}U oxide or other pure U compounds; MOX or other nonirradiated pure mixtures containing PU, U (^{233}U+^{235}U>20%); Pu, HEU, and/or ^{233}U in scrap or other miscellaneous impure compounds	Order of days (7-10)
PU, HEU, or ^{233}U in irradiated fuel State without declared reprocessing Non-weapon states are no permitted to possess reprocesing plants	Order of months (1-3)
U containing <20% ^{235}U and ^{233}U; Th State without declared enrichment Non-weapon states are not permitted to posses enrichment plants	Order of weeks to months

Table 5. Recommended Material Conversion Times for Finished Pu or U Metal Components.

ENDNOTES - CHAPTER 6

1. International Atomic Energy Agency (IAEA), INFCIRC/153, Paragraph 28, Vienna, Austria: IAEA.

2. Marvin Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" Nuclear Control Institute, available from *www.nci.org/k-m/mmsgrds.htm*.

3. *Ibid*.

4. *Ibid*.

5. IAEA, *IAEA Safeguards Glossary*, 2001 Ed., International Verification Series, No. 3, 2002, Paragraph 3.14.

6. Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," Natural Resources Defense Council, revised April 13, 1995, Paragraph 3.13.

7. Table 1 is identified as Table II in the *IAEA Safeguards Glossary*.

8. *Ibid*., p. 9.

9. *IAEA Safeguards Glossary*, 2001 Ed., Paragraph 3.15.

10. *Ibid*., Paragraph 3.13.

11. *Ibid*. Table 3 here is identified as Table I in the glossary.

12. *Ibid*., Paragraph 3.20.

13. Victor Gilinsky, Marvin Miller, and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors*, Washington, DC: The Nonproliferation Policy Education Center, September 2004, p. 22, makes this point with regard to light water reactor (LWR) inspections.

14. Manson Benedict, Thomas Pigford, and Hans Levi, *Nuclear Chemical Engineering*, New York: McGraw-Hill Book Company, New York, 1981, p. 430.

15. *Plutonium Handbook*, Vol. I, O. J. Wick, ed., La Grange, IL: The American Nuclear Society, 1980, p. 564.

16. D. E. Ferguson to F. L. Culler, Intra-Laboratory Correspondence, "Simple, Quick Processing Plant," Oak Ridge, TN: Oak Ridge National Laboratory, August 30, 1972, 22 pp.

17. J. P. Hinton *et al*., *Proliferation Resistance of Fissile Material Disposition Program(FMDP) Plutonium and Disposition Alternatives: Report of the Proliferation Vulnerability Red Team, Sandia National Laboratories*, Report No. SAND97-8201, October 1996, Section 4.1.1.3.

18. Marvin Miller, "The Feasibility of Clandestine Reprocessing of LWR Spent Fuel," Appendix 2, in Gilinsky, Miller, and Hubbard.

19. Gilinsky, Miller, and Hubbard, p. 21.

20. *Ibid.*, p. 23.

21. Marvin Miller, "The Gas Centrifuge and Nuclear Proliferation," Appendix. 1, p. 38, in Gilinsky, Miller, and Hubbard.

22. That is, the IAEA currently cannot verify the separative capacity of a centrifuge plant as stated by the operator. Thus, the operator could understate the plant's true separative capacity and feed undeclared uranium to the cascades, producing excess, undeclared LEU after the inspectors have left the plant following their monthly visits, which normally last several days.

23. This is based on the use of 5kg SWU/yr P2 centrifuges which each occupy an area of about 0.25 m^2 and have an energy consumption of about 150 kW/kg SWU.

24. Such reconfiguration can be accomplished in various ways depending on the plant design. For example, in URENCO plants, which consist of many parallel independent cascades each producing LEU product, the LEU product of one cascade can be used as feed material for another cascade, and so on, until the desired HEU product concentration is achieved. By contrast, centrifuge plants of Russian design are configured as one large cascade whose product and tails concentrations can be changed remotely from the plant control room by changing the valve connections on the centrifuges.

25. Gilinsky, Miller, and Hubbard.

26. Capacity scales as V_2L, where V is the peripheral speed and L is the rotor length.

27. Individual centrifuge capacity values are from Miller, "The Gas Centrifuge and Nuclear Proliferation," Appendix. 1, Table 1, in Gilinsky, Miller, and Hubbard.

APPENDIX

NON-PROLIFERATION TREATY

The Non-Proliferation Treaty (NPT) was signed July 1, 1968, and entered into force March 5, 1970. All non-weapon state parties to the NPT are required to comply with International Atomic Energy Agency (IAEA) safeguards, as indicated under Article III of the NPT Treaty:

> III.1. **Each non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards**, as set forth in an agreement to be negotiated and concluded with the International Atomic Energy Agency **in accordance with the Statute of the International Atomic Energy Agency and the Agency's safeguards system**, for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices. **Procedures for the safeguards required by this article shall be followed with respect to source or special fissionable material whether it is being produced, processed or used in any principal nuclear facility or is outside any such facility.** The safeguards required by this article shall be applied to all source or special fissionable material in all peaceful nuclear activities within the territory of such State, under its jurisdiction, or carried out under its control anywhere. (Emphasis added)

The following nuclear weapon states are **NOT** parties to the NPT:

- Israel
- Pakistan
- India
- Democratic People's Republic of Korea (DPRK or North Korea).

The first three, Israel, India, and Pakistan, are known to have nuclear weapons and have never been signatories to the NPT. The DPRK is believed to have nuclear weapons and has declared that it has possesses nuclear weapons. On January 10, 2003, DPRK announced that it was withdrawing from the NPT effective immediately. All other states of any consequence are members of the NPT, and with the exception of the United States, United Kingdom, France, Russia, and China, all are non-weapon states subject to IAEA safeguards.

IAEA'S ENABLING STATUTE

The IAEA was established in 1957, 11 years prior to the inception of the NPT. Under Article III, paragraph A. 5, of its enabling statute, the Agency is authorized:

> **To establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose**; and to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement,

> or at the request of a State, to any of that State's activities in the field of atomic energy; (Emphasis added)

The safeguards system is defined primarily in Article XII of the IAEA Statute. Article XII of the IAEA Statute states in part:

> A. With respect to any Agency project, or other arrangement where the Agency is requested by the parties concerned to apply safeguards, **the Agency shall have the following rights and responsibilities** to the extent relevant to the project or arrangement:
>
> 1. **To examine the design of specialized equipment and facilities**, including nuclear reactors, **and to approve it only from the viewpoint of assuring that it will not further any military purpose**, that it complies with applicable health and safety standards, **and that it will permit effective application of the safeguards provided for in this article**;
>
> . . .
>
> 5. **To approve the means to be used for the chemical processing of irradiated materials solely to ensure that this chemical processing will not lend itself to diversion of materials for military purposes** and will comply with applicable health and safety standards; to require that special fissionable materials recovered or produced as a by-product be used for peaceful purposes under continuing Agency safeguards for research or in reactors, existing or under construction, specified by the member or members concerned; and **to require deposit**

with the Agency of any excess of any special fissionable materials recovered or produced as a by-product over what is needed for the above-stated uses in order to prevent stockpiling of these materials, provided that thereafter at the request of the member or members concerned special fissionable materials so deposited with the Agency shall be returned promptly to the member or members concerned for use under the same provisions as stated above.

6. To send into the territory of the recipient State or States **inspectors**, designated by the Agency after consultation with the State or States concerned, **who shall have access at all times to all places and data and to any person who by reason of his occupation deals with materials, equipment, or facilities which are required by this Statute to be safeguarded, as necessary to account for source and special fissionable materials supplied and fissionable products and to determine whether there is compliance with the undertaking against use in furtherance of any military purpose** referred to in sub-paragraph F-4 of article Xl, with the health and safety measures referred to in sub-paragraph A-2 of this article, and with any other conditions prescribed in the agreement between the Agency and the State or States concerned. Inspectors designated by the Agency shall be accompanied by representatives of the authorities of the State concerned, if that State so requests, provided that the inspectors shall not thereby be delayed or otherwise impeded in the exercise of their functions; (Emphasis added)

IAEA AGREEMENTS WITH MEMBER STATES

The IAEA administers its safeguards requirements pursuant to agreements that the IAEA has with member states.

As of November 2004, there were 138 member states and 65 intergovernmental and nongovernmental organizations worldwide having formal agreements with the Agency, and 232 safeguards agreements in force in 148 states (and with Taiwan) involving 2,363 safeguards inspections performed in 2003.[1] The DPRK joined the IAEA in 1974, but withdrew its membership on June 13, 1994; and Cambodia, which joined the IAEA in 1958, withdrew its membership on March 26, 2003.

Since the IAEA was established in 1957, over the years the IAEA safeguards requirements have been upgraded and strengthened. The more explicit requirements are set forth in a series of IAEA Information Circulars, the most important of which are INFCIRC/26 (the Agency's Safeguards approved by the Board of Governors on January 31, 1961), INFCIRC/66 (designed to be applied in any state that concluded a safeguards agreement), and INFCIRC/153 (used as a basis for agreements with states that are parties to the NPT-and the Additional Protocol.

The "Basic Undertaking" of IAEA safeguards agreements with other parties is currently set forth in INFCIRC/153 (Corrected), June 1972:

> **The Agreement should contain, in accordance with Article III.l of the Treaty on the Non-Proliferation of Nuclear Weapons), an undertaking by the State to accept safeguards, in accordance with the terms of the Agreement,**

on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere, **for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices**. (Emphasis added)

COMPREHENSIVE, OR FULL-SCOPE, SAFEGUARDS

A comprehensive safeguards agreement is an IAEA safeguards agreement that applies safeguards on all nuclear material in all nuclear activities in a state. These are primarily safeguards agreements pursuant to the NPT, concluded between the IAEA and non-nuclear–weapon state (NNWS) parties as required by Article III.1 of the NPT, but they also include agreements pursuant to the Tlatelolco Treaty; the *sui generic* agreement between Albania and the IAEA; and the quadripartite safeguards agreement between Argentina, Brazil, the Brazil-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), and the IAEA. As of July 19, 2005, 37 NNWS parties to the NPT have not yet brought into force comprehensive safeguards agreements with the IAEA. Most of these 37 countries do not have significant nuclear facilities.[2]

IAEA INFORMATION CIRCULAR 153

INFCIRC/153 places constraints on the agency's safeguards implementation:

IMPLEMENTATION OF SAFEGUARDS

The Agreement should provide that safeguards **shall be implemented** in a manner designed:

a. **To avoid hampering the economic and technological development** of the state or international cooperation in the field of peaceful nuclear activities, including international exchange *nuclear material* 2);

b. **To avoid undue interference in the state's peaceful nuclear activities**, and in particular in the operation of *facilities*; and

c. To be **consistent with** prudent management **practices required for the economic and safe conduct of nuclear activities**.

INFCIRC/153 defines the:

OBJECTIVE OF SAFEGUARDS

28. The Agreement should provide that the **objective of safeguards is the timely detection of diversion of significant quantities of *nuclear material* from peaceful nuclear activities to the manufacture of nuclear weapons** or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.

29. To this end the Agreement should provide for the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures.

30. The Agreement should provide that the technical conclusion of the Agency's verification

activities shall be a statement, in respect of each *material balance area*, of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated.

Also, INFCIRC/153 calls for a:

NATIONAL SYSTEM OF ACCOUNTING FOR AND CONTROL OF NUCLEAR MATERIAL

> 31. The Agreement should provide that **the state shall establish and maintain a system of accounting for and control of all nuclear material** subject to safeguards under the Agreement, and that such safeguards shall be applied in such a manner as to enable the Agency to verify, in ascertaining that there has been no diversion of nuclear material from peaceful uses to nuclear weapons or other nuclear explosive devices, findings of the state's system. The Agency s verification shall include, *inter alia*, independent measurements and observations conducted by the Agency in accordance with the procedures specified in Part II below. The Agency, in its verification, shall take due account of the technical effectiveness of the state's system.

IAEA SAFEGUARDS GLOSSARY

The *IAEA Safeguards Glossary* includes the definitions of several terms that are important to a discussion of the adequacy of the IAEA's safeguards with respect to timely warning, namely "diversion rate," "conversion time," "significant quantity," and "detection time":[3]

3.10. Diversion rate—the amount of nuclear material which could be diverted in a given unit of time. If the amount diverted is 1 SQ or more (see No. 3.14) of nuclear material in a short time (i.e., within a period that is less than the material balance period [see No. 6.47]), it is referred to as an **"abrupt" diversion**. If the diversion of 1 SQ or more occurs gradually over a material balance period, with only small amounts removed at any one time, it is referred to as a "**protracted" diversion**.

3.13. Conversion time—the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device. Conversion time does not include the time required to transport diverted material to the conversion facility, or to assemble the device, or any subsequent period. The diversion activity is assumed to be part of a planned sequence of actions chosen to give a high probability of success in manufacturing one or more nuclear explosive devices with minimal risk of discovery until at least one such device is manufactured. The conversion time estimates applicable at present under these assumptions are provided in Table I. [Reproduced as Table 3 above.]

3.14. Significant quantity (SQ)—the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses. Significant quantities are used in establishing the quantity component of the IAEA inspection goal (see No. 3.23). Significant quantity values currently in use are given in Table II. [Reproduced as Table 1 above.]

3.15. Detection time—the maximum time that may elapse between diversion of a given amount of nuclear material and detection of that diversion by IAEA safeguards activities. Where there is no additional protocol in force or where the IAEA has not drawn a conclusion of the absence of undeclared nuclear material and activities in a state (see No. 12.25), it is assumed: (a) that all facilities needed to clandestinely convert the diverted material into components of a nuclear explosive device exist in a state; (b) that processes have been tested (e.g., by manufacturing dummy components using appropriate surrogate materials); and (c) that nonnuclear components of the device have been manufactured, assembled and tested. Under these circumstances, **detection time should correspond approximately to estimated conversion times** (see No. 3.13). Longer detection times may be acceptable in a state where the IAEA has drawn and maintained a conclusion of the absence of undeclared nuclear material and activities. Detection time is one factor used to establish the timeliness component of the IAEA inspection goal (see No. 3.24).

3.20. IAEA timeliness detection goal—the target detection times applicable to specific nuclear material categories (see No. 4.24).

These goals are **used for establishing the frequency of inspections** (see No. 11.16) and safeguards activities at a facility or a location outside facilities during a calendar year, in order to verify that no abrupt diversion (see No. 3.10) has occurred. Where there is no additional protocol in force or where the IAEA has not drawn and maintained a conclusion of the absence of undeclared nuclear material and activities in a state (see No. 12.25), **the detection goals are as follows:**

— One month for unirradiated direct use material,

— Three months for irradiated direct use material,

— One year for indirect use material.

Longer timeliness detection goals may be applied in a state where the IAEA has drawn and maintained a conclusion of the absence of undeclared nuclear material and activities in that state.

3.22. IAEA inspection goal—performance targets specified for IAEA verification activities at a given facility as required to implement the facility safeguards approach (see No. 3.3). **The inspection goal for a facility consists of a quantity component** (see No. 3.23) **and a timeliness component** (see No. 3.24). These components are regarded as fully attained if all the Safeguards Criteria (see No. 3.21) relevant to the material types (see No. 4.23) and material categories (see No. 4.24) present at the facility have been satisfied, and all anomalies involving 1 SQ or more of nuclear material have been resolved in a timely manner (see No. 3.26). (See also Nos 12.23 and 12.25.)

3.23. Quantity component of the IAEA inspection goal—relates to the scope of the inspection activities at a facility that are necessary for the IAEA to be able to draw the conclusion that there has been no diversion of 1 SQ or more of nuclear material over a material balance period and that there has been no undeclared production or separation of direct use material at the facility over that period.

3.24. Timeliness component of the IAEA inspection goal—relates to the periodic activities that are necessary for the IAEA to be able to draw the conclusion that there has been no abrupt diversion (see No. 3.10) of 1 SQ or more at a facility during a calendar year. (Emphasis added)

ADDITIONAL PROTOCOL

The Additional Protocol is a legal document granting the IAEA complementary inspection authority to that provided in underlying safeguards agreements. A principal aim is to enable the IAEA inspectorate to provide assurance about both declared and possible undeclared activities. Under the Protocol, the IAEA is granted expanded rights of access to information and sites, as well as additional authority to use the most advanced technologies during the verification process.[4]

At the end of the Persian Gulf War, the world learned about the extent of Iraq's clandestine pursuit of an advanced program to develop nuclear weapons. The international community recognized that the Agency's international inspection system needed to be strengthened in order to increase its capability to detect secret nuclear programs. After 4 years of work by the Secretariat of the Agency, an Agency committee agreed on a Model Additional Protocol (the "Model Protocol") for strengthening nuclear safeguards. The Model Protocol was approved by the Agency's Board of Governors in 1997. The Model Protocol was designed to be used to amend existing safeguards agreements to strengthen such safeguards by requiring NNWS to provide, *inter alia,* broader declarations to the Agency about their nuclear programs and nuclear-related activities, and by expanding the access rights of the Agency. The new safeguards measures become effective in each state when it brings its protocol into force.[5]

The Model Protocol requires states to report a range of information to the Agency about their nuclear and nuclear-related activities and about the planned developments in their nuclear fuel cycles. This includes expanded information about their holdings of uranium and thorium ores and ore concentrates and of other plutonium and uranium materials not currently subject to Agency safeguards, general information about their manufacturing of equipment for enriching uranium or producing plutonium, general information about their nuclear fuel cycle-related research and development activities not involving nuclear material, and their import and export of nuclear material and equipment.[6]

As of July 19, 2005, 69 states and Euratom have ratified Additional Protocols.[7] Thirty-three additional states have signed, but not ratified Additional Protocols, bringing the total number of states that have signed to 102. The IAEA Board has approved Additional protocols for six additional states that have not signed. Notable countries that have not signed an Additional Protocol include:

- Algeria (IAEA Board Approval)
- Argentina
- Belarus
- Brazil
- DPRK
- Egypt
- India
- Israel
- Pakistan
- Serbia and Montenegro
- Syria
- Thailand
- Venezuela
- Vietnam

ENDNOTES - CHAPTER 6 APPENDIX

1. Available from *www.iaea.org/About/by_the_numbers.html*.

2. The Republic of the Congo has two small research reactors, at least one of which is not operable, and Niger is involved in uranium mining.

3. *IAEA Safeguards Glossary*, 2001 Ed., International verification Series, No. 3, Vienna, Austria: International Atomic Energy Agency (IAEA), 2002.

4. Available from *www.iaea.org/Publications/Factsheets/English/sg_overview.html*.

5. Available from *www.state.gov/t/np/trty/11757.htm*.

6. Available from *www.state.gov/t/np/trty/11757.htm*.

7. The IAEA also applies safeguards, including the measures foreseen in the Model Additional protocol, in Taiwan.