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International Safeguards – Accounting for Nuclear Materials

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Summary

Nuclear safeguards applied by the International Atomic Energy Agency (IAEA) are one element of the "non-proliferation regime", the collection of measures whose aim is to forestall the spread of nuclear weapons to countries that do not already possess them. Safeguards verifications provide evidence that nuclear materials in peaceful use for nuclear-power production are properly accounted for. Though carried out in cooperation with nuclear facility operators, the verifications can provide assurance because they are designed with the capability to detect diversion, should it occur.

Traditional safeguards verification measures conducted by inspectors of the IAEA include book auditing; counting and identifying containers of nuclear material; measuring nuclear material; photographic and video surveillance; and sealing.

Novel approaches to achieve greater efficiency and effectiveness in safeguards verifications are under investigation as the number and complexity of nuclear facilities grow. These include the zone approach, which entails carrying out verifications for groups of facilities collectively, and a randomization approach, which entails carrying out entire inspection visits some fraction of the time on a random basis. Both approaches show promise in particular situations, but, like traditional measures, must be tested to ensure their practical utility.

INTERNATIONAL SAFEGUARDS—ACCOUNTING FOR NUCLEAR MATERIALS

by Leslie G. Fishbone

Introduction[1]

Since the early years of nuclear weapons (Figure 1), countries of the world have sought to stop their spread—primarily to prevent catastrophic war but also to facilitate the peaceful uses of nuclear energy. This goal of stopping the spread of nuclear weapons has been partly realized through treaties and international inspections, the latter constituting a novel but now widely accepted breach of national sovereignty.

Most countries whose nuclear facilities are inspected by the International Atomic Energy Agency (IAEA) are signers and ratifiers of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and have agreed not to develop or possess nuclear weapons. These countries undergo "full-scope" safeguards, that is, all of their nuclear materials used for peaceful nuclear purposes are subject to safeguards inspections by the IAEA. Other countries, which have not acceded to the NPT or an equivalent treaty, undergo safeguards on some of their nuclear facilities as agreed between the country, the IAEA, and possibly a third party that has supplied the nuclear facility or nuclear materials.

Figure 1. The first nuclear explosion (photo courtesy of the Los Alamos National Laboratory).

To put these remarks into context, Figure 2 shows a highly developed nuclear fuel cycle, whose central facilities are electric-power-producing nuclear reactors. Although some power reactors are fueled by uranium at natural enrichment, 0.71% U-235 and 99.3% U-238, most are fueled by low-enriched uranium containing 2% to 4% U-235. Enrichment takes place in specialized plants that enrich the uranium by gaseous diffusion or ultracentrifugation. It is the U-235 whose fission in the reactor into smaller fission products and neutrons initially supplies the power. Concurrent with the U-235 neutron chain reaction, neutron capture by U-238 leads to the production, within the reactor fuel, of Pu-239 and more massive isotopes of plutonium and of transplutonic elements as well. As time passes, fission of Pu-239 supplies a substantial fraction of the reactor's power due to its gradual buildup and the gradual depletion of U-235. After about three years of operation, not enough of either isotope is present for the fuel to be used efficiently. If the remaining plutonium that was produced or the residual uranium is to be reused in other reactors (Figure 2), it must be separated from the highly radioactive fission products and from the transplutonic elements. This separation is done in an irradiated-fuel chemical reprocessing plant. Alternatively, the spent fuel can be disposed of directly as waste.

Since nuclear-fission weapons (atomic bombs) can be constructed from both very highly enriched uranium and plutonium with a high abundance of Pu-239, the primary goal of international safeguards is to provide evidence that the nuclear materials and facilities of the

[1]This lecture will necessarily touch upon political as well as technical subjects. Therefore, though I shall be giving my best interpretation of the subject, I emphasize that my views should not be construed as an official position of Brookhaven National Laboratory, the International Atomic Energy Agency, or any branch of the United States Government.

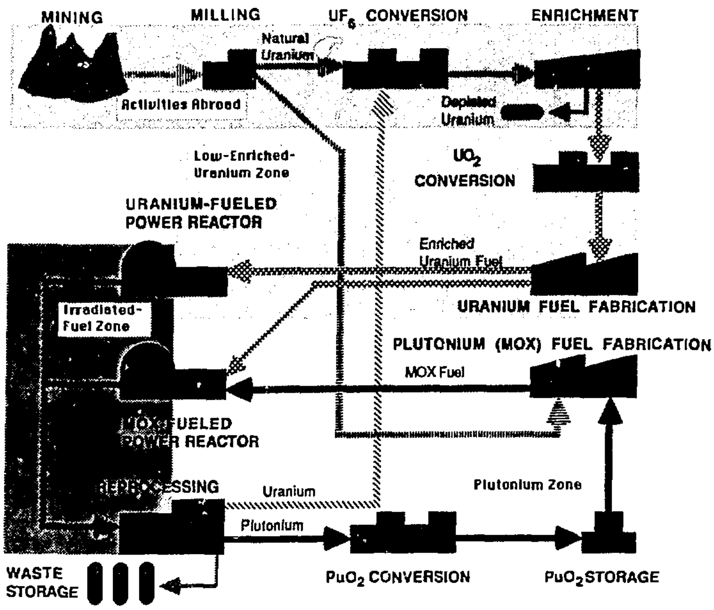

Figure 2. Facilities and flows of nuclear material in a highly developed nuclear fuel cycle incorporating the recycle of separated plutonium. The subdivision of the fuel cycle into zones accords with an analysis described later in the lecture.

peaceful nuclear fuel cycle are not misused for nuclear weapons.

My aims in this lecture are threefold. First, I shall review non-proliferation arrangements and the role of the IAEA; second, I will describe how the IAEA conducts safeguards inspections in a nuclear facility; and third, I shall explain certain newer approaches to safeguards, developed at Brookhaven and elsewhere, that are designed to promote greater efficiency and effectiveness. I hope you will be left with a sufficient understanding of nuclear non-proliferation policy and safeguards and that you will be able to evaluate news that bears on these aspects of international affairs.

Several key terms that require definition will recur throughout this presentation. "Nuclear proliferation" means the spread of nuclear weapons to countries that do not already have them. Such spread should not be confused with the further development of nuclear weapons by countries that already possess them. To make the distinction explicit, the terms "horizontal nuclear proliferation" and "vertical nuclear proliferation" are sometimes used for the former and latter concepts. The "non-proliferation regime" is the collection of measures, both political and technical, whose aim is to forestall horizontal nuclear proliferation. IAEA safeguards form one key technical element of the non-proliferation regime, namely, inspection measures to detect and deter the diversion of nuclear materials from peaceful, civilian use. IAEA safeguards are only one element of the non-proliferation regime—necessary but by no means sufficient to forestall proliferation.

Safeguards fall into international and domestic measures. The latter include the physical protection of nuclear material. This is the responsibility of the countries which possess nuclear materials. The IAEA has no role other than facilitating the exchange of information. I shall say no more about this domestic responsibility in this lecture.

It is worthwhile to put these concepts into their historical context. Figure 3 depicts the time when six countries first detonated nuclear explosives: the United States, the Soviet Union, the United Kingdom, France, China, and India. All but India possess declared nuclear weapons. Figure 3 also shows events that are important in the history of non-proliferation. The Baruch Plan was an early plan for the international control of nuclear technology. The Eisenhower Proposal led to the formation of the IAEA. Euratom, a multinational organization in Europe with wide responsibility for nuclear facilities there, was set up at the the same time. Of similar importance was the adoption of the NPT, based upon a proposal by Ireland. The

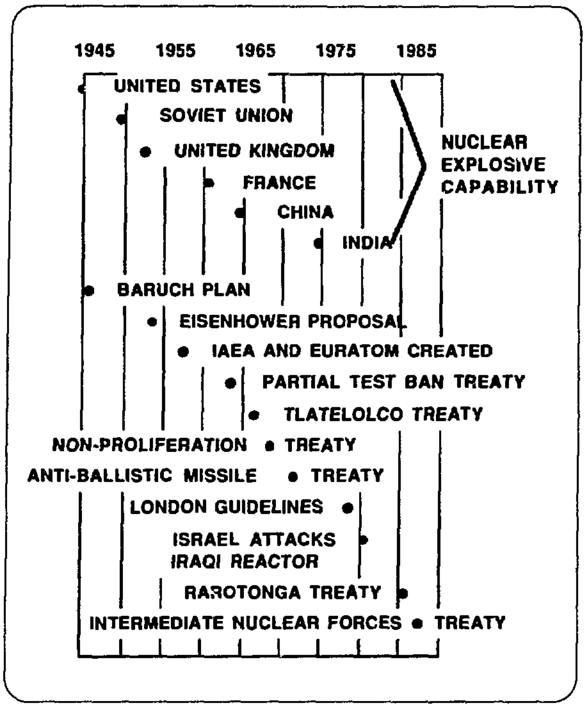

Figure 3. Historical context of the nuclear non-proliferation regime (based in part on a diagram in IAEA Safeguards: Aims, Limitations, Achievements*).*

Tlatelolco and Rarotonga[2] Treaties codified nuclear-weapons-free zones in Latin America and the South Pacific, respectively. With regard to the former, however, Cuba has not signed the treaty, while Argentina, Brazil, and Chile have not completed all the steps for it to be in force. The London Guidelines were formulated by countries that export nuclear technology to regulate items or technologies exported and to help ensure that no exported technology is used to aid in the development of nuclear weapons. Finally, adoption of the Partial Test Ban, Anti-Ballistic Missile, and Intermediate Nuclear Forces Treaties throughout the same period shows that efforts to control vertical proliferation have proceeded concurrently with the efforts to control horizontal proliferation; many would argue, however, that the pace of strategic arms control, the former, has been too slow.

Differing in kind from these diplomatic achievements, the attack by Israel on a research reactor in Iraq called into question the effectiveness of IAEA safeguards, among other repercussions.

The Non-Proliferation Regime

Mentioning the political aspects of proliferation and non-proliferation is important for putting the role of IAEA safeguards into proper context.

A country might wish to develop nuclear weapons because of concerns for national-security that conventional forces cannot allay, for domestic prestige, or to influence international affairs.

Countering these motivations are the negative factors that enter the calculus of the potential proliferating country. First, a political liability in possessing nuclear weapons is the motivation it would give to neighboring or rival countries to develop such weapons themselves. Second, the economic cost of a nuclear-weapons program is large. Third, there could be a loss of the supply from other countries of nuclear technology and materials for peaceful purposes, as well as other sanctions, for countries that proliferate. Fourth, there could be a moral cost to acquiring nuclear weapons, just as there might be for any significant change in national (or, indeed, individual) behavior.

Consider next the elements of the non-proliferation regime: First, there are measures to inhibit the motivation to acquire nuclear weapons. These measures include the NPT and similar treaties, defense alliances and security guarantees, and conventional arms sales and grants. A second set of measures helps control nuclear materials and information. These measures consist of the export guidelines, controls and bilateral supply treaties of nuclear supplier countries, information classification, and multinational operation of sensitive facilities. Third, there are the warning elements, IAEA safeguards (the focus of this lecture) and intelligence information.

To complete this picture, there are reasons other than declared or secret nuclear-weapon status why a country might not wish to become party to the NPT or a similar treaty. All such treaties are infringements on national sovereignty and they codify an inequality of countries

[2] I will say nothing more about the Rarotonga Treaty in this lecture. The parties to it are Australia, the Cook Islands, Fiji, Kiribati, New Zealand, Niue, Tuvalu, Western Samoa, Nauru, and the Solomon Islands (As of mid 1989).

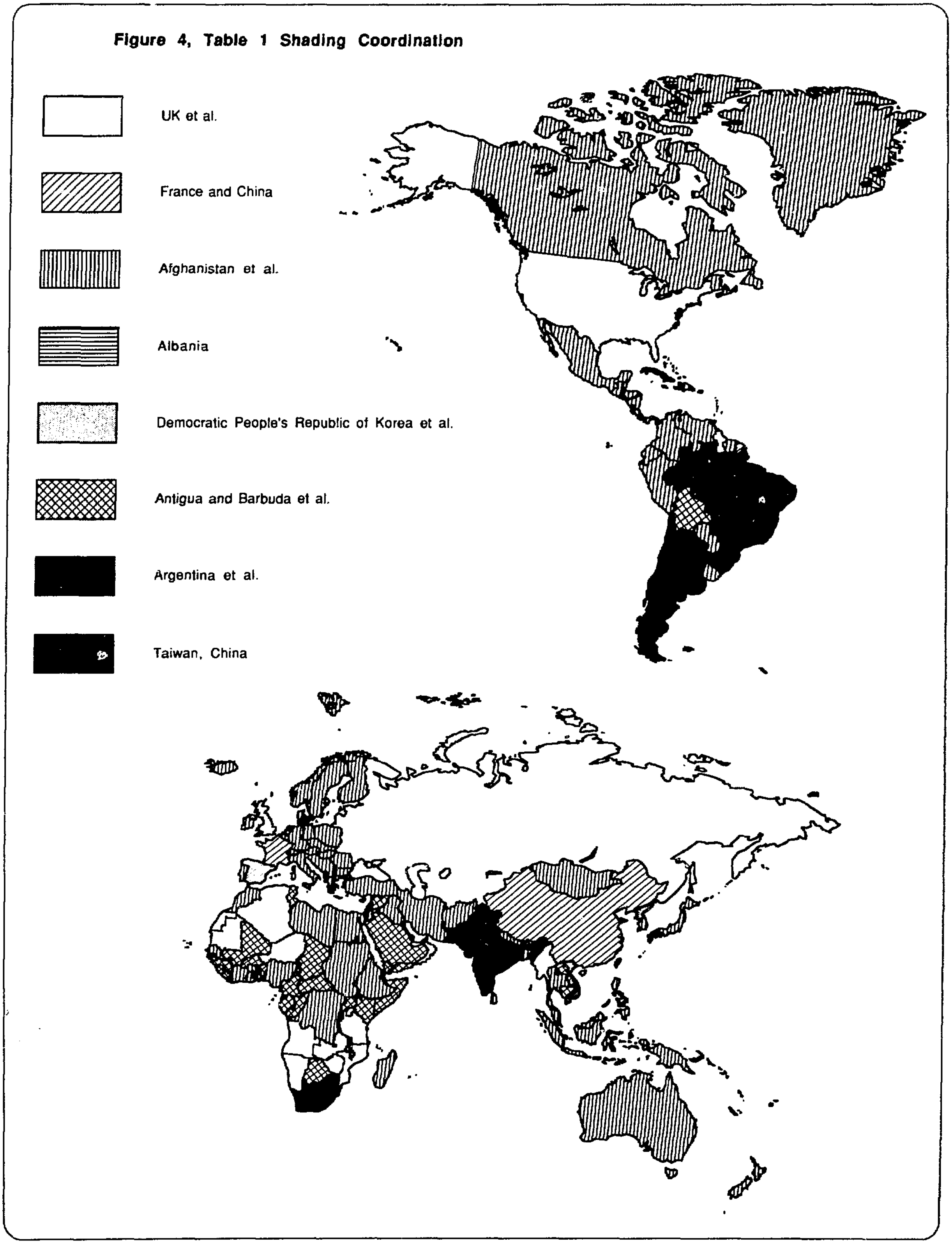

Figure 4. Status of countries with respect to the Non-Proliferation Treaty (and Tlatelolco Treaty, where applicable) and the application of International Atomic Energy Agency safeguards.

Table 1

Map Explanation

Nuclear - Weapon Countries Party to the NPT

United Kingdom[a]
United States of America[a]
Union of Soviet Socialist Republics[a]

Nuclear - Weapon Countries Not Party to the NPT

China
France[a]

Non-Nuclear Weapon Countries Party to the NPT or Tlatelolco Treaty (or both) with NPT or Tlatelolco Safeguards Agreements in Force[b]

Afghanistan
Australia
Austria
Bangladesh
Belgium
Brunei Darussalam
Bulgaria
Canada
Colombia[c,d]
Costa Rica[c]
Cote d'Ivoire
Cyprus
Czechoslovakia
Denmark
Dominican Republic[c]
Ecuador[c]
Egypt
El Salvador[c]
Ethiopia
Fiji
Finland
Gambia
German Democratic Republic
Germany, Federal Republic of
Ghana
Greece
Guatemala[c]
Holy See
Honduras[c]
Hungary
Iceland
Indonesia
Iran, Islamic Republic of
Iraq
Ireland
Italy
Jamaica[c]
Japan
Jordan
Korea, Republic of
Lebanon
Lesotho
Libyan Arab Jamahiriya
Liechtenstein
Luxembourg
Madagascar
Malaysia
Maldives
Mauritius
Mexico[c]
Mongolia
Morocco
Nauru
Nepal
Netherlands
New Zealand
Nicaragua[c]
Nigeria
Norway
Panama[c]
Papua New Guinea
Paraguay[c]
Peru[c]
Philippines
Poland
Portugal
Romania
Samoa (Western)
Senegal
Singapore
Sri Lanka
Sudan
Suriname[c]
Swaziland
Sweden
Switzerland
Thailand
Turkey
Uruguay[c]
Venezuela[c]
Yugoslavia
Zaire

Non-Nuclear-Weapon Countries Not Party to the NPT with Full-Scope Safeguards Agreements in Force

Albania

Table 1 con't.

Non-Nuclear Weapon Countries Party to the NPT With Non-NPT Safeguards Agreements in Force (NPT Safeguards Agreement Not Yet in Force)

Democratic People's Republic of Korea
Spain
Viet Nam

Non-Nuclear-Weapon Countries Party to the NPT or Tlatelolco Treaty (or both) with NPT or Tlatelolco Safeguards Agreements Not Yet in Force

Antigua and Barbuda
Bahamas
Bahrain
Barbados
Belize
Benin
Bhutan
Bolivia
Botswana
Burkina Faso
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Congo
Democratic Kampuchea
Democratic Yemen
Dominica
Equatorial Guinea
Gabon
Grenada
Guinea
Guinea-Bissau
Haiti
Kenya
Kiribati
Lao People's Democratic .epublic
Liberia
Malawi
Mali
Malta
Rwanda
St. Lucia
St. Vincent and the Grenadines
San Marino
Sao Tome and Principe
Saudi Arabia
Seychelles
Sierra Leone
Solomon Islands
Somolia
Syrian Arab Republic
Togo
Tonga
Trinidad and Tobago
Tunisia
Tuvalu
Uganda
Yemen Arab Republic

Non-Nuclear-Weapon Countries Not Party to the NPT or Tlatelolco Treaty with Non-NPT or Non-Tlatelolco Safeguards Agreements in Force

Argentina
Brazil
Chile
Cuba
India
Israel
Pakistan
South Africa

The IAEA also applies safeguards under Non-NPT agreements to the nuclear facilities in Taiwan, China on a non-governmental basis.

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[a]Voluntary-offer Safeguards Agreements are in force in these countries; safeguards are applied therein to nuclear material in a small selection of facilities.
[b]NPT Agreement unless otherwise noted.
[c]Tlatelolco Agreement.
[d]Party to the NPT as well.
[e]The Safeguards Agreement refers to both the NPT and Tlatelolco Treaty.

The map and legend are based on data from The (IAEA) Annual Report for 1987 and more recent information through the end of 1988. The country listing "does not imply the expression of any opinion whatsoever on the part of the" (IAEA) "Secretariat concerning the legal status of any country or territory or of its authorities or concerning the delimitation of its frontiers.".

The map was constructed by means of the Mapmaker™ program of Select Micro Systems, Inc., on a Macintosh™ Plus computer of Apple Computer, Inc.

regarding nuclear weapons. In addition to these points of principle, not being party to one of the treaties would be a way to keep adversaries uncertain about a country's military intentions and capabilities.

A major success of the non-proliferation regime is that no advanced industrial countries have become nuclear-weapons powers in 24 years. But this success must be tempered by the realization that several other countries have not renounced the legal right to develop nuclear weapons, and various degrees of knowledge and suspicion exist about their intentions and capabilities.

The Non-Proliferation Treaty

By virtue of its categorical provisions and wide acceptance, the NPT plays a key political role in the non-proliferation regime. Its wide acceptance is illustrated in Figure 4, which depicts the treaty status of countries of the world.

In part, the NPT is a bargain between three of the nuclear-weapons countries, the United States, the Soviet Union, and the United Kingdom, and countries without nuclear weapons. The former have agreed to supply peaceful nuclear technology to the latter and to pursue negotiations aimed at ending the nuclear arms race. The latter have agreed to forego nuclear weapons and to accept IAEA safeguards on all peaceful nuclear activities. Other important provisions are that all countries party to the treaty shall insist on IAEA safeguards on all exports of nuclear fuels or processing equipment. Research about nuclear energy and use of nuclear energy for peaceful purposes shall not be hindered; if anything, the treaty encourages it.

Two of these provisions deserve special comment. First, the aforementioned bargain has been partly superseded because even some countries without nuclear weapons are suppliers of peaceful nuclear technology, though this has not affected the central treaty aspects of non-proliferation and safeguards. Second, to "sweeten" the bargain by sharing the burden and possible commercial disadvantage of safeguards, the nuclear-weapons countries have voluntarily accepted IAEA safeguards on some of their peaceful nuclear activities.

While the treaty specifies that nuclear exports should undergo IAEA safeguards, it does not say that exports should only go to countries that are themselves party to the treaty. Thus, it is a policy decision for each supplier country to decide whether it shall permit safeguarded exports to go to countries that have indigenously developed nuclear facilities not under safeguards.

International Atomic Energy Agency

The IAEA is an international organization with headquarters in Vienna, Austria. Though part of the United Nations "family" of specialized agencies, it has its own Statute, governing board, and budget. The Board of Governors is made up of representatives from its 113 member countries. Employees of the IAEA come from around the world for initially temporary posts in such areas as nuclear-reactor safety, technical assistance and cooperation based on nuclear isotopic techniques, and nuclear-power planning—as well as safeguards.

In 1987 the budget for IAEA safeguards was about $44 million, representing about one-third of total expenditures. There were about 470 safeguards personnel, including those with administrative, developmental, and clerical responsibilities. On average, the 195 inspectors spent about 100 days in the field, with 56 of those in facilities doing actual safeguards inspections. The number of inspections was 2133 in 631 installations.[3] Inspectors have to do much preparation before and summary after the inspections, and the travel required to get to facilities is often lengthy. The job is, indeed, a demanding one.

Research and development (R&D) for the IAEA are carried out largely by its member countries through their national laboratories. In the United States, such R&D are conducted primarily at Department of Energy (DOE) laboratories and plants and are supported both by DOE directly as well as by the interagency

[3] By comparison, the Three Village School District encompassing Stony Brook, Setauket, and Old Field on Long Island, where I live, has a current budget of about $66 million and employs some 550 teachers to educate 7100 students during a school year of 180 days.

Program for Technical Assistance to IAEA Safeguards. The latter involves the Department of State, DOE, the Arms Control and Disarmament Agency, and the Nuclear Regulatory Commission. My colleagues and I perform tasks for both. Though in this lecture I shall, as is customary, highlight R&D at Brookhaven, R&D of safeguards have been and continue to be a widespread effort involving other U. S. national laboratories, similar laboratories abroad, and commercial firms. There is extensive sharing of ideas and equipment and cooperative field-testing and demonstration of equipment and techniques.

IAEA Safeguards

Safeguards verifications conducted by the IAEA are part of a framework that devolves, in most cases, from the NPT (or Tlatelolco Treaty) and a general, full-scope safeguards agreement between each country (or group of countries in the case of Euratom) and the IAEA. The agreement, which takes the same form for all countries without nuclear weapons, provides rules for the general application of safeguards and is supplemented by facility-specific arrangements. For countries not party to the NPT, the framework devolves from a bilateral or multilateral treaty or agreement for nuclear cooperation with a supplier country and possibly the IAEA as well, and separate agreements with the IAEA that provide for generally limited-scope safeguards.

That there is a collection of negotiated agreements providing a foundation for IAEA safeguards demonstrates, at a legal level, the cooperative nature of the enterprise. At the working level, IAEA inspectors require cooperation in the nuclear facilities to conduct verification measures. These cooperative features contrast with the adversarial basis upon which the technical verification measures are designed. As Figure 5 specifies, the design goal is to detect diversion. In practice, what is usually provided is evidence that all nuclear material is accounted for. Such a technical result lends credence to the underlying political declarations.

28. (a) 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.

(b) Section 3. The Agency undertakes to apply its safeguards system in accordance with the terms of this Agreement to all items referred to in Section 2 so as to ensure that no such item is used for the manufacture of any nuclear weapon or to further any other military purpose or for the manufacture of any other nuclear explosive device.

Figure 5. (a) Objective of safeguards for countries subject to full-scope safeguards (from the IAEA document "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons"). (b) Objective applicable to recent individual projects for countries not subject to full-scope safeguards (from the IAEA document "The Text of the Agreement of 18 September 1987 Between Chile and the Agency for the Application of Safeguards to Nuclear Material Supplied from the People's Republic of China").

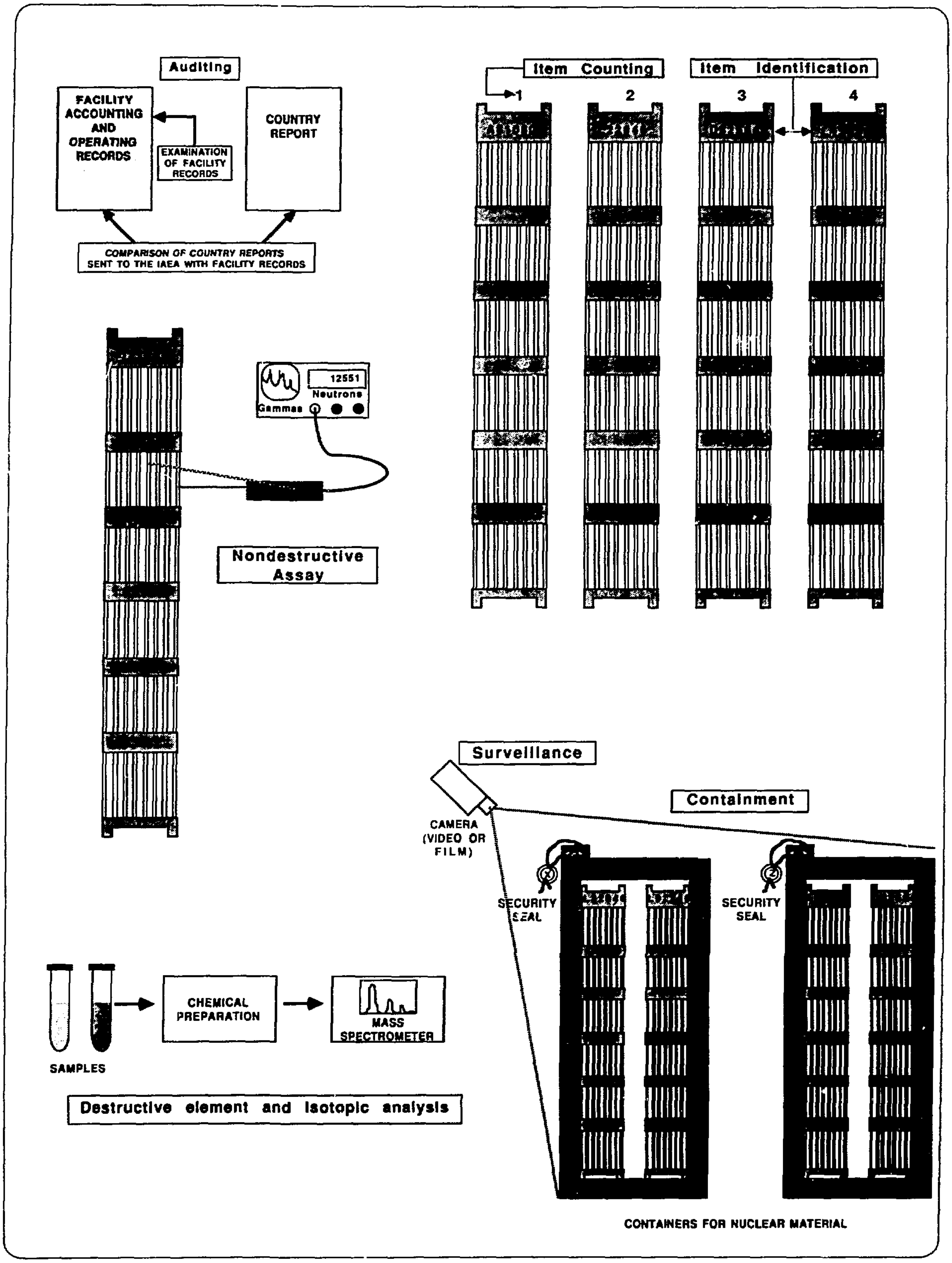

Figure 6. IAEA measures for safeguards verification (based upon diagrams in IAEA Safeguards: Introduction).

Given the legal framework, the countries submit periodic reports to the IAEA on the disposition of nuclear material and on anything additional that is subject to safeguards. Then, during on-site inspections, IAEA inspectors verify the information in the countries' reports. Annually, the IAEA summarizes its findings and a substantial extract of the results is published.

In "The Annual Report for 1987", the IAEA concluded:

> In 1987, as in previous years, the Secretariat, in carrying out the safeguards obligations of the Agency, did not detect any anomaly which would indicate the diversion of a significant amount of safeguarded nuclear material - or the misuse of facilities, equipment or non-nuclear subject to safeguards under certain agreements - for the manufacture of any nuclear weapon, or for any other nuclear explosive device, or for purposes unknown... It is considered reasonable to conclude that nuclear material under Agency safeguards in 1987 remained in peaceful nuclear activities or was otherwise adequately accounted for. This statement should be seen in the light of the following observations:
>
> ...
>
> (b) About 290...., mostly minor, discrepancies or anomalies were found. All cases were satisfactorily explained upon subsequent appraisal or investigation;...

For perspective, know that the benign conclusion for 1987 has not always been drawn. For 1981 through 1983, there were cases where the IAEA was unable to draw conclusions and so stated. Additional technical measures proposed by the IAEA were put into effect during 1983 and thereafter facilitated effective verification.

Examples of minor discrepancies or anomalies referred to in point (b) above are inconsistencies in bookkeeping and the malfunction of the IAEA's surveillance equipment.

Figure 6 illustrates the verification measures carried out by IAEA inspectors. The simplest are the bookkeeping measures of a standard audit. Next in difficulty are counts of items containing nuclear fuel. The most difficult are the actual measurements of the nuclear material, ranging from weighing plus sampling and chemical analysis to nondestructive assay. The last method encompasses heat measurements in a calorimeter for, say, pure plutonium compounds, passive neutron and gamma ray measurements of irradiated reactor fuel, and measurement of the coincident neutrons caused by the (active) neutron-induced fission of fresh reactor fuel. It is both efficient and effective to avoid remeasurements. Thus, containment and surveillance measures are also applied by IAEA inspectors to provide evidence of the continued integrity of batches of nuclear material. Containment measures include application of security seals similar to those on home utility meters, while surveillance measures include film and video cameras with adjustable frame intervals.

For power reactors and fuel-cycle facilities, inspectors carry out these measures during physical-inventory verifications, when (most) facilities are shut down and all easily accessible nuclear material is available for verification, and during interim verifications, when the facilities are in operation and less of the material is available for verification. Physical-inventory verifications typically occur once or perhaps twice a year. Interim verifications take place at a frequency dependent on the safeguards significance of the material at the plant and upon the rate of processing at the plant. This frequency can vary from quarterly inspections for a light-water reactor to continuous, daily inspections for spent-fuel reprocessing plants.

Before many inspections, operators of the facility characterize nuclear material as to elemental and isotopic composition, so the inspector has values against which to compare the results of the verification measurements.

Spent-Fuel Reprocessing Plant

To understand better the nature of IAEA safeguards, consider a spent-fuel reprocessing plant. It separates the plutonium and uranium in spent reactor fuel from the highly radioactive fission products, so that the first two materials can be reused as fuel—either in thermal power reactors (Figure 2) or in fast-neutron breeder reactors. Fabrication of fuel containing plutonium takes place in special, mixed-oxide (MOX; uranium and plutonium oxides) fuel-fabrication plants. Both the Federal Republic of Germany and Japan, for example, have reprocessing plants and MOX fabrication plants that are under IAEA safeguards and have begun using recycled plutonium fuel in reactors.

Figure 7 shows the pressure vessel of a pressurized-water reactor with the fuel assemblies inside. A typical assembly is 4.07 meters long and 21 centimeters on a side and weighs 620 kilograms, of which 423 kilograms is the initial fuel load of uranium (plus plutonium in the case of fresh MOX fuel); the form of the fuel is ceramic oxide pellets contained in 264 long, thin, hollow cladding rods of a zirconium alloy. After irradiation in a reactor core for several years, the "spent" fuel assemblies are removed and stored in a pool for another few years at the reactor facility to permit some decay of the radioactivity and fall in heat production. Then they may be transported to a reprocessing plant in heavily shielded casks and stored again in a pool before reprocessing.

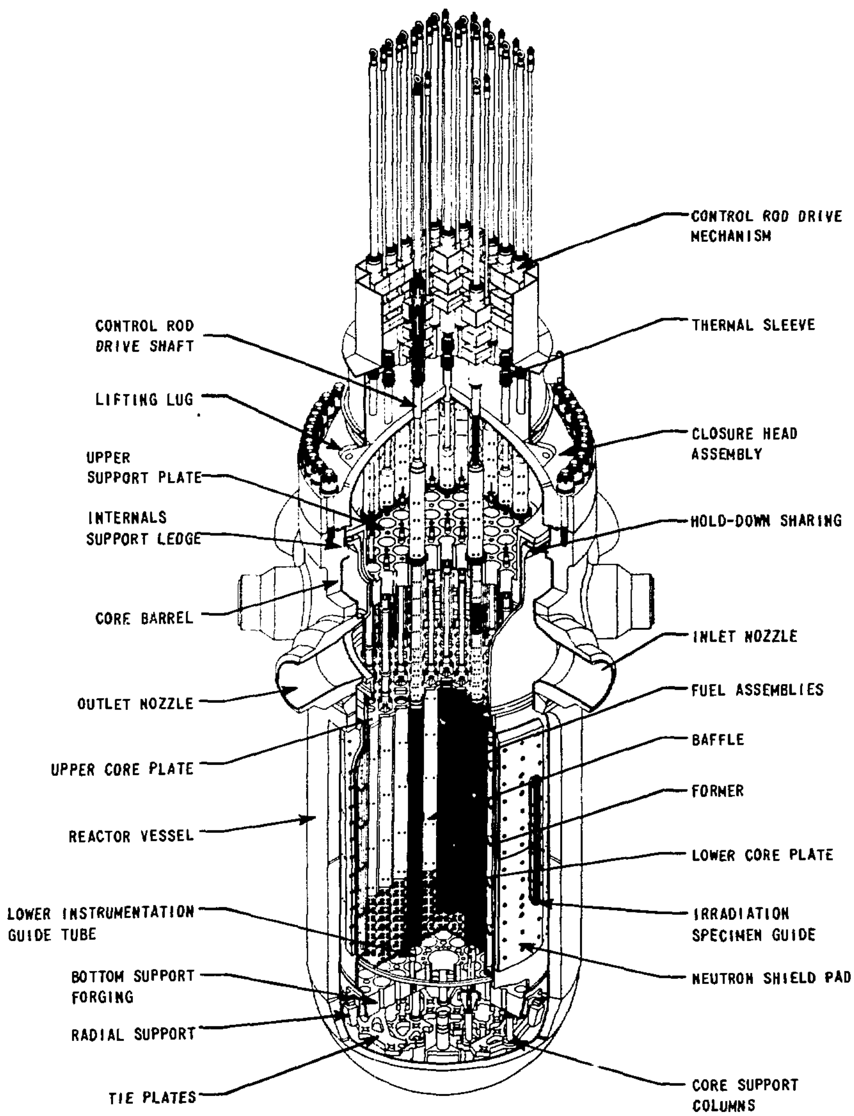

Figure 7. Core of a pressurized-water reactor showing the fuel assemblies (courtesy of the Westinghouse Electric Corporation).

An irradiated-fuel reprocessing plant is a highly complex chemical plant with a maze of tanks and pipes. For safety reasons with respect to chemical toxicity, nuclear criticality, and radiation, it must be built with thick, radiation-resistant walls and designed as much as possible for remote maintenance. Figure 8 shows a schematic diagram of the major operations of such a plant according to the "Purex" (plutonium-uranium extraction) process.

In brief, after interim storage in a pool,

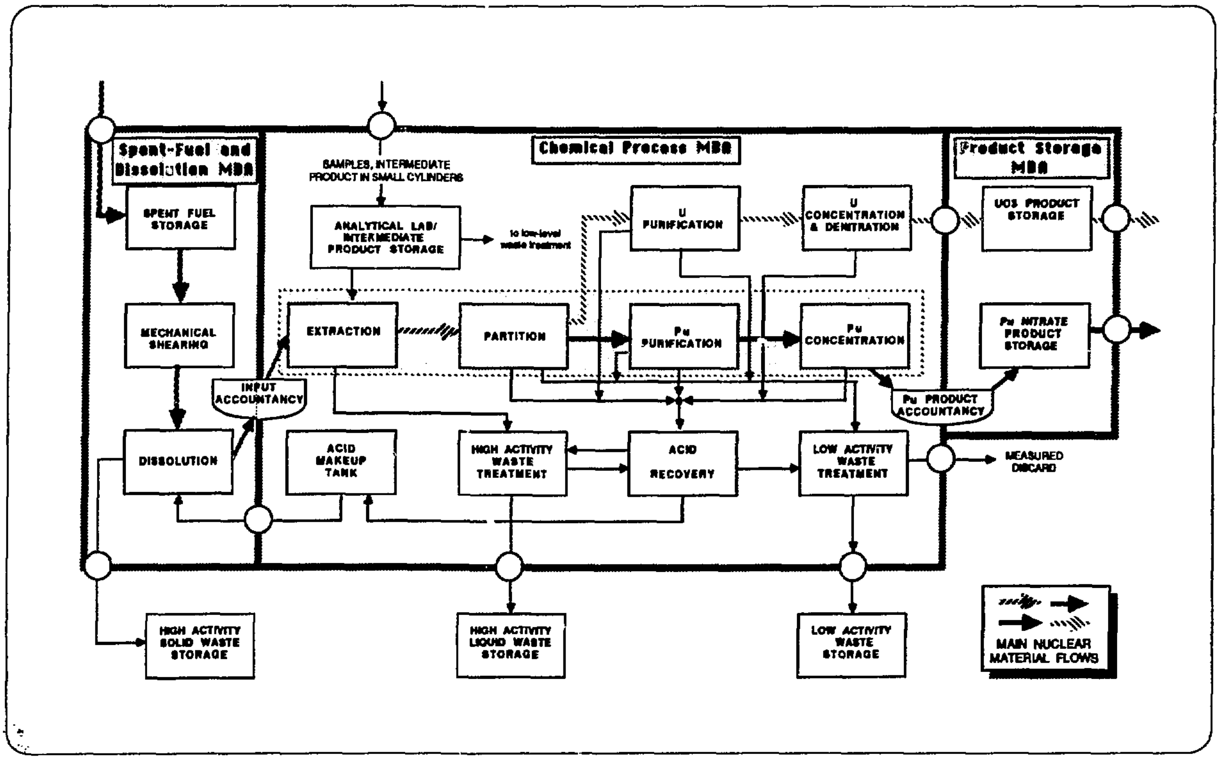

Figure 8. Schematic diagram of a spent-fuel reprocessing plant.

assemblies are sheared into small pieces. The chopped pieces are then immersed in nitric acid to dissolve the fuel, while the cladding is removed as waste. After dissolution, the fission products are removed in a solvent extraction stage, leaving uranium and plutonium. Subsequently, the uranium and plutonium are separated from each other in partition stages, and finally, these two products are purified and concentrated. The uranium is typically converted to a solid oxide powder in the reprocessing plant itself, while the plutonium is converted from nitrate solution to oxide powder in a separate processing area.

Reprocessing-Plant Safeguards

Because of the expected operation of large new reprocessing plants, safeguards measures for reprocessing plants continue to be actively developed. Given this caveat, consider the general procedures that the IAEA would follow in applying safeguards to such an operation. Some procedures take place frequently, as fuel is processed; others occur infrequently, during plant shutdowns.

First, the inspectors audit the facility records and compare them with reports sent to the IAEA.

Next, they verify the calibration of measurement equipment, their own as well as plant equipment whose data are crucial to safeguards, particularly equipment for measuring tank volumes.

Given calibrated tanks, the inspectors verify the flow of plutonium and uranium through the plant by determining the amounts in the feed to and products and wastes from the process. These amounts are calculated by multiplying the solution volume times the nuclear material concentration. The concentration is verified either by analytical chemical analysis in Vienna of samples of process solutions given to the IAEA inspectors by the plant operators, or by nondestructive assay of the samples in instrumentation installed at the plant but subject to control or careful check by the IAEA. For solid uranium product, a weighing substitutes for a volume measurement. In addition to its own Safeguards Analytical Laboratory in Vienna, the IAEA has access to a Network of Analytical Laboratories worldwide. To complement these flow measurements, inventory measurements would also be done once or twice per year after the plant's process equipment is flushed clean and the residual inventory of nuclear material confined to a small number of tanks.

This set of measurements leads to the notion of material balance (Figure 9). This balance encompasses all the flows entering and leaving the plant during a delineated period, as well as inventories taken at the beginning and the end of this material-balance period. Since all measurements are of limited accuracy and precision, the result of the material balance, the "material unaccounted for" (MUF), is not zero even in the absence of such confounding factors as small amounts of material adhering to pipes and vessels, let alone diversion. The MUF value plus other indicators are then appraised for both statistical and safeguards significance.

NUCLEAR MATERIAL UNACCOUNTED FOR (MUF) =

+ BEGINNING INVENTORY
+ ADDITIONS TO INVENTORY (E.G., DISSOLVED FUEL)
- ENDING INVENTORY
- REMOVALS FROM INVENTORY (E.G., Pu AND U PRODUCTS AND PROCESS WASTE)

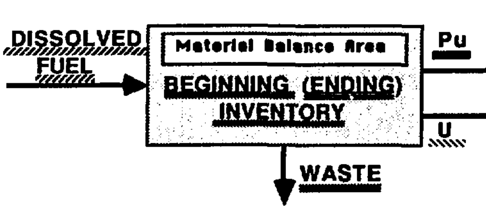

Figure 9. Material balance for the chemical process of a spent-fuel reprocessing plant.

In addition to the inventory verifications that take place at the beginning and end of a material-balance period, interim inventory verifications not involving a cleanout take place even more frequently. At all inventories, seals on containers of nuclear material and on safeguards equipment are checked (see Figure 6) and surveillance equipment serviced and records reviewed, as appropriate.

Finally, while the inspectors do discuss their work with the plant personnel, particularly to resolve any minor discrepancies that are uncovered, they bring any significant anomalies to the attention of IAEA management promptly, in addition to summarizing the results of their inspections. The final conclusions on safeguards applied to the nuclear material at the reprocessing plant depend on the results of the totality of safeguards measures, including attempts to resolve discrepancies and anomalies.

Liquid Volume Determinations

An important contribution by Brookhaven to reprocessing-plant safeguards was the development, by Sylvester Suda, of the computer-controlled electromanometer system for determining the volume of liquid in a tank. He and Bernard Keisch first demonstrated the system at the Tokai Reprocessing Plant in Japan as part of a multinational safeguards R&D program. This system was later reproduced elsewhere for operational and safeguards purposes. It improved the precision of volume measurements of dissolver feed to and of plutonium nitrate product from reprocessing plants from about 1.0% to 0.1% compared to measurements previously made by reading liquid manometers by eye. Improvements of this sort help to reduce the overall uncertainty of measurement.

Consider the tank in Figure 10. Though it is not shown in the diagram, an actual tank at a reprocessing plant is likely to be replete with pipes and guides and slablike rather than circular in cross section. The problem is to determine the liquid level in the tank, which is found from the relation:

Pressure = Density x Depth x Gravitational acceleration g.

The volume is then obtained by reference to the carefully but infrequently conducted calibration procedure of filling the tank incrementally with known volumes and measuring the changes in level.

To understand how the electromanometer system works, notice the three bubbler probes (pipes) within the tank (Figure 10). Nitrogen gas flows out of the probes at a pressure just sufficient to maintain bubble formation; this pressure is monitored, with the vapor pressure above the liquid surface serving as a general reference. Given that the liquid level is above the end of the middle probe's opening, the liquid density is found from the pressure difference between the gas in it and that in the bottom probe, whose depth difference is precisely known. Then the liquid level above the bottom probe is calculated from the pressure difference between it and the reference probe.

The pneumatic scanner shown in Figure 10 routes gas at the reference pressure above the liquid to the single electromanometer. One system can service more than one tank. The heart of the electromanometer, shown in Figure 11, is a coiled quartz Bourdon tube that untwists when a gas, whose pressure differs from the reference pressure, fills it. The movement is sensed optically and nulled magnetically. Given a calibration, a very accurate measurement of the current required to null the untwisting yields the pressure. Computer control of the electromanometer system has two great advantages. First, the pressure can be measured at very frequent intervals and provides a detailed picture of the filling and emptying of tanks, as Figure 12 shows. Second, IAEA inspectors can load their own computer program to help ensure the veracity of the results.

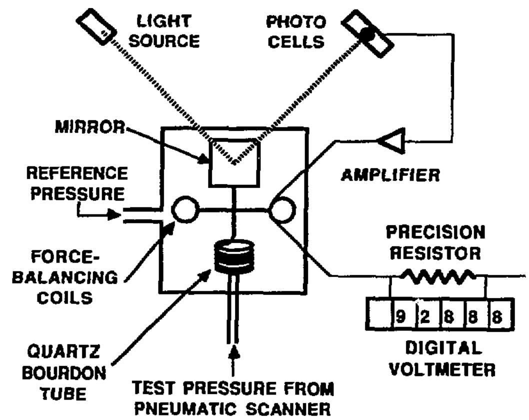

Figure 11. Schematic diagram of a Bourdon tube electromanometer (based upon a diagram in S. Suda, "An Automated System for Volume Measurements in Accountancy Tanks," a paper given at the 1st Annual Symposium on Safeguards and Nuclear Material Management of the European Safeguards Research and Development Association).

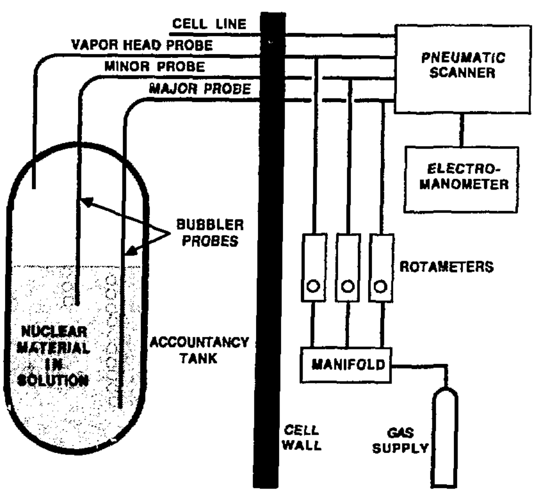

Figure 10. Schematic diagram of the pneumatic part of the electromanometer system for measuring liquid levels in tanks (based upon a diagram in S. Suda, "An Automated System for Volume Measurements in Accountancy Tanks," a paper given at the 1st Annual Symposium on Safeguards and Nuclear Material Management of the European Safeguards Research and Development Association).

Advanced Safeguards Approaches

Let me turn now from traditional safeguards methods to advanced approaches. The impetus to consider them is the growth in nuclear material under safeguards and the complexity and automated character of the facilities handling it. Figure 13 exhibits one aspect of the growth: the amount of especially sensitive nuclear material under safeguards as a function of time. While the plutonium contained in spent reactor fuel is extremely abundant, of greater concern is the increasing amount of separated plutonium destined for recycle fuel in reactors

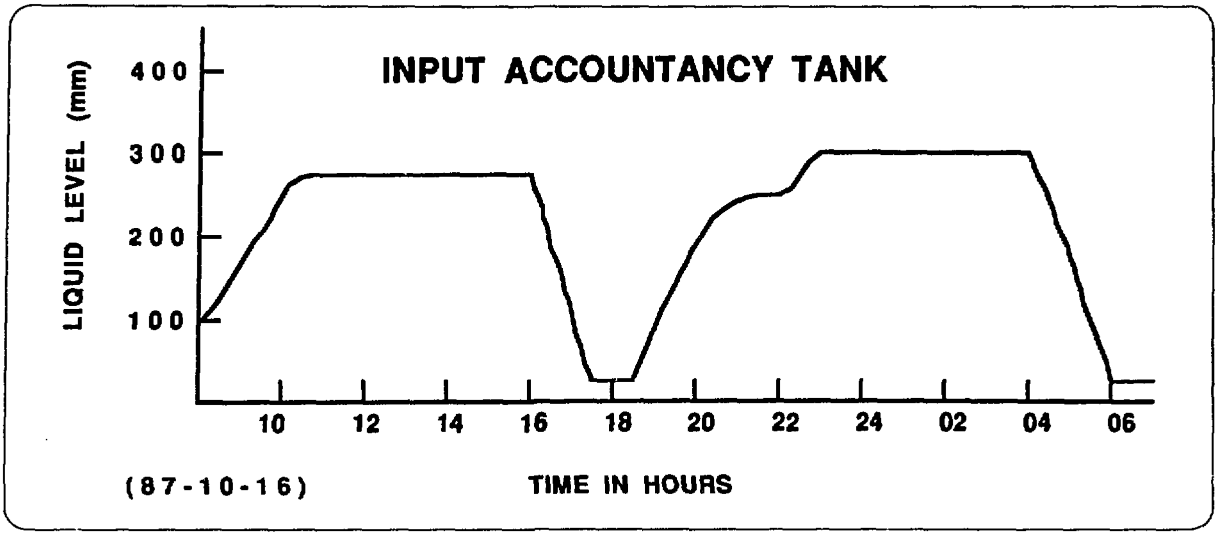

Figure 12. Simulated results from an automated electromanometer of liquid level in a tank in a reprocessing plant (based on a graph in the IAEA monograph TASTEX: Tokai Advanced Safeguards Technology Exercise*).*

(see Figure 2). Another measure of this growth is the effort applied for safeguards by the IAEA: 3985 inspection days in 1980, 6599 in 1984, and 9556 in 1987. Despite the difficulties in the nuclear industry in the United States, the nuclear industries in other countries continue to develop. Thus, the trend in inspection effort, met in part by more inspectors, would continue were it not for budget limitations. This trend is an additional factor spurring the development of advanced approaches.

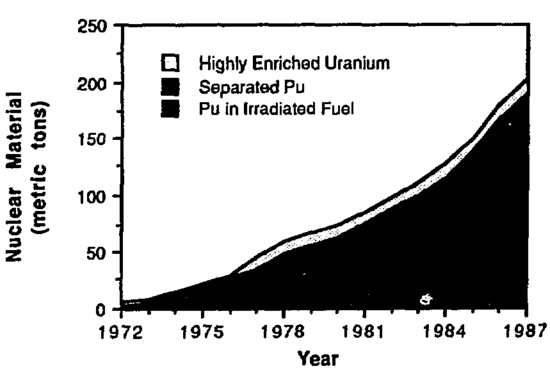

Figure 13. Approximate amounts of plutonium and highly enriched uranium subject to IAEA safeguards except that safeguarded voluntarily according to agreements with nuclear-weapons countries (based upon data from IAEA Annual Reports*).*

The growth increases the burden on the IAEA to carry out safeguards while the complexity and automation of new facilities increases the difficulty in applying standard measures, particularly those based on sampling and analysis. The development and use of nondestructive assay devices and containment and surveillance equipment continue to improve the efficiency and effectiveness of safeguards. Ideally, advanced safeguard approaches would do so in additional ways. The advanced approaches I shall discuss are the zone approach and randomization. Though both show promise for particular situations, they must be tested to ensure their practical utility—just as are traditional measures.

Zone Approach

Since the basic political undertaking in the NPT is made by countries, one could argue that there is no fundamental need to verify the material balance individually for each nuclear facility in the countries. Verification of the balance for groups of facilities or, indeed, for the totality of facilities in each country as a single group, might be acceptable. (This notion only applies to countries where all of the facilities, or at least all of those in the prospective groups, are under safeguards.) To the degree possible, it is most efficient to apply this concept to facilities handling nuclear material of similar safeguards significance. Thus, the fuel cycle in Figure 2 encompasses zones for natural or low-enriched uranium, irradiated reactor fuel, and separated plutonium. Although the IAEA currently takes account of certain aspects of a country's entire fuel cycle in carrying out its verifications, in the present context I shall refer to the existing approach as a "facility-oriented" approach in contrast to the "zone approach".

The first main feature of the zone approach is that flows of nuclear material would only be verified if they cross a zone boundary. Flows between facilities within the zone would not be verified, though the countries would still report them. The second important feature is that physical-inventory verifications for all of the facilities within the zone would be conducted simultaneously or nearly so, e.g., during a single week. These features are tantamount to treating the facilities within the zone as a single facility with a single verified material balance.

The IAEA has begun applying one key feature of the zone approach to the fresh-fuel facilities of the nuclear fuel cycle of Canada, whose reactors rely on uranium of natural enrichment. The feature applied is nearly simultaneous physical-inventory verifications at these facilities.

William Higinbotham and I studied the approach for the fresh-fuel facilities of a nuclear fuel cycle whose reactors use low-enriched uranium fuel. Figure 2 illustrates the facilities in this zone and the flows of nuclear material among them. We assumed that all of the enrichment occurs in another country, so we did not introduce the complication of an enrichment plant. Theodor Teichmann and I are extending the work to the zone of facilities handling separated plutonium.

Table 2 shows the main result of the work on the low-enriched-uranium zone. There is a significant decrease in the inspection effort required for IAEA safeguards verifications from the most intensive facility-oriented approach to the maximal use of the zone approach, with several variations having intermediate requirements. The figures relate to a zone with one conversion plant (uranium hexafluoride to uranium oxide), three low-enriched-uranium fuel-fabrication plants, and 21 reactors. The figures do not include the inspection effort for facilities in other zones, nor do they include savings in travel if most flow verifications at a given type of facility are eliminated.

Table 2

Inspection Effort for Different Safeguards Approaches Applied to the Low-Enriched-Uranium Zone

Safeguards Approach	Effort (Inspector-Days)
Maximal Facility-Oriented[a]	770
International Flow Unverified	713
Intermediate Facility-Oriented[b]	617-644
Zone[c]	488-548

[a]Verifications of uranium oxide flow at shipper and receiver.
[b]One verification of the uranium oxide flow.
[c]No verifications of the uranium oxide flow.

The effort savings suggested by Table 2 accrue to the IAEA. But there would generally be equivalent savings for the facilities under safeguards, because IAEA inspectors are often escorted by facility representatives. However, since the current approach of the IAEA involves the intermediate facility-oriented approach in Table 2, the extreme savings indicated are not realizable by either side.

While the zone approach permits inspection with less effort than does the facility-oriented approach, there is a concomitant loss of verified information about the location of nuclear material. Instead of the verified material balances applying to each facility, there would instead be a single verified material balance applying to the zone as a whole.

It is by no means clear whether the absence of verified location information inherent in the zone approach is a significant problem, especially for natural or low-enriched uranium having relatively low safeguards significance. Such material could not be used to make a nuclear weapon without further enrichment or nuclear transmutation plus reprocessing.

Analysis of the zone approach for plutonium facilities may not show savings in inspection effort similar to the savings found for facilities processing low-enriched uranium. The basic reason is that plutonium has high safeguards significance and requires more frequent safeguards inspections according to current IAEA goals.

Randomization

Randomization has always played a role in safeguards measures, but its traditional use has been in selecting a sample of items from a larger population at an inventory for verification. A properly chosen and verified random sample will lead to safeguards conclusions that are statistically valid.

In more advanced applications of randomization, the population from which a sample is drawn can be a set of inspection activities, a group of facilities, or a group of inspections at a single facility. These various possibilities have been under study at several institutions. The one I shall describe was investigated for uranium enrichment plants by David Gordon and Jonathan Sanborn, and has potential application elsewhere in the nuclear fuel cycle. Of key importance in any such application is that the conditions for randomization be met: the entire population must be subject to selection and the items chosen must not be altered or their characterization changed on the basis of the selection.

Uranium hexafluoride, the working material for commercial enrichment plants, is transported in large cylinders. Figure 14 shows one being weighed by an IAEA portable system, a lower-capacity version of which was developed in part by Anthony Fainberg. Enriched product cylinders are filled sequentially at these plants. Suppose that IAEA inspectors, subject to limits on the total effort they expend at each plant,

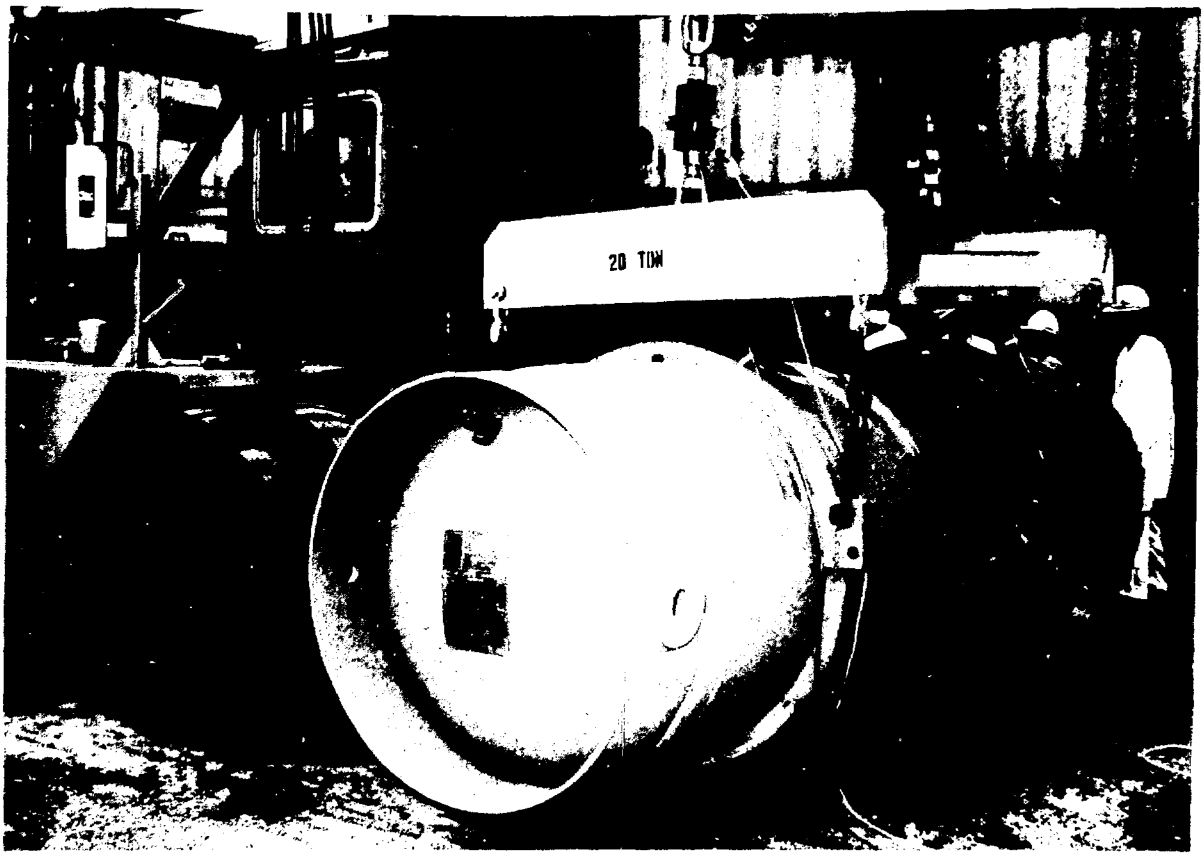

Figure 14. Uranium hexafluoride cylinder being weighed by a portable load-cell-based weighing system developed for IAEA inspectors (photo from J. N. Cooley and T. J. Huxford, "Demonstration and Evaluation of the 20-Ton-Capacity Load-Cell-Based Weighing System, Eldorado Resources, Ltd.", courtesy of Martin Marietta Energy Systems).

can visit at any time they wish. What is their best strategy for verifying the content of the cylinders, or, conversely, for detecting cylinders with less product than is specified ("defected" cylinders)?

To find the solution, suppose that the problem is predominantly one of determining the probability that any given cylinder is present during an inspection. By assumption, the complementary probability that a cylinder is selected for verification during an inspection and any defect detected is 0.90. The overall defect detection probability is their product.

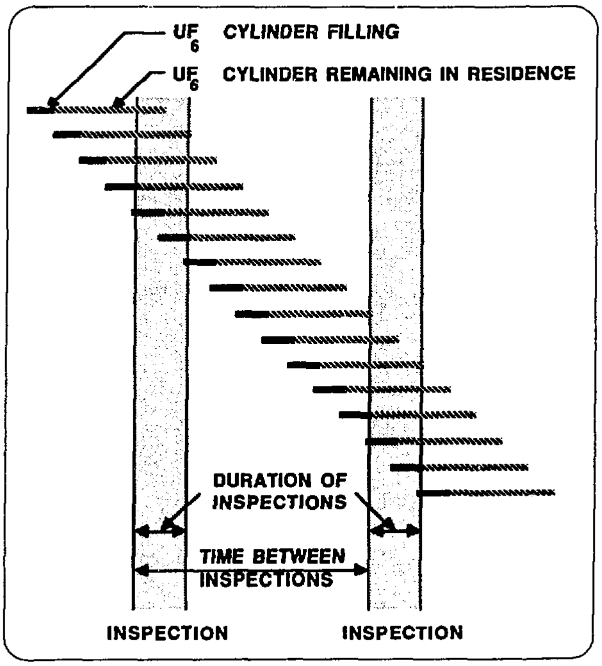

Figure 15. Schematic diagram of the timing situation for verification of uranium hexafluoride cylinders at an enrichment plant.

Figure 15 illustrates the situation. The cylinders take a certain time to fill and, by arrangement, remain at the plant for an additional time to permit verification. Inspectors visit the plant at regular intervals and stay for a fixed period. In terms of the other time parameters, it is possible to calculate how often the inspectors must visit to have an opportunity to check every product cylinder. If, instead, they conduct each visit with a probability less than one, so that the expected number of visits per year is less than in the case of full coverage, then the probability of encountering any given cylinder during an inspection will itself be less than unity.

The solution to this problem for a reasonable set of parameter values is depicted in Figure 16. The detection probability appears there as a function of cylinder residence time for two different inspection rates and for three different durations of inspection. Notice that, for many values of the residence time, the wiser strategy is to make frequent short inspections; one caveat in the real situation is that travel time to the plant would also play a role. Nevertheless, the graph does show vividly two central features of a randomization approach: what detection probabilities are achievable at what cost in inspection resources. The analysis thereby provides a way to compare different strategies.

Appraisal

With this review of IAEA safeguards as background, what is a reasonable appraisal of this feature of the non-proliferation regime? I list in Table 3 a spectrum of possible opinions on their

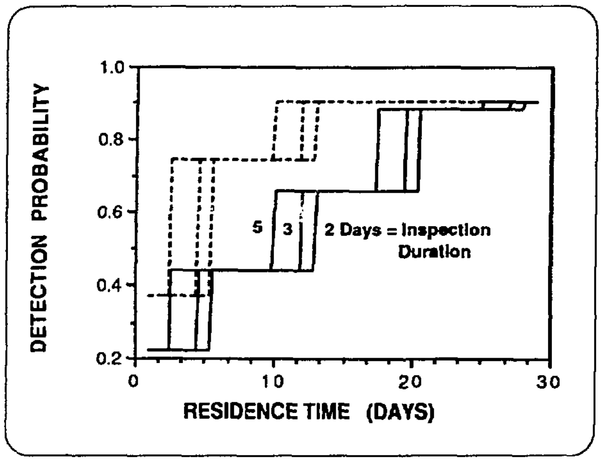

Figure 16. Results of the analysis of verification of uranium hexafluoride cylinders according to a randomization approach. Dashed lines give results for 20 inspections annually and solid lines, for 12 inspections annually. Within each set, detection probabilities for inspections of 5,3, and 2 days are graphed.

role. At one end of the spectrum is the feeling that the mere political commitment of the NPT is sufficient to forestall proliferation among countries party to the treaty—so that technical safeguards are completely unnecessary. At the other end is the belief that the NPT political commitment plus technical safeguards are irrelevant – no matter how well applied. The rationale here is that a country can simply renounce the treaty or, according to the Treaty's provisions, can withdraw from it after three months' notice if extraordinary events related to the Treaty's purview jeopardize the country's supreme interests. Intermediate positions differ in the value ascribed to IAEA safeguards and the ability to continue improving their technical effectiveness.

Table 3

Spectrum of Possible Opinions on the Role of Safeguards in Countries Party to the NPT*

The NPT political commitment is sufficient.
Audits and inspector presence are sufficient complements.
Routine, constantly improving independent verification must supplement auditing.
The technical promise of routinely applied safeguards will never be achieved in practice.
Safeguards could never be sufficiently foolproof.
The NPT and safeguards are irrelevant.

(*or equivalent treaty)

I feel that the role of safeguards is summarized by the third of the range of opinions in Table 3. Given the importance of the nuclear industry to many countries, safeguards verifications carried out by the IAEA serve the world well in providing evidence about the peaceful uses of nuclear energy and maintaining a capability to detect and deter diversions of nuclear material. These safeguards verifications are accepted by many countries as important confidence-building measures, even though they represent a dimunition of national sovereignty. By no means perfect, the measures are continually improving. But they require sustained political and financial support and cooperation from facility operators as the number of nuclear facilities and their complexity increase. As a practical matter, the safeguards role of the IAEA would be difficult to replace.

Finally, the most significant aspect of the nuclear-proliferation problem lies outside the purview of IAEA safeguards. Namely, several key countries (see Figure 4) have so far declined to become party to the NPT or equivalent treaty, so have not renounced the right to develop or acquire nuclear weapons. Inducing these countries to do so and permit IAEA safeguards on all of their nuclear materials is a worthy foreign-policy goal.

Acknowledgments

My work in international safeguards during the past nine years has virtually always involved joint efforts. I am grateful to the members of the Technical Support Organization in Brookhaven's Department of Nuclear Energy, particularly William Higinbotham, for their work with me as well as for some direct assistance on this lecture and the figures. Others also helped on this manuscript and with figure preparation. I also acknowledge those members of the larger national and international communities in this discipline with whom I have collaborated and from whom I have learned.

Previous Brookhaven Lectures in the same general area as mine were:
"Limiting the Nuclear Club", by Herbert Kouts, #85, June, 1969;
"Nuclear Material Safeguards", by William Higinbotham, #138, September, 1976; and
"National Laboratories in Support of International Safeguards", by Leon Green, #178, November, 1980.

Many of the figures in the text were generated on a Macintosh computer system with the following software: MapMaker (Select Microsystems), MacDraw (Claris), and Cricket Graph (Cricket Software).

Suggestions for Further Reading

A. General Material

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2."Nuclear Proliferation Today", 1984;
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3."IAEA Safeguards: Glossary, 1987 Edition", 1987;
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"IAEA Safeguards: An Introduction", 1981;
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12."TASTEX: Tokai Advanced Safeguards Technology Exercise", IAEA/STI/DOC/10/213, 1982, International Atomic Energy Agency, Vienna, Austria.

About the Author

Leslie G. Fishbone has spent the last nine years as a scientist in the Department of Nuclear Energy's Technical Support Organization, whose main functions include performing systems analyses of international and domestic nuclear-safeguards situations. The international work periodically brings Fishbone and his colleagues to the International Atomic Energy Agency for consultations.

Before his safeguards work, Fishbone worked in the National Center for Analysis of Energy Systems on a multinational project to determine, by computer optimization techniques, candidate energy technologies for development according to such criteria as least cost or minimum oil imports.

Leslie Fishbone earned his undergraduate degree in physics from the California Institute of Technology and received his Ph. D. in 1972 from the University of Maryland. Thereafter, he went to the Soviet Union as a participant in the research exchanges between the National Academy of Sciences and the Academy of Sciences of the U.S.S.R.; he was attached to the Landau Institute of Theoretical Physics.

Married and with two children, Fishbone has tried in his spare time to reestablish and embellish the electric train set that he himself enjoyed when he was a child.