Modern fuel cycle technologies and IAEA safeguards

A look at foreseeable developments and their potential effects

by Adolf von Baeckmann

After the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was opened for signature in 1968, the task fell upon the IAEA of implementing a system of safeguards in NPT non-nuclear-weapon States to provide assurances that peaceful nuclear activities were not being used for the manufacture of nuclear explosive devices. For this purpose, the IAEA had to extend and improve its safeguards system substantially.

Most IAEA safeguards concepts and technologies, therefore, were developed during the early 1970s when complete nuclear fuel cycles only existed in the nuclear-weapon States. In particular, uranium-235 enrichment technologies were only available in these States and the transfer of these technologies to non-nuclear-weapon States was carefully avoided. Reprocessing of spent fuel at that time was not considered to be sensitive — but in practice there was very little fuel fabrication from uranium-plutonium mixed oxide (MOX) and the use of plutonium in non-nuclear-weapon States concentrated on research devices for fast-breeder reactors (FBRs), such as fast critical assemblies.

The situation has changed since. Several non-nuclear-weapon States have mastered the light-water reactor (LWR) fuel cycle. They developed their own enrichment capabilities based on ultracentrifuge technology and on other gas-dynamic processes (UCOR and nozzle technology), and gained considerable experience in spent-fuel reprocessing (e.g. EUROCHEMIC, WAK, Tokai Mura, and Tarapur). FBRs were also developed in several non-nuclear-weapon States and heavy-water production plants have been built there.

The situation continues to change: the Chernobyl and Three Mile Island accidents have left their marks. The booming of the nuclear industry in the early 1970s has given way to a policy of consolidation. FBR projects have been stopped or delayed. The number of new orders for power reactors has decreased substantially, reprocessing plants and MOX fuel fabrication plants have been seriously delayed and, perhaps with the exception of ultracentrifuge uranium-235 enrichment plants, the nuclear fuel cycle industry is in a period of stagnation.

Despite these developments, a closer look reveals that the situation is not that bleak: although many programmes have been delayed, they have not been stopped. And since the pressure of urgency is off, the developments are often more carefully considered and planned. The most remarkable ones are visible in the fields of automation — in particular in reprocessing and MOX fuel fabrication, reactor fuel economy, and spent-fuel storage. Laser enrichment technology may find its way into the nuclear fuel cycle, and tritium separation from deuterium moderator and coolant may become routine.

This article analyses some foreseeable developments and their impact on IAEA safeguards. However, other — non-technical — developments that will significantly affect the future of IAEA safeguards must not be forgotten, the most challenging of which might be the full implementation of IAEA safeguards on all nuclear material in all peaceful nuclear activities in the nuclear-weapon States.

Developments in automation

Reasons of economy and the need to minimize the level of radiation exposure to persons working in the nuclear industry are strong incentives for a high degree of automation in nuclear fuel cycle facilities, particularly

Mr von Baeckmann is adviser to the IAEA Deputy Director General for Safeguards. This article reflects his personal opinion and does not represent the official view of the IAEA or its Department of Safeguards.

in spent-fuel reprocessing and fuel element fabrication plants. However, automation and remote handling may make the nuclear material less accessible for verification.

New procedures for in-process inventory verification are therefore required. Near-real-time material accountancy, running-inventory-taking, and the use of isotopic batch signatures have been suggested for supplementing or replacing the usual procedure for inventory taking. Operations monitoring and a wider use of complex containment and surveillance (C/S) techniques are also under development. Mathematical calculation of in-process inventories is being investigated and the use of installed measurement equipment (either specifically installed for safeguards purposes or plant instrumentation for plant control) is being considered.

These new safeguards techniques are not without problems: improved tamper resistance and authentication of data being used for safeguards purposes are needed and a more detailed knowledge of the plant design and its functioning is required. Since plant automation is usually linked with a high degree of computerization, special skills and knowledge related to computer operation are essential. In particular, the new facilities for reprocessing and MOX fuel fabrication fall into this category.

Uranium-235 enrichment

The spread of enrichment technology is substantial. At least five non-nuclear-weapon States operate enrichment plants and several research and development (R&D) facilities have been built in addition. The commercial enrichment of uranium-235 can no longer be considered the exclusive prerogative of nuclear-weapon States.

For enrichment plants based on the ultracentrifuge technology, the Hexapartite Safeguards Project has elaborated an acceptable safeguards approach based on limited frequency unannounced access (LFUA) of the inspectors to the cascade areas.* This approach carefully balances the requirements for protecting (commercially) sensitive information with the need for performing reliable verification activities. Since the uranium hexafluoride inventory in the LFUA area is rather low, the safeguards approach for it combines closing the material balance outside the cascade area and verification of non-production of highly enriched uranium (HEU) inside the cascade area.

Very few other technologies for uranium-235 enrichment are presently used in the enrichment R&D facilities under IAEA safeguards, but the situation may change soon. If the South African UCOR process comes under safeguards, additional measures may become necessary since the cascade area contains very substantial quantities of uranium hexafluoride. The same would be true if the German-Brazilian nozzle process is used for a commercial-size enrichment plant under safeguards, or if a diffusion plant is made subject to safeguards. Since several operational parameters are considered commercially sensitive in these plants and the (large) in-process inventory could not be established without knowledge of some of these parameters, the development of special verification procedures might be required.

Laser enrichment facilities would not necessarily cause special problems. As in the case of the ultracentrifuge enrichment technologies, the in-process inventory would be relatively small as compared to a diffusion plant of equal capacity and only one very narrow process step contains the sensitive laser enrichment technology. From a proliferation point of view, the major problem with laser enrichment technology would be that a laser separation plant might be rather small and easy to hide if a country were to decide to build a clandestine production capability for highly enriched uranium. The (possible) existence of unsafeguarded enrichment plants would, however, lead to a change in the safeguards concepts for low-enriched uranium. New safeguards approaches for uranium would have to be based on the separative work (value) contained in the enriched uranium, rather than on the (artificial) borderline of 20% enrichment between highly enriched (direct use) uranium and low-enriched (non-direct use) uranium.

LWR fuel economy and thermal recycling

Certain measures to improve fuel economy for LWRs have led to the development of highly sophisticated low-enriched uranium (LEU) fuel elements and to the recycling of plutonium. Both measures are not without effect on the safeguards system of the IAEA:

The verification of fuel content in unirradiated fuel assemblies by non-destructive assay (NDA) techniques is significantly complicated if the uranium enrichment level in the fuel elements is not homogeneous or if burnable neutron poisons are present. Also the use of recycled uranium, containing traces of uranium-236, complicates the standard procedures for enrichment measurement and uranium content measurement in fresh fuel. Although the available gamma-spectrometric and neutron collar measurement techniques remain applicable in principle, design-specific calibrations of the measurement equipment are required. These are time consuming and expensive, and usually less accurate if good standards are not available.

Pin exchange is an additional complication for safeguarding most of the more modern LWR fuel assemblies. In particular, the possibility of pin exchange in fresh and used fuel elements leads to a more complicated and more intrusive safeguards strategy, requiring the application of additional C/S measures and additional measurements. The situation would be further compli-

* "The Hexapartite Safeguards Project, a Review by the Chairman", by F. Brown, IAEA-SM-260/57, Vienna (1983).

cated if — as it has been suggested — the spent-fuel assemblies are routinely disassembled at the reactor site and only the spent-fuel pins sent to the storage, reprocessing, or final disposal site. In this case, very manpower-intensive human surveillance activities might be required during the disassembling process and the loading of the shipping cask.

Thermal recycling. MOX fuel assemblies are now being produced more frequently for thermal recycling of reactor plutonium in LWRs. One major safeguards problem originates from the short timeliness goals for separated plutonium: the fresh MOX fuel assemblies must be inspected rather frequently (once per month). Moreover, it is difficult to verify or reverify the plutonium in the fresh MOX assemblies through NDA measurements. Since fresh MOX assemblies are frequently stored underwater at reactor sites, and no NDA technique currently exists for underwater NDA measurement, intrusive fuel handling is needed for reverification, or additional C/S measures must be applied.

One additional complication for the verification of plutonium in MOX fuel assemblies is the fact that the isotopic composition of the plutonium in individual pins frequently differs so that calibration becomes very complicated. It should, however, be recognized that thermal recycling at this moment is the main process in the LWR fuel cycle by which separated plutonium is being consumed.

Spent-fuel storage

Since no facilities for the final disposal of spent-fuel assemblies have been established, most of the spent-fuel elements are usually stored for long periods of time in engineered retrievable storages. Many countries have not made a decision as to whether the spent-fuel elements will later be placed in a final (irretrievable) spent-fuel storage or whether they will be reprocessed. In nearly all cases the reprocessing option is being kept open.

For effective safeguards on spent fuel, new concepts, NDA techniques, and C/S techniques must be developed. A recent development is an ultrasonic seal designed for underwater *in-situ* reverification which is now routinely used in some Candu reactor spent-fuel ponds. Also, for some LWRs automatic monitoring devices for the transfer of spent-fuel elements into the shipping casks have been developed.

The IAEA has under consideration safeguards approaches for long-term spent-fuel storages (multilayer water ponds and air-cooled storages), and has started investigating the possibilities for safeguarding final disposal facilities for spent-fuel elements. *(See the article beginning on page 16.)* In those cases where the spent-fuel is loaded into a long-term storage container already at the reactor site, human surveillance of the loading process might be the only reasonable verification technique. Once the spent-fuel cask is filled, only C/S measures can be applied to assure that no spent fuel has been diverted.

One important safeguards consideration related to spent-fuel storage is the fact that spent fuel — or more precisely the plutonium contained in spent fuel — becomes more accessible with increasing cooling time due to the decay of major fission products. This means that the degree of radiological self-protection is decreasing and the potential attractiveness for diversion is increasing. This aspect is frequently overlooked by proponents of long-term spent-fuel storage. Indeed, the Agency has never clearly addressed this question and established a reasonable borderline between the categories of "separated plutonium" (with short detection time and a high degree of verification requirements) and "plutonium contained in spent fuel" (with medium detection time and a medium degree of verification requirements). In fact, the plutonium contained in spent fuel with a low burnup that is cooled over long-time periods might be significantly more attractive for nuclear-weapon production than separated plutonium originating from high-burnup fuel being stored in the form of high-temperature sintered mixed oxide fresh fuel elements. Since spent-fuel cooling times in general are increasing, as is the burnup for LWR fuel, this question will gain importance in the future. It can certainly not be ignored if (and when) final disposal facilities are being opened for spent-fuel elements (plutonium mines).

Heavy-water production plants

In 1991 the first heavy-water production plant under IAEA safeguards is expected to start production. For the IAEA this is a new, very unusual challenge. Such a plant is not really a fuel-cycle facility and no nuclear material is to be safeguarded. A heavy-water production plant is a very complex chemical factory with hundreds of kilometers of piping, vessels, exchange columns, pumps, heat exchangers, etc.

The IAEA, in close co-operation with the State and the construction company involved, is in the process of developing a safeguards concept for this plant which will be based on deuterium balance closing.* Specific attention is being given to the plant design, operational configurations, deuterium extraction, in-plant inventory, natural losses, and measurement uncertainties. The concepts and techniques under development include substantial monitoring of operational parameters and are only applicable to this specific plant, which in some of

* "Selection of a Safeguards Approach for the Arroyito Heavy-Water Production Plant", by A. von Baeckmann and M.D. Rosenthal, IAEA-SM-293/140, Vienna (1987).

its major features is unique in the world. A longer period of testing and demonstration will be needed before a satisfactory, effective, and efficient safeguards system can be implemented.

However, it has been suggested that because of the relatively low proliferation importance of heavy water and the limited resources available for Agency safeguards, the IAEA should concentrate its safeguards activities at heavy-water production plants to the verification of the final product.

Tritium

As nuclear-weapon technologies develop, the items and materials considered to be sensitive may change. Nuclear-grade graphite was considered sensitive in the 1960s and early 1970s, but in practice nuclear-grade graphite has practically no role in IAEA safeguards. On the other hand, certain transuranium elements and tritium may play important roles in non-proliferation issues. This is particularly so for any cut-off situation for the production and renewal of nuclear weapons in nuclear-weapon States if and when nuclear arms limitation agreements come into being.

Recently some discussions have been initiated on tritium. Tritium appears to be essential for many nuclear weapons and its production might be a limiting factor in renewing and maintaining stockpiles. It has therefore been suggested that IAEA safeguards might be extended to tritium. In nuclear-weapon States, tritium is normally produced in special production reactors designed for the production of tritium and plutonium by nuclear reaction. In principle IAEA inspectors could be used to verify the absence of the necessary irradiation facilities or the non-use of existing irradiation facilities for tritium production. It must, however, be realized that larger quantities of tritium are also being produced as an inadvertent by-product in power reactors cooled and/or moderated with heavy water. To exclude the possibility of unreported removal of tritium from the heavy water of safeguarded reactors, the tritium content and inventory would have to be permanently monitored in such reactors. Such a task however, would be complicated by the fact that the separation of tritium from heavy water in power reactors might be done for reasons of radiation protection and possibly also for peaceful commercial use.

At this moment the IAEA safeguards system is not designed to detect or verify tritium production. In fact, tritium is not even mentioned in any safeguards agreement, the IAEA Statute, or in the information regarding rules of exports received by the IAEA (INFCIRC/209 and INFCIRC/254) from certain Member States. If the non-production of tritium were an issue for IAEA safeguards, new safeguards measures would have to be developed and implemented. INFCIRC/153 would have to be revised and all relevant existing safeguards agreements would need amendment.

Other developments

Developments relevant to IAEA safeguards are not limited to technological ones in peaceful nuclear activities in non-nuclear-weapon States. As more modern techniques become available for improving fuel-cycle activities and for verification activities, these techniques might also become available to potential diverters and must be taken into consideration in the so-called diversion analyses. Improved computer programs may help the IAEA to analyse in a more credible form the available safeguards-relevant data on nuclear material flows and inventories, but they may also help the potential diverter to optimize his diversion strategies. This is one reason why IAEA safeguards cannot be based on concepts and criteria carved immutably in stone, but must continue to evolve through constant development and adaptation.

Political developments also have to be taken into consideration. In the final analysis the non-proliferation policy can find its justification only if, in the long run, it is complemented by a policy of nuclear arms control and disarmament. If (and when) nuclear arms reduction agreements enter into force, the role of IAEA safeguards in nuclear-weapon States might be extended to a more complete system of international verification. This would indeed be the most significant challenge IAEA safeguards might have to face during the next decade.

Furthermore, the process of economical integration in Western Europe will increase the links between the nuclear fuel cycles of Western European States by which reprocessing of spent fuel may concentrate in the two nuclear-weapon States, France, and the United Kingdom. In addition, the new political and economical developments in Eastern Europe may lead to further concentrations in nuclear fuel cycle services in Europe so that eventually IAEA safeguards activities there might be focused on a number of larger facilities.

One other development which significantly influences the effectiveness of IAEA safeguards is the increasing number of facilities and quantities of nuclear material remaining outside the IAEA safeguards system in those non-nuclear-weapon States that have not accepted full-scope safeguards. Reactors and practically all types of fuel-cycle facilities, including uranium-235 enrichment plants, reprocessing plants, and heavy-water production plants, have been brought into operation outside IAEA safeguards in those countries. The degree of universality of IAEA safeguards is visibly decreasing. This not only complicates the application of IAEA safeguards to the nuclear material subjected to it. It also reduces the degree of international commitment to an internationally verified non-proliferation policy. For the future of the non-proliferation regime and of IAEA safeguards, it will be essential to reverse this trend.

Finally, the increasing trend to overregulate nuclear activities, which can be observed in some countries in the aftermath of the Chernobyl accident, may delay or hamper the implementation of safeguards measures. In particular with regard to the shipment of safeguards samples, the movement of fuel, and access procedures, increasing difficulties in complying with new national regulations and requirements have been observed.

Outlook

How is the Agency addressing these challenges? Technical challenges are usually addressed by the Agency's inspectors and development staff through consultants, advisory groups, and safeguards support programmes. National R&D laboratories in several Member States co-operate with the Agency through these programmes.* Also, the Standing Advisory Group on Safeguards Implementation (SAGSI) frequently addresses pertinent developments in its deliberations and advises the Agency accordingly.

National or international projects for support of safeguards R&D and contracts with commercial companies may be used for the development of safeguards concepts, instruments, methods, and techniques. The Tokai Advanced Safeguards Technology Exercise (TASTEX), the Hexapartite Safeguards Project, and the Large Scale Reprocessing Safeguards Programme (LASCAR) are examples for international safeguards projects.** In some cases, safeguards requirements have been taken into account during the construction of new nuclear industrial facilities, but more guidance and more effort in this direction are required. In addition, specific projects have been created within the IAEA Department of Safeguards to address safeguards implementation at complex facilities, on an interdivisional basis.

One important component of the IAEA capability to respond successfully to new developments is a sound financial basis. Unfortunately, it has been working for several years under the constraints of a near zero-growth safeguards budget which has forced some redirection of resources from R&D work to meet the pressing demands for expanding inspection activities. The development work is therefore suffering from insufficient resources and in the long run this defect will become more and more visible. If safeguards were to be extended further in nuclear-weapon States, significant additional resources would be needed, or the present intensity of safeguards measures would have to be reduced. Sufficient resources and continuing co-operation in the field of safeguards R&D and implementation are essential to enable the Agency to cope successfully with its increasing safeguards task.

* "Role of Support Programmes in Safeguards", by H. Kurihara, *IAEA Bulletin*, Vol. 30, No.1, Vienna (1988).

** For TASTEX, see *Tokai Advanced Safeguards Technology Exercise*, Technical Reports Series No. 213, IAEA, Vienna (1982).

IAEA safeguards coverage extends to more than 900 nuclear facilities worldwide.