Research

Concerns when designing a safeguards approach for the back-end of the Swedish nuclear fuel cycle

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SKI:s perspective

Background

Sweden has for many years collected the spent nuclear fuel originating from nuclear power plants. This fuel must at all times be kept under supervision to render a diversion impossible; this is of course due to the possibility to make weapons from the material. One idea is to keep the nuclear material in a repository deep under the ground; this is not only to keep the material safe from theft but also to have a safe long-time storage as respect to the environment. As yet, no country has taken a deep repository in use; therefore, there are no routines for how the safeguarding of the nuclear material will be implemented.

Aim

The aim of this project has been to pick up ideas of how the safeguarding of an encapsulation plant and a deep repository can be facilitated. This is needed in order to give directions to the nuclear facilities on how the material shall be safeguarded.

Results

This report indicates a few different ways of how to safeguard the Swedish material. It also identifies areas where more investigative work remains to be done to get a good basis for decision making.

Continued efforts

The author of this report is continuing her research in the area, aiming at a licentiate thesis. This will hopefully give the authorities more facts on which they can base their decisions. Several research projects and instrument development projects are under way. This is aimed at providing sufficient tools and methods required in the encapsulation plant and the deep repository.

Handling officer

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Project number

200510010

Sammanfattning

Det planerade svenska systemet för att hantera det radioaktiva avfall som produceras i kärnkraftreaktorerna bygger på ett slutförvar flera hundra meter ner i berggrunden. I detta ska det använda bränslet placeras, inneslutet i kopparkapslar, varpå slutförvaret fylls igen med sprängsten och lera. Uppförandet av en inkapslingsanläggning och slutförvaret beräknas starta inom tio år. På grund av Sveriges internationella åtaganden om icke-spridning måste det svenska safeguardssystemet utökas till att omfatta även dessa nya anläggningar. Slutförvaret har vissa unika särdrag som ställer safeguardssystemet inför helt nya utmaningar. Dessa särdrag är bland andra den långa tidsrymd som anläggningen är tänkt att innehålla kärnmaterial samt att det material som är placerat i förvaret kommer att vara mycket svårt att få tillgång till. Slutförvarets otillgänglighet innebär att det inte är tänkbart att man kommer att kunna verifiera att dess innehåll är på plats.

I denna rapport presenteras de tekniker som idag finns tillgängliga för uppbyggnaden av ett safeguardssystem för slutstegen i den svenska kärnbränslecykeln. Viktiga aspekter att ta hänsyn till under planering och implementering av safeguardssystemet har undersökts, vilket i vissa fall har lett till en identifiering av områden inom vilka ytterligare utredning kommer att bli nödvändig.

Resultaten inkluderar tre möjliga sätt att införa safeguards i anslutning till inkapsling och slutförvar. Dessa har utvärderats på basis av safeguardsmyndigheternas uppställda krav. Även utveckling och arbete som gjorts i anslutning till safeguardsproblematiken kring slutförvaring av använt kärnbränsle har sammanställts.

Summary

In Sweden, the construction of an encapsulation plant and a geological repository for the final disposal of spent nuclear fuel is planned to start within the next ten years. Due to Sweden's international agreements on non-proliferation, the Swedish safeguards regime must be extended to include these facilities. The geological repository has some unique features, which present the safeguards system with unprecedented challenges. These features include, inter alia, the long period of time that the facility will contain nuclear material and that the disposed nuclear material will be very difficult to access, implying that physical verification of its presence in the repository is not foreseen.

This work presents the available techniques for creating a safeguards system for the back-end of the Swedish nuclear fuel cycle. Important issues to consider in the planning and implementation of the safeguards system have been investigated, which in some cases has led to an identification of areas needing further research.

The results include three proposed options for a safeguards approach, which have been evaluated on the basis of the safeguards authorities' requirements. Also, the evolution and present situation of the work carried out in connection to safeguards for geological repositories has been compiled.

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1. Introduction

1.1 Background

The nuclear politics in Sweden is based on the principle that generations benefiting from the use of nuclear energy also should be responsible of the disposal of the waste in such a way that it will not affect future generations. Sweden was a pioneering country to implement this concept politically as well as legislatively and plans are in progress on constructing a geological repository for the nuclear waste. Finland has followed the Swedish development and will probably be the first country to implement this idea in practice.

The entire nuclear system is surrounded by a control mechanism, so called safeguards, to ensure the authorities and the public that no nuclear material is lost in the fuel cycle and that knowledge or technology that can be used for non-civilian purposes are not proliferated. Now, the control needs to be extended to enclose the back-end of the nuclear fuel cycle, which includes the encapsulation plant where the nuclear fuel is prepared for emplacement in the repository, the repository itself and the required transports.

The development of an approach for the safeguards of the repository contains some new challenges as no similar facility has been under safeguards before. The repository presents some unique features where the most important is that the fuel emplaced in the repository is difficult to access and therefore not available for re-verification. This means that there is no way of verifying that the spent fuel actually remains where it should .

The problems surrounding safeguards for activities connected to a geological repository are yet to be solved. The Swedish nuclear power plant operators are responsible for the construction of the facilities of the back-end of the fuel cycle. The operators jointly own the Swedish Nuclear Fuel Management Company, SKB (Svensk Kärnbränslehantering AB), which is carrying out this obligation. The SKB will submit an application for the construction of the encapsulation plant in the summer of 2006 to the Swedish Nuclear Power Inspectorate, SKI (Statens Kärnkraftsinspektion), which is the national safeguards authority. To grant the SKB permission to construct the encapsulation plant the SKI needs to make sure that it is possible to safeguard the nuclear material in the facility in a credible way.

1.2 Purpose of this work

The specific design of a nuclear facility is an important factor when developing a safeguards approach for it; certain design features can make it difficult to implement credible safeguards. As an example, the safeguards activities require a certain amount of space, and if that is not provided in the design of the facility the safeguards approach will be compromised. Therefore the SKI and the SKB must agree on designs for the facilities in the back-end of the fuel cycle. These designs should serve the operational purpose of the

facility and be possible to implement safeguards on. This implies that the objectives of the safeguards must be well defined in order for the authority to be able to draw conclusions about the efficiency of the safeguards implemented onto the facilities.
The purposes of this work were to

- identify issues important to the implementation of safeguards for the encapsulation plant and the geological repository. These issues will be important to consider in the design of the facilities. Also,in trying the application from the SKB to construct these facilities, the SKI must see to that the safeguards issues can be resolved within the proposed design. The issues regard, for instance, how documentation relevant to safeguards should be handled, and how much importance should be placed on measurements of the nuclear material to determine its characteristics. Also, to
- summarise the present situation of progress and gathered knowledge in the area of safeguards for the back-end of the fuel cycle.

1.3 Disposition of the work

The work was divided in two parts: The first part was to create an overview of the present situation in the area of safeguards of a repository. This included consultations with the central parties involved in handling and safeguarding nuclear material regarding how these parties work in this area, and of how the discussions in the area are evolving. In this part of the work the issues addressed at the workshop arranged by the SKI in Oskarshamn in October 2005 were also included. During the workshop in which representatives from all relevant parties participated, the question of safeguards for the back-end of the fuel cycle was discussed. To create the sought overview extensive literature studies was also necessary.

The second part of the work was to identify important safeguards issues and to investigate how the issues can be considered for an effective implementation of safeguards in the encapsulation plant and the repository.

2. Introduction to nuclear safeguards

2.1 Safeguards – a brief historical account

The International Atomic Energy Agency, IAEA, plays a key role in the area of safeguards. The IAEA is a related organization to the United Nations, directly subordinated the Security Council and the General Assembly (see figure 1.). When the IAEA was founded in 1957 it was in a zeitgeist of both expectations and fears of what nuclear technology could bring.

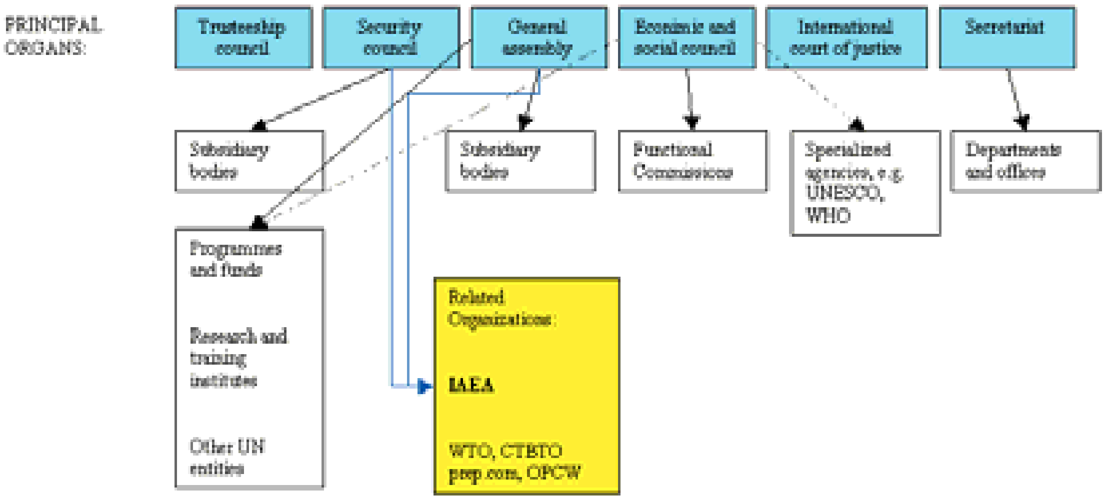

Figure 1: The United Nations system. Modified from the UN webpage http://www.un.org, March 2006

As more countries mastered nuclear technology, concern deepened that they would sooner or later acquire nuclear weapons. In 1964, when the number of countries with nuclear devices had grown to five, it became clear that the IAEA lacked adequate tools to prevent further proliferation. At the same time there was growing support for international, legally binding commitments and comprehensive safeguards to stop the further spread of nuclear weapons and to work towards their eventual elimination. [1]

In response to this situation, the IAEA launched the Treaty on Non-Proliferation of Nuclear Weapons, NPT [2], in 1968. The two main goals of the NPT are to prevent the diversion of fissile material for weapons use through safeguards and to promote cooperation regarding peaceful nuclear technology and equal access to this technology for all States included in the NPT [3]. During the seventies it was clear that the NPT had had a major impact on the handling of nuclear technology in the world. It was accepted by a large number of states, and almost all of the states with direct interest in nuclear technology accepted it. The NPT gave the IAEA the possibility to introduce safeguards and perform inspections in every part of the member states' fuel cycles.

During the first decade of its existence the NPT functioned well as a tool for the world community for safeguarding the peaceful use of nuclear technology. In this period the nuclear power industry grew immensely and the IAEA's responsibilities and importance increased accordingly. In the late 70's and 80's however, a number of incidents including the discovery of the nuclear weapon programmes of Iraq and North Korea indicated that the means for the IAEA to do its work were insufficient [1].

2.2 The present situation

The discovery of the fact that member states could maintain a clandestine nuclear weapons programme while being under the IAEA safeguards system raised the question whether the NPT needed to be extended. In 1997 the IAEA Board of Governors approved the Additional Protocol to Safeguards Agreement [4]. A member state that has agreed to sign the Additional Protocol is extensively evaluated by the IAEA. The quantitative and qualitative evaluation is based on a wide variety of information covering "the state as a whole". The information arising from Additional Protocol-related activities is evaluated for consistency with all other information relevant to the IAEA and conclusions may be drawn about the safeguards situation in the country. If the information is consistent, *integrated safeguards* can be implemented [5]. Integrated safeguards refer to "the optimum combination of safeguards available to the IAEA under a comprehensive safeguards agreement and an Additional Protocol to achieve maximum effectiveness and efficiency, within available resources, in meeting the IAEA's safeguards objectives" [6]. Integrated safeguards can include for example unannounced inspections and surveillance. Sweden has signed both the NPT (in 1968) and the Additional Protocol (in 1998) [7]. In May 2005 Sweden was still being evaluated under the Additional Protocol for the possible implementation of integrated safeguards [8].

2.3 Agreements and safeguards

The instruments the IAEA use to carry out its non-proliferation mission are on one hand the agreements with the member states where the states undertake to accept safeguards and to not divert any nuclear material or technology to the making of nuclear weapons. On the other hand, the IAEA perform safeguards activities to check the compliance of the states to the agreements.

The technical objective of safeguards is as follows: "The timely detection of diversion 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." [9] This implies that all significant quantities of nuclear material in a state should be under safeguards, from the uranium ore used to produce the fuel all the way through the nuclear power plant to the final storage.

Safeguards should not be confused with nuclear safety or physical protection. Nuclear safety refers to the safety of humans and the biosphere from harmful radiation. Physical protection is carried out to prevent the theft of nuclear material by for example terrorists. Safeguards are a system of measures aiming at controlling the state and its intentions with its nuclear material. This system should deter the diversion of nuclear material, and if the state is determined to divert nuclear material to the manufacturing of nuclear weapons, this should be detected with timeliness, i.e. before a nuclear device could be completed.

The safeguards activities consist of, inter alia, visits to the nuclear facilities, inventories of nuclear material, investigation of operators' accountancy for the detection of inconsistencies and surveillance of the operations in the facilities. Supporting the verification activities is safeguards technology: Measuring techniques are necessary for the confirmation of the information given about the state's nuclear activity, surveillance cameras are used to monitor facilities between inspections and seals are used to assure that containments are not secretly breached. The technology is crucial for the credibility of safeguards.

3. Technical means to fulfil safeguards criteria

The following sections contain brief descriptions of various supportive techniques used in the verifying activities.

3.1 Nuclear material accountancy

Nuclear material accountancy, NMA, has been the cornerstone of the verifying regime of the traditional safeguards system, and will probably remain an important part in the future. NMA is the practice of nuclear material accounting implemented by the operators and other involved parties (the SKI and Euratom in Sweden) to fulfil the safeguards agreements between the state and the IAEA. The IAEA receives the documentation from the operators and perform activities such as inspections, surveillance and non-destructive assay to independently verify that the declared information is correct.

Included in the NMA activities is, inter alia

- the formal division of operations involving nuclear material into material balance areas, MBAs;
- the maintenance of records on the quantities of nuclear material held within each MBA;
- the periodical determination of the quantities of nuclear material present within each MBA through the taking of physical inventory; and
- the provision of a measurement control programme to determine the accuracy of calibrations and measurements and the correctness of recorded data. [10]

3.2 Non-destructive assay

Non-destructive assay, NDA, is used to measure characteristics relevant to safeguards on items of nuclear material. Here, item means virtually any object that has safeguards implications. Typical items considered are spent nuclear fuel assemblies or canisters. The IAEA defines non-destructive assay as “a measurement of the nuclear material content or of the element or isotopic concentration of an item without producing significant physical or chemical changes in the item.” [10]

For safeguards purposes the amount of fissile material in an item is of interest, and especially the concentration of uranium and plutonium, respectively. The integrity of fuel assemblies (in the sense that the assembly has not been disassembled and reconstructed without notice) is also important to verify since such a scenario may indicate diversion of nuclear material. Furthermore, to verify the correctness of operators’ declarations, and spent fuel characteristics like burnout, cooling time and decay heat may be of interest.
“To verify” an item is usually defined as to check the compliance of its characteristics with the declarations of the item provided by the operators. The NDA techniques used should be

able to provide a possibility to determine fuel characteristics also in cases where declared information is doubtful or even missing altogether [11].

NDA techniques can be divided in quantitative and qualitative techniques. Quantitative techniques are for example gamma spectroscopy, neutron counting and measurements of physical properties such as weight. A subdivision of the quantitative techniques in passive and active analysis can be made. Passive analysis performs measurements based on spontaneous emissions of gamma rays or neutrons while active analysis where the measurements require stimulated emission. An example of active analysis is neutron counters that measure the amount of ^{235}U in an item by inducing fission in it using external neutrons from a neutron source. The neutrons emitted in the fission reactions are then detected, and conclusions may be drawn about the ^{235}U content in the item.

Examples of qualitative techniques are Cerenkov viewing devices and various fuel attribute testers such as S-FAT [12].

The levels of accuracy of the verification are defined by the IAEA. The levels that define amounts of missing material are gross defect, partial defect and bias defect. An NDA method that can detect gross defects in fuel assemblies can determine if the assembly is replaced by a dummy or is missing. A partial defect is defined as the case where 50 percent of the fuel pins in an assembly are missing or replaced by dummies [13]. The level of bias defect is not defined but is used to describe the small amounts of nuclear material that could be diverted and added up to a significant quantity eventually. The best NDA method approved by the IAEA for safeguards use is at the moment the Fork Detector, FDET [14], (see figure 2) which uses a combination of gamma and neutron detection to determine fuel characteristics. In an evaluation of the performance of the FDET as a partial defect tester it was concluded, "a general partial defect test cannot be based solely on independent FDET measurements" [15]. This means that at the moment no approved NDA technique can perform a 50 % partial defect test.

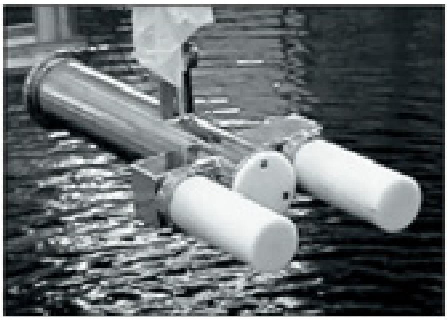

Figure 2: The Fork Detector. The prongs are placed around the fuel assembly to be measured. Image from STUK report STUK-YTO-TR 175, 2001

3.3 Containment and surveillance

Containment and surveillance, C/S, is used to complement nuclear material accountancy through maintenance of the continuity of knowledge between verifications of the accountancy. The most common C/S measures are optical surveillance and seals. Optical surveillance is typically used in a storage area to verify that the movements of nuclear material in and out of the area have been performed as declared. Seals are for example used on containers of nuclear material to ensure that no material has been added or removed from the container since the last verification of its contents. Seals are designed so that they cannot be removed and replaced without detection, and they can also be used as identification of the item being sealed. C/S has the advantage that it functions in unattended mode, which is less intrusive on operations, and more cost efficient than inspections.

In the following section some definitions with relevance for C/S are presented.

3.3.1 Definitions

Containment
Containments are structural features of a facility, containers or equipment which are used to establish the physical integrity of an area or items (including safeguards equipment or data) and to maintain the continuity of knowledge of the area or items by preventing undetected access to, or movement of, nuclear or other material, or interference with the items. Examples are the walls of a storage room or of a storage pool, transport flasks and storage containers. The continuing integrity of the containment itself is usually assured by seals or surveillance measures (especially for containment penetrations such as doors, vessel lids and water surfaces) and by periodic examination of the containment during inspection. [10]

Surveillance
Surveillance is the collection of information through inspector and/or instrumental observation aimed at detecting movements of nuclear material or other items, and any interference with containment or tampering with safeguards equipment, samples and data. Surveillance may also be used for observing various operations or obtaining relevant operational data. Safeguards inspectors may carry out surveillance assignments continuously or periodically at strategic points. [10]

Dual C/S
A dual C/S system use two independent surveillance or monitoring systems that are based on different principles, implying that there is not a common failure or defeat mode for both systems [13].

Continuity of Knowledge
Continuity of knowledge is kept if the safeguards authorities have knowledge of the amount and location of the nuclear material under safeguards at all times.

Robustness
A robust device or system has the ability to deliver a relevant signal despite of disturbances in its environment. For example, the device or system should be able to perform despite power failures, radiation, tampering attempts, electromagnetic noise etc. Inherent properties such as the quality of the components are also possible “disturbances” whose negative effects should be minimized for robustness.

Assurance and Performance
The performance of a C/S device is describing how well it performs its function in reference to its design requirements. The requirements could be that the device should function in the intended environment, that it is robust (see “Robustness” above), and that it

can deliver the desired signal. Assurance is all measures made in order to confirm that a device or system has been tested and approved to be compliant with specified standards for both its manufacture and performance.

3.4 Design information verification

The safeguards authorities carry out design information verification, DIV, in order to verify the correctness and completeness of the design information of facilities as declared by the operators. The design information is "information concerning nuclear material subject to safeguards under the agreement and the features of facilities relevant to safeguarding such materials" [16]. This includes the facility layout, the process description, the form, quantity, location and flow of nuclear material being used and the procedures for nuclear material accountancy. An initial DIV is performed on newly built facilities to confirm that the construction is as declared, and thereafter periodically to confirm that no undeclared changes have been made [10]. The DIV is also aiming at finding any design features for which there is no justification and that could be converted for some undeclared purpose [17]. Using the verified design information the safeguards authorities can design the safeguards approach for the plant including key measurement points and determination of material balance areas [10].

3.5 Monitoring techniques

The IAEA convened Advisory Group Meeting on Safeguards Related to Final Disposal of Nuclear Material in Waste and Spent Fuel recommended that safeguards should apply to spent fuel in geological repositories as long as safeguards apply to spent fuel elsewhere, implying that safeguards should be kept as long as the non-proliferation treaty is in force [18]. This means that the spent fuel in deep geological repositories will not be considered irretrievable, but must be monitored to detect any attempts at breaching the containment of the repository. Below are listed techniques that may be possible to use for such monitoring. The possibility to use satellite, environmental and seismic monitoring for safeguards purposes in Finland, which has a climate and bedrock similar to Sweden's, has been investigated in the STUK report "Safeguards for the geological repository at Olkiluoto in the pre-operational phase" [19], and the following is a summary of what is stated there.

3.5.1 Satellite monitoring

The objective of satellite monitoring of the repository site is to detect any anomalous activities that could be interpreted as attempts to gain access to the closed repository. These activities could be increased traffic, heavy machinery, new facilities, road constructions and large amounts of rock residue from drilling and blasting. To determine if any undeclared changes have been made to the repository site by the use of imaging obtained from satellite monitoring there has to exist a so-called *baseline* for comparison with the unaffected area. The baseline database consists of especially collected imagery of the repository site: A digital map covering the repository site, information of all buildings, roads and other constructions and optical imagery with high resolution (some decimetres), and a digital elevation model. This information is used to create a three-dimensional model of the repository site. In addition, imagery of the unaffected area produced by the monitoring equipment to be used should be included in the baseline database. This database will act as a reference to which collected safeguards data will be compared. Optical imagery is not sufficient for safeguards purposes since it cannot record anything relevant during nighttimes when it is dark or when clouds cover the repository site. Infrared imaging that detects thermal occurrences is an option during the night but cannot be used through clouds. Synthetic Aperture Radar, SAR, is an imaging technique functional in all weather conditions. The resolution is a couple of meters (see figure 3), so the SAR monitoring should be complemented with high-resolution optical imagery that can be used when the weather conditions are appropriate.

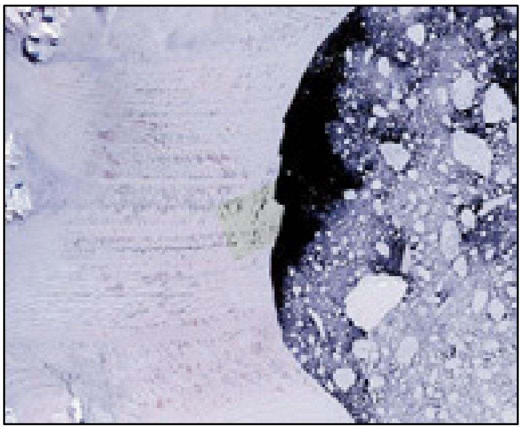

Figure 3: SAR image of Larsen's shelf, Antarctica, by the Canadian satellite RADARSAT-1. Image from http://svs.gsfc.nasa.gov /search/Instrument/SAR.html, March 2006

3.5.2 Seismic monitoring

The aim of seismic monitoring is to detect any blasting, drilling or boring in the repository area with the purpose to access the spent fuel. When monitoring seismic activity the background noise has to be considered, implying that a seismic noise baseline has to be created before the construction of the repository is commenced. Traffic, industry, wind against buildings and the monitoring equipment itself create the background noise, which is normally concentrated to the working hours. The registrations from seismic monitoring stations could be compared to this baseline to detect any anomalies. Rapid or unannounced changes in the weekly and daily seismic patterns of the repository area can be regarded as attempts to gain access to the repository, which calls for actions by the safeguards authorities.

3.5.3 Environmental monitoring

Environmental monitoring could be used for safety reasons to detect radioactive particles in the environment adjacent to the repository, which would indicate a failure of the repository barriers. The same monitoring could be utilised for safeguards purposes, in which case an unusually high radiation level could be interpreted as a wilful breaching of the repository containment. Reprocessing activities would also release both volatile radionuclides and radioactive particles. A baseline containing the natural radiation background is needed in this monitoring technique as well as the others. The monitoring is carried out via collection and analysis of environmental samples.

4. Nuclear safeguards in Sweden

The nuclear safeguards in Sweden are not very well known in the general public although the area involves a large organization including several parties. In this section these parties are briefly presented and their respective responsibilities explained.

The parties involved in safeguarding the Swedish geological repository are:

- The operators of the Swedish nuclear power plants through their jointly owned Swedish Nuclear Fuel Management Company, SKB
- The Swedish Nuclear Power Inspectorate, SKI
- The European Union's safeguards authority, Euratom
- The International Energy Agency, IAEA.

4.1 Operators

Swedish legislation enjoins anyone involved in nuclear activities to safely handle and dispose of any nuclear waste from the activity [20]. To carry out this duty the Swedish operators founded the SKB. The SKB owns an interim storage in Oskarshamn, Clab, and a repository for low- and intermediate level waste in Forsmark, the SFR. For transports between the power plants and these storage sites the SKB uses an especially constructed ship, named Sigyn. The SKB is also responsible for the design, construction and operation of the planned geological repository. For the research needed in connection to the repository the SKB has a laboratory in Oskarshamn called the Äspö laboratory, an underground site where research can be performed in the same environment as the future repository. Finally, the SKB has a capsule laboratory in Oskarshamn where the disposal canisters are developed and tested.

The operators in Sweden, here represented by the SKB, have the firm standpoint that they do not have any responsibility in developing a safeguards approach for the final repository on its own initiative since this is the responsibility of the inspecting authorities Euratom, the IAEA and the SKI. However, the operators have other responsibilities directly connected to safeguards:

- Establishment and operation of a nuclear material accountancy and control system;
- Establishment and maintenance of conditions that are required to facilitate effective use of agreed monitoring, containment and surveillance measures;
- Facilitation of access of designated inspectors;
- Facilitation for the authorities to perform their work and monitoring etc. in a credible and rational way;
- Facilitation, on their part, of clarification of any anomaly and inconsistency, and from their part; Insurance that
  - the implementation of safeguards is not hampering the economic and technological development or international cooperation in the field of peaceful nuclear activities;

- the health, safety, physical protection and other security provisions as well as the rights of individuals are respected, and that;
- every precaution is taken to protect commercial, technological and industrial secrets.

The SKB will not execute any research or development on safeguards equipment or methods [21]. However, the SKB follows the international development on the area and participate in the international Experts Group on Safeguards for Final Disposal of Spent Fuel in Geological Repositories. The purpose is to keep up to date and to contribute with an operator's knowledge and point of view.

To facilitate the implementation of safeguards the SKB has made the design of the planned facilities in the back end of the fuel cycle as transparent as possible, and space for safeguards equipment will be provided [22].

4.2 Safeguards authorities

The structure of the safeguards authorities involved in the Swedish safeguards system is shown in figure 4.

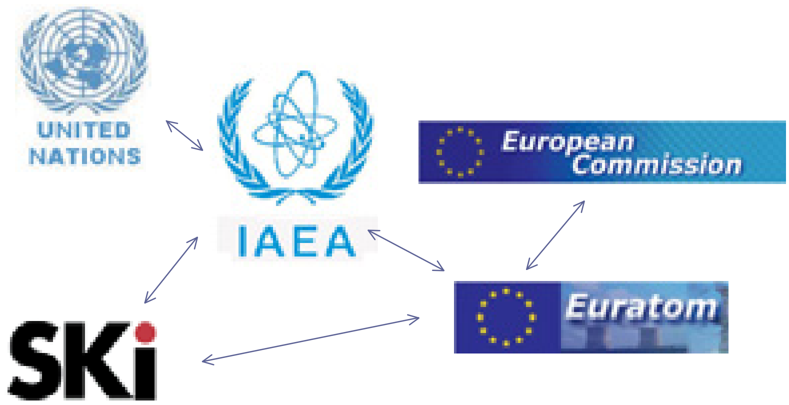

Figure 4: The authorities involved in safeguarding the nuclear material in Sweden

4.2.1 SKI

SKI, the Swedish Nuclear Power Inspectorate, is the national safeguards authority in Sweden. The responsibilities of the SKI are regulated in Swedish law.

As the inspecting authority the SKI is regulating and exercising control on the use of nuclear material in Sweden. Also, the SKI handles tasks concerning safeguards that are placed upon Sweden as a result of the international safeguards agreements or of other reasons if it is in a general public interest [20]. In this capacity, the SKI should satisfy itself that all nuclear material in the country is under its control to ensure that no such material will be used in any way opposing the Swedish legislation or Sweden's international non-proliferation agreements.

Anyone conducting nuclear activities in Sweden has the responsibility by law to ensure that the requirements of the non-proliferation agreements are met [20]. The SKI, as the inspecting authority, should monitor the operators' work in meeting these requirements and establish an independent picture of how well this is performed [7]. This means that the SKI does not have any safeguards responsibilities of their own, but that they should supervise the safeguards responsibilities of the operators of the nuclear power plants. However, if the SKI considers it necessary, the inspectorate can place additional national safeguards requirements on the operators.

The SKI is presently prioritising the formulation of national safeguards requirements for the back-end of the Swedish fuel cycle. A part in this work has been the arrangement of the workshop in Oskarshamn in October 2005 where representatives from the IAEA, Euratom, the SKI, SKB and Uppsala University were present. Safeguards issues concerning the back-end of the fuel cycle were discussed.

4.2.2 Euratom

Sweden's accession to the European Union in 1995 meant that Sweden became a part of the Euratom, the safeguards authority of the European Union. According to the Euratom Treaty [23] the European Commission shall satisfy itself that, in the territory of the member states; ores, source materials and special fissile materials are not diverted from their intended uses as declared by the users. To accomplish this the Commission can, with support from the Euratom treaty and the Euratom regulation no. 302/2005, place upon the operators to establish and maintain a system of accountancy and control of nuclear material from which the Commission can require information, acquire technical data of nuclear installations in the member states and perform on-site inspections.

Also, the Commission shall adopt particular safeguards provisions for each nuclear facility. These provisions shall include material balance areas, key measurement points, measures for containment and surveillance etcetera [24]. Furthermore, the Commission is enjoined by the agreement between the IAEA, Euratom and the states of Euratom to provide the Agency with the information obtained through its safeguards systems in the Member States [16].

The Euratom is thereby functioning similar to how the national inspecting authorities do in states outside of the EU. That is that it handles the contact with the nuclear facilities in the states and provides the Agency with the operators' data. The Euratom should also support the Agency's work in the states [25].

4.2.3 IAEA

The text of agreement between the states of Euratom, Euratom and the IAEA in connection with the NPT was met in September 1973. The accession of Sweden took place in 1995 after the joining of the European Union. In the agreement it is stated: "The [IAEA], in the light of its statutory responsibilities and its relationship to the General Assembly and the Security Council of the United Nations, has the responsibility to assure the international community that effective safeguards are applied under the treaty" [16]. All data generated by the safeguards systems should be clarified and verified by the IAEA independently so that there is credible assurance of the member states compliance to its safeguards obligations.

In the implementation of safeguards the IAEA shall take into account the need to:

- Avoid hampering the economic and technological development or international cooperation in the field of peaceful nuclear activities;
- respect health, safety, physical protection and other security provisions as well as the rights of individuals, and that;
- take every precaution to protect commercial, technological and industrial secrets. [26]

In 1994 the IAEA started the Program for Development of Safeguards for the Final Disposal of Spent Fuel in Geological Repositories, SAGOR. The objective was to develop a generic safeguards approach that could be used as a reference in the development of site-specific safeguards approaches for future repositories. The report was published in September 1998. In 1999 the Agency established the Geological Repository Safeguards Experts Group. The group was later named ASTOR (Application of Safeguards to Repositories) and the objective of this group's meetings was to discuss more practical issues like the use of geophysical techniques and the establishment of baseline knowledge.

As an example of how the IAEA is working in the area of safeguards it can be mentioned that Finland is presently conducting a Member State Support Program for the Agency where methods and tools for safeguards of the geological repositories are developed and/or evaluated. The Support Program tasks run between the IAEA and the Member State: the IAEA defines a need, and submits it to those Member States that are supposed to be able to provide an answer. After acceptance of the task proposal, there are regularly working meetings, and progress meetings between the participants (including the IAEA). This interactive way of working enables the IAEA to give feedback to the member states [25, 27].

5. The Swedish nuclear fuel cycle

The fuel used to generate electric energy in nuclear power plants, NPPs, originates in uranium ore. The ore is firstly mined, then enriched and processed into fuel and later used as a source of energy in the nuclear power plants. Since uranium mining and enrichment is forbidden by Swedish law these services are imported. The fuel for Swedish NPPs is either imported or manufactured in Westinghouse' fuel factory in Västerås.

There are three sites with operating nuclear power plants in Sweden today: Oskarshamn with three boiling water reactors (BWRs), Ringhals with one BWR and three pressure water reactors (PWRs) and Forsmark with three BWRs. Located in Forsmark is also the repository for low- and intermediate level waste, the so called SFR. The locations of all reactor sites are by the shores of Sweden enabling marine transports of high-level waste by the especially designed ship Sigyn.

The Swedish NPPs run in cycles of typically eleven months with a following revision, which takes place during the summer when the energy demand is at its lowest. During the revision the reactor is refuelled and inspected for safety. When a fuel assembly has been irradiated for approximately five cycles it is considered spent and is then removed from the reactor core and replaced with fresh fuel. The spent fuel is cooled in a pool for about one year at the power plant before being transferred to the interim storage Clab, located in Oskarshamn.

The interim storage for high-level waste Clab is an important facility in the Swedish nuclear fuel cycle. Since the start of the Swedish nuclear program in 1971, all irradiated fuel is in storage in Clab awaiting the transfer to a repository. In the end of 2005 more than 4200 tons of spent nuclear fuel was stored in Clab and 300 tons is received annually. After a recent expansion the storage capacity in Clab has increased from approximately 5000 to 8000 tons of spent fuel. When the repository is in operation the spent fuel will be stored for 30-40 years in Clab in order for the radioactivity level and decay heat to decrease before it is transferred to the repository via the encapsulation facility, see figure 5.

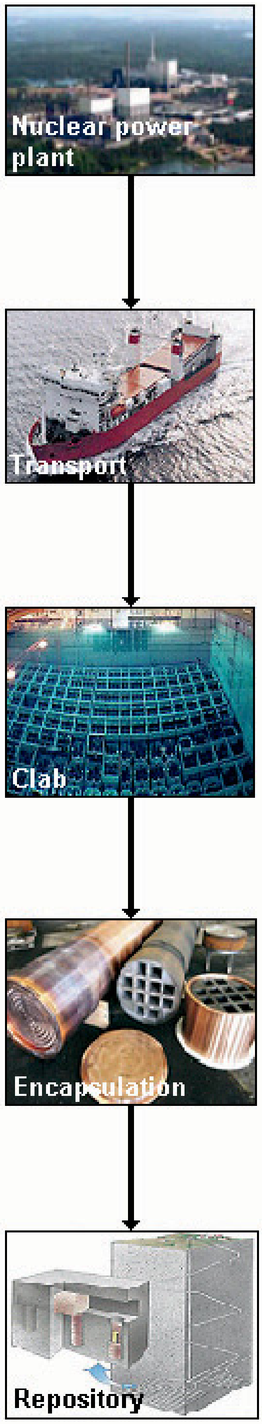

Figure 5: Handling of spent fuel in Sweden. Images from the SKB image archive.

6. KBS-3 – The Swedish system for managing spent fuel

Every producer of nuclear power in Sweden is enjoined by Swedish law to present a scheme for a safe waste disposal [20]. This commitment is performed by the SKB who has been working on several approaches for the disposal of nuclear waste since the 1970's. The option considered being the most suitable is called KBS-3 and it is the main alternative today. The planning of KBS-3 is well evolved; the research is now in the phase of full-scale testing and pilot experimentation [21].

The KBS-3 model for a final storage of spent fuel is a geological repository located at a depth of 400 – 700 meters in bedrock. The spent fuel will be stored in copper canisters embedded in bentonite clay, which expands greatly when it absorbs water. The bentonite prevents direct water flow onto the canister, and protects it from minor bedrock movements through its deformation. The repository will be sealed when the last canister is in place. Besides the repository the spent fuel handling system will include an encapsulation plant (conditioning facility) and the interim storage Clab. The KBS-3 system is designed to safely keep the radioactive material from the biosphere until the radiation level has reached that of natural uranium ore, which requires a storage time of the order of 100 000 years.

6.1 The barriers

The concept behind KBS-3 is based on three barriers that, even one by one, should be able to protect the environment above ground from radiation. If the first barrier, the copper canister, fails, the buffer (the bentonite clay) should be able to keep the radioactive material from reaching the biosphere. If that barrier too should fail there is still about 500 meters of rock to hinder the transport of radioactive particles. The transportation of particles would be via the transport of water and the transportation speed at the depths planned for the repository is calculated to be small enough for the radioactive material to not reach the biosphere if the canister and buffer barriers should fail.

6.2 Encapsulation

In the encapsulation plant the fuel assemblies will be placed in copper canisters with cast iron inserts. A lid will be placed on top and the canister will be sealed using friction stir welding[1]. Before the encapsulation a determination of the decay heat and the content of fissile material should be performed for safety reasons. When the encapsulation plant is in operation it is estimated that 200 canisters should be filled and sealed annually. This means that between 2000 and 3000 fuel assemblies will have to be processed each year. Such an amount places strict requirements on the various safeguards measures used in connection to encapsulation.

1 Friction stir welding is the main alternative for sealing the disposal canisters chosen by the SKB. Information on friction stir welding can be found on the SKB's website: http://www.skb.se /templates/SKBPage____10997.aspx

The main alternative for the location of the encapsulation plant is adjacent to Clab in Oskarshamn. This way, the spent fuel can be transferred directly from the storage pool at Clab to the fuel handling pools in the encapsulation plant. Furthermore, the experience of large-scale fuel handling gained at Clab will be available at both facilities. The other considered alternative is to locate the encapsulation plant near the repository [21], however, this means that the synergy effects of a location near Clab will not be attained.

6.3 The repository

The repository will be constructed 400-700 meters below ground level. To access the level of the repository where the spent nuclear fuel will be emplaced both a ramp and shafts will be constructed. The disposal canisters will be carried down the ramp in transport casks on trucks. The casks will then be transported into a tunnel where the emplacement holes have been drilled. The main alternative is presently emplacement in vertical holes drilled in the tunnel floor. (Another option is to drill long horizontal holes in which the disposal canisters will be placed in rows distanced from each other with blocks of bentonite.) These holes will be lined with bentonite clay in which the canisters will be placed. When the last canister of a tunnel is emplaced, the tunnel will be backfilled with a mixture of rock and bentonite and sealed using concrete. The repository will also be backfilled with rock and bentonite after the sealing of the last tunnel.

Figure 6: Possible locations of the repository

Numerous site investigations and a few detailed site investigations has narrowed the choice down to two sites suitable for the location of the geological repository, namely in the municipalities of Oskarshamn, near Clab, and Östhammar, near the Forsmark NPP and the SFR [21], see figure 6.

7. Safeguards and KBS-3

The main purposes of the safeguards system in the different parts and stages of the back-end of the fuel cycle are presented here, and what measures could be used to fulfil these purposes. This work has already to a great extent been done within the SAGOR project, but on a generic level. To be operative, this generic approach has to be evolved into a more specific approach, which is discussed in chapter 8.

7.1 A generic safeguards approach – the encapsulation plant

7.1.1 Design information verification

The design information about the encapsulation plant provided by the operators must be verified in order to credibly rule out any clandestine rooms that could be used as caches or reprocessing areas. During operation the design information verification, DIV, must continue in order to make sure that the facility is operated as declared and that it has not been reconstructed in any way. (See also section 3.4.).

7.1.2 Pre-encapsulation

For safeguards reasons it is important to assure that the information about the nuclear material is correct before the encapsulation since the fuel will not be easily accessible for verification afterwards. This implies that the fuel assembly identity and properties should be verified prior to encapsulation. There may be IAEA requirements that the fuel must be verified at a gross or partial defect level (see section 3.2) before it becomes difficult-to-access, that is, when it is placed in the canister.

7.1.3 Encapsulation and transport to repository

During the encapsulation process a safeguards priority is to get credible assurance that the nuclear material received at the encapsulation plant is encapsulated and leaves the plant in declared disposal canisters. A photograph of the fuel assemblies' identity numbers when they are emplaced in the canister but before the lid is placed could be taken for the sake of traceability. The canisters should be given a unique identification number to facilitate their tracking from the encapsulation and onwards. A method of "fingerprinting" each canister has been requested [28] using some physical property of the canister and/or its contents that cannot be duplicated or changed, unlike the identification numbers. During transport to the repository an acceptable containment and surveillance system should be applied to maintain the continuity of knowledge. (Definitions of these terms can be found in section 3.3.1)

7.2 A generic safeguards approach – the repository

7.2.1 Pre-operational phase

The pre-operational phase starts with the decision by a state to construct a geological repository, and ends when the first disposal canister arrives. In this phase of the geological repository DIV is the most important safeguards measure. The absence of any undeclared rooms, tunnels, shafts or other areas must be verified to secure that no reprocessing or diversion activities can be carried out without detection.

7.2.2 Operational phase

The operational phase starts as the first disposal canister with spent fuel arrives and continues until the final closure of the repository. The main safeguards objective during the operation of the repository is to assure the emplacement of the canisters and that any undeclared removal of nuclear material from the repository is detected. This implies that the canisters should be well monitored from the encapsulation all the way down to the emplacement holes. This is possible due to the identification numbers on the canisters but would be more credible if a fingerprinting method as described in section 7.1.3 could be successfully implemented. DIV should be used to verify the continued correct operation of the repository and to detect any undeclared constructions. Some measures should be taken to make sure that no fuel is moving through the reverse of the material stream, i.e. that no fuel is removed from the repository. C/S measures need to verify that the emplaced nuclear material remains in emplacement until the tunnel is backfilled and sealed.

7.2.3 Post-closure phase

The closed repository should be monitored to detect any attempts to gain access to the repository through drilling and/or blasting. This may be performed by the use of satellite, environmental and seismic monitoring. The information and documentation of the repository relevant to safeguards should be preserved as long as the spent fuel in the repository remains under safeguards so that the continuity of knowledge of the nuclear material is not lost. The preservation of such information over long periods of time is one of the challenges encountered and this issue is further discussed in section 8.7.4.

8. Outlines of a Swedish safeguards system that includes encapsulation and the repository

8.1 Prerequisites: Authorities requirements

No formal requirements have yet been formulated for the safeguards system of a geological repository by the safeguards authorities. The most important authority here is the IAEA since the Euratom and SKI requirements cannot be lower than those of the IAEA if they are to have an impact on the safeguards system, since the IAEA requirements must in any circumstance be fulfilled due to the NPT and the safeguards agreements. Although no formal requirements are issued some guidelines have been presented by the IAEA on this area.

A generic requirement is that spent fuel in geologic repositories is subject to safeguards, and that safeguards should be applied on the nuclear material for as long as the safeguards agreements remain in force. Also, on a consultants group meeting in 1995 it was recommended that spent fuel only would be disposed of as verified nuclear material on which continuity of knowledge (definition in section 3.3.1) has been kept [29].

A definition of the state where continuity of knowledge has been kept has not been formulated for nuclear material designated for emplacement in a repository. However, it is defined for material designated to become "difficult-to-access". These requirements could be applicable to the nuclear material in a repository, which will become difficult to access when encapsulated. For items designated difficult-to-access, the following is valid: The evaluation of the maintenance of the continuity of knowledge could be based on an evaluation of the C/S system as a whole, provided that, inter alia

- the nuclear material is verified prior to its becoming difficult-to-access by item counting, item identification (where feasible) and NDA, using sampling plans that provide a high detection probability for gross and partial defects, and dual C/S applied; and
- both the C/S systems are evaluated as "conclusive positive". Then no re-verification is needed before encapsulation [30]. In contrast, if the attained level of assurance is lower than that of a dual C/S system, the SAGOR group recommended that a gross defect level verification should be performed. This action serves to verify that no item substitution has occurred and that the continuity of knowledge in fact has been kept [13].

The IAEA also states that the safeguards system for a repository should be based on design information verification, (section 8.5) verification of receipts and flow that no nuclear material is removed by any declared or undeclared access routes (section 8.2); and maintenance of continuity of knowledge on the nuclear material content (sections 8.4 and 8.6).

Finally, the IAEA enjoins the state planning the repository to retain safeguards relevant information and documentation for as long as the nuclear material in the repository remains under safeguards (see section 8.7).

8.2 Nuclear material accountancy at the back-end of the fuel cycle

Nuclear material accountancy, NMA, is in practice in Sweden today but some features of the back-end of the fuel cycle require careful deliberation before the implementation of NMA. The most important feature is that once the fuel is encapsulated in the disposal canisters it will no longer be available for the taking of a physical inventory, or a verifying measurement. The NMA will then refer to the disposal canisters, but once they are emplaced in the repository they too will become unavailable for inventories. These shortcomings will be helped by the use of containment and surveillance. The part of NMA including verifying measurements to control the correctness of recorded data also needs consideration: The encapsulation plant is the last place where it is possible to perform a verifying measurement. The circumstances of this aspect are treated further in section 8.3.1 and in chapter 9.

8.3 Verification by measurement

8.3.1 Verification: Why measure?

Experience has shown that correct information about spent fuel assemblies is not always easy retrievable and in some cases the information may even be considered questionable [31]. Therefore a verifying measurement is necessary in order to discover any errors before the fuel is encapsulated since it is difficult to verify the fuel assemblies afterwards. Hence verifying measurements prior to encapsulation is required, both from the operator’s as well as the authorities points of view, for multiple reasons:

- The operators need to ensure that critical conditions never will be reached in the canisters. This aspect has an impact on the safety of the repository.
- The operators need to verify that the total decay heat generated in the canisters remains below a limiting value since heat may seriously affect the buffering properties of the bentonite clay.
- The operators need to verify the integrity (in the sense that the fuel rods or assemblies are undamaged) of the fuel for operational safety reasons.
- The safeguards authorities need to verify the identity of the fuel in a credible manner.
- The safeguards authorities need to verify the accountancy of the fuel assemblies.
- The safeguards authorities need to verify that the integrity of the fuel assemblies is intact to rule out any unnoticed disassembling and following reconstruction. This is important since such a scenario could be a part of a diversion scheme.

8.3.2 System aspects for verifying measurements

When developing a system for verifying measurements to be used for safeguards purposes a number of considerations have to be made:

a.) Costs are an important factor but in this work it will only be covered indirectly since it is to a large extent depending on the choice of measuring equipment, which is outside the scope of this generic discussion.
b.) Non-intrusiveness is a strict demand on all safeguards measures.
c.) The system of verifying measurements must be able to provide relevant information at the right time.

In the specific situation of performing verifying measurements on spent nuclear fuel prior to its encapsulation, these considerations can be developed further.

Considering a.), the costs, the safeguards authorities need to consider the need for personnel directing the measurements: The encapsulation of spent fuel is a continuous operation. If the safeguards authorities should carry out the verifying measurements they need an inspector on the site full time. This is a very resource demanding solution, and the authorities will probably try to avoid this by enjoining the operators to perform the measurements. This will, however, imply that the data must be authenticated and transferred to the safeguards authorities with guaranteed confidentiality and integrity (see section 8.7).

For the issue b.) of non-intrusiveness, spatial and temporal considerations are two important features. Regarding the spatial consideration, the measuring stations cannot be allowed to form obstacles for the operation of the facility. This means that any installations required for the measuring stations must be carefully included in the design of the facilities or placed where they do not hinder operations. The time allowed for measurements on fuel assemblies must be short enough to not constitute a bottleneck to operations. A means to avoid such problems is the use of parallel measuring stations working with basically the same task. Altogether a parallel approach would increase redundancy and secure a smooth and efficient processing of the fuel assemblies. For example, if one station fails, another is operative and the processing is not halted. An obvious drawback, however, is increased overall costs.

The third aspect, c.), that the system of verifying measurements must be able to produce the relevant information at the right time must also be considered. This requirement could partly be met by lining up the measuring stations in series. In this way the task of each station can be differentiated both in space and in time. An example of a time dependent application is measurements benefiting from high-intensity radiation that would provide the best performance if it is implemented early in the processing chain.
Another advantage by separating the measuring stations in time is due to the fact that the storage time in Clab extends over several decades in many cases. An implication of this fact is that if an assembly is verified through measurement only directly before encapsulation and it is discovered that the accountancy is incorrect, it might have been forty years since the error was made. In a situation like that it is probably difficult to trace the documentation

and find the reason for the mistake and to hold anyone responsible for the possibly missing material.

8.3.3 Non-destructive assay

The requirements for NDA techniques to be used for the verifying measurements are based on the need for information prior to encapsulation. In addition, some generic requirements can be placed on the measuring techniques: They should be robust, satisfyingly accurate, have a low failure probability and the measuring time should be as short as possible to avoid intrusion on the operation of the facility.

The measurements should be able to provide information, directly or indirectly, on the content of fissile material, the integrity and the identity of the measured fuel assembly with defined levels of confidence.

When discussing a concept that involves difficult-to-access storing for periods of thousands of years one may anticipate a need for formulating higher standards regarding measuring accuracies, confidence levels and integrity verification (for example down to fuel pin level) than those used presently. For example, it may turn out that verifying only the engraved ID-number of a fuel assembly is not sufficient to get a conclusive identification but must be complemented with a verified match of measured and declared fuel parameters.

NDA techniques that can verify various fuel parameters with accuracies that may be proved to be acceptable already exists [11, 12, 32]. However, as described in section 3.2, there is not yet an NDA technique approved by the IAEA capable of determining a partial defect in a fuel assembly. The information required on the integrity of the fuel can thus not be accessed via the NDA methods presently used by the IAEA.

Partly, this situation can be referred to the design requirements that usually apply to all equipment used at inspections: It should be portable, not very heavy, user friendly etc. In the case of the encapsulation plant the situation is rather different. The NDA measurements should not be performed every three months at inspections, but continuously since 200 canisters should be filled with verified fuel each year during operation. A stationary measurement station is more suited for this frequent usage. Hence, the design requirements of low weight and portability can be relaxed which makes it possible to use new and perhaps more accurate measuring equipment for the NDA verification. New measuring techniques have been proposed to the IAEA for approval [11, 32]. These techniques offer, besides results with high accuracy, also the possibility to quantify statistical parameters such that the resulting statements may be assigned a certain confidence.

8.4 Containment and surveillance

8.4.1 Device requirements

A device used in C/S systems should be robust in the sense that it should be functional in its working environment and have a low probability of a break down. The devices should also have a low "false alarm" frequency to avoid unnecessary and expensive turnouts.

The assurance and performance of a C/S device are important factors to consider when designing a C/S system. High assurance and performance ensures that the desired signal is obtained continuously with sufficient certainty. Important traits concerning assurance and performance are tampering resistance and possibility to indicate tampering. To make a device tampering resistant it could for example be placed in a containment that is hard to breach. An indication of tampering is a signal to the safeguards authorities that a tampering has occurred. Active seals could be used on C/S devices to obtain the ability of tampering indication. A related quality is the ability for a device to report its status of health to the safeguards authorities so that the possibility to detect breakdowns in devices exists.

It is reasonable that the initial stages for designing a safeguards system intended to be applied on the encapsulation facility and the repository should address the above issues. Here it should be possible to benefit on the work within the ESARDA Working Group on Containment and Surveillance, which specifically addresses these issues [33].

8.4.2 System requirements

From a safeguards perspective, the properties of a C/S system are more important than the properties of the separate parts constituting the system; if the system is functioning well, the quality of the components is of subordinate significance. The system should be robust and have a high level of assurance and performance. These qualities could be obtained by using devices that stand up to the demands one by one, but this is not the only option. A functional system could be built even if the available pieces of equipment are not up to code. This is achieved through redundancy: The use of back-up equipment handles the problem with devices that have an unacceptably high probability of a breakdown. And by using devices that functions on different physical properties the probability of a disturbance that defeats the entire system is lowered. (Dual C/S is an example of this strategy.)

The use of redundancy (like dual C/S) also makes undetected diversion less credible in a different way: An optical surveillance system could be fooled by a dummy with the same appearance as a fuel assembly, and a radiation monitoring system could be fooled by a radiation source with similar properties to a fuel assembly. Thus, if a system using both optical surveillance and radiation monitoring is applied it could only be fooled if both the appearance and the radiation signature is duplicated, which is an ambitious project compared to the efforts needed to surpass only one of the systems.

As for devices, tamper resistance and tamper indication is an important trait for safeguards systems. Also the ability to report the status of health of the system is important so that the safeguards authorities have the possibility to take the proper measures in a timely manner if there should be a problem with the C/S system.

Finally, all credible diversion paths must be covered by the C/S system in order for it to be of significance.

Since methodologies such as automated data interpretation (see section 8.7.3) are emerging, it may be, as in the case of NDA, anticipated higher requirements than presently used also for C/S systems intended for encapsulation and final storage.

8.4.3 C/S system

On a consultants group meeting in 1995 it was recommended that spent fuel only would be disposed of as verified nuclear material on which continuity of knowledge has been kept [29]. The continuity of knowledge can be considered kept if an acceptable C/S system covering all diversion paths has been applied. For spent fuel in disposal canisters (difficult-to-access) designated for emplacement in a repository, dual C/S on all credible diversion paths may provide an acceptable level of assurance that the continuity of knowledge is kept. Such a system has been worked out as a support program to the IAEA by the US Nuclear Regulatory Commission and is enclosed in Annex 1.

Regarding the Swedish project, a question immediately arises from the statement above: what is the meaning of "acceptable"? Can it be quantified? This question and other of generic (and perhaps philosophical) nature call for answers.

8.5 Design information verification

8.5.1 DIV procedures

The SAGOR activity 3 "Design Information Verification" [17] includes a proposed approach to DIV activities that is summarised in this section. The activities are separated in two types of activities: Informal and formal DIV. This is advantageous since the time available for DIV activities after the completion of the facility may be limited because of the high radiation levels in some parts of the operated facility. The informal DIV is initiated even before construction starts and leaves fewer questions to be answered during the formal DIV.

The informal activities should start as soon as the basic design of the facility is submitted to the regulatory authority for approval in principle. At this point the safeguards authorities should be informed about plant parameters, plant layout, process description, nuclear material accountancy and the operator's intention to implement their safeguards responsibilities. The informal information provided to the safeguards authorities should be enough for an appreciation of the operators' intentions and identification of areas relevant for safeguards.

The formal design information verification is carried out after the completion of the facility construction. The following activities have been identified in the SAGOR activity as important to complete before the operations start in the facility:

- *Categorise all aspects relevant to safeguards*, namely locations with the potential for containing significant holdings of spent fuel, identification of areas where undeclared operations could possibly be carried out, instrumentation and associated wiring etcetera.
- *Prioritise the performance of the verification activities*. All aspects need to be evaluated to determine how important they are to undermining safeguards.
- *Ensure that all design changes are verified.* This task can partly be carried out using containment and surveillance (C/S) measures such as optical surveillance and seals.

The overriding requirement at this stage should be to verify the information as declared by the operators to find and investigate any inconsistencies. At this stage the design information need to be verified through physical visits where for instance distances and wall thicknesses could be measured.

8.5.2 Diversion activities only detectable by DIV

Diversion activities where DIV is necessary for detection are identified in the SAGOR activity 3. Some activities' detection relies mostly on C/S measures but DIV is needed for the C/S to be effective. These include transferring of material to undeclared containers, replacing fuel pins or such with dummies etc. since they require space for completion. This space can be obtained by declaration of more space than needed for the regular operation that later could be partitioned off.

Some diversion activities can only be detected by DIV. For example caches for dummy pins, equipment that only could be used for diversion activities, undeclared access routes, extra, undeclared levels in the repository and temporary storage areas for diverted material.

8.5.3 DIV of the encapsulation facility

DIV of the encapsulation plant is relatively straightforward. As described above DIV could be accomplished by performing informal DIV from the design stage of the encapsulation plant and onwards, also in constructed areas as they become available, and formal DIV in especially safeguards significant areas. When the encapsulation plant is in operation, the continued knowledge of the facility design and operation will be obtained by inspections, use of C/S measures, use of operation data to monitor the processes and the knowledge that the presence of radioactivity aggravates gaining of access to carry out changes.

8.5.4 DIV of the repository

The repository presents design information verification with unprecedented challenges due to some inherent properties, which enhance the role of DIV in safeguarding the repository. These include that the construction of the repository will continue after operations have started, that the design may have to be altered due to previously undiscovered geological features of the site, that the material will not be available for verification and that most of the construction is hidden underground so that adjacent activity cannot be observed from the outside. These conditions imply that DIV must be carried out in a credible and continuous way throughout the lifetime of the repository. The DIV must provide assurance that:

- the design information of the repository with all its access routes and other features are verified,
- the back-filling of emplacement tunnels is completed as declared with no voids and other means (like softer fill material) whereby removal of the spent fuel can be made easier in the future,
- the sealing of the back-filled areas are completed as declared,
- the integrity of the repository's sealed areas has been maintained throughout the construction phase,
- when the final stages of the operational life of the repository has been reached, the back-filling of the access routes to the repository are completed as declared,
- the decommissioning is completed as declared with the removal of all surface facilities and equipment, which could be used later to facilitate the undeclared removal of spent fuel,
- even before construction starts, there are no undeclared excavations or boreholes around the repository within a given distance and that none are excavated either during operation, or after the sealing.

8.6 Monitoring of the closed repository

Monitoring of the closed repository is necessary to fulfil the safeguards criteria to maintain safeguards on the nuclear material in the repository for as long as the safeguards agreements are in force. Since it is very difficult to monitor each disposal canister in the repository it is more reasonable to monitor the repository as a whole to detect any attempts of breaching the containment.

An attempt to gain access to the nuclear material at the emplacement level of the repository can be detected indirectly due to the environmental effects of an excavation. Any tunnelling must involve drilling or blasting; activities that create noise and vibrations. The residues from drilling will consist of large amounts of rock that needs to be stored or hid. This requires transporting activities that may be detected. Also, to be able to construct and use a tunnel, installations to provide drainage, ventilation and power must be constructed [19]. Still, if a tunnel is completed without detection, any underground reprocessing or removal of disposal canisters from the repository will emit radioactive particles that are detectable.

The monitoring techniques presented in section 3.5; Satellite monitoring, seismic monitoring and environmental monitoring, could form a combination with a high detection probability of any attempts to reach the emplacement levels of the repository. Imagery provided by satellite monitoring could reveal facilities, transporting activities and large amounts of drilling residues. Seismic monitoring could be used to detect the noise originating in drilling or blasting in the repository area, and environmental monitoring may be used to detect radioactive particles. If the operator of the repository finds it necessary to carry out environmental monitoring for safety reasons the results from their activity could be used by the safeguards authorities instead of them performing a parallel environmental sampling plan.

8.7 Data handling

The application of safeguards implies that vast amounts of information generated by the safeguards system should be reviewed. This is for example C/S data and data obtained through measurements. To strengthen the safeguards system operator and safety data could also be used for safeguards purposes. Some data that are of importance for safety but also are relevant for safeguards are among others the reactivity of the fuel, the decay heat and the fuel integrity.

The operator will keep record of all activities performed on the fuel. In the encapsulation plant the transport canister will be identified and opened, the contained fuel assemblies will be identified and tracked through the encapsulation process via their respective ID number. Finally, the disposal canister containing the fuel assemblies will be identified and transported to the repository. Identification of the disposal canisters will be verified in the repository as well, at the arrival and directly before emplacement [34].

All this data need to be securely transferred, authenticated and interpreted in a fast and credible manner to be of use to the safeguards authorities.

8.7.1 Data transfer

The information obtained through measurements and C/S measures must be communicated to the safeguards authorities. The available alternatives are to store the data at the site awaiting the inspections or to transfer it to the safeguards authorities via e.g. satellite or the Internet. While the first alternative provides a relatively higher degree of confidence that the data is not tampered with, it requires a high inspection frequency for the timely detection of any inconsistencies in the data. The second alternative with remote transference of information is less human resource intensive and therefore more cost effective but it implies some effort to authenticate the data and to transfer it in a manner that is satisfactory to both the safeguards authorities (for authenticity reasons) and the operator (for confidentiality).

The alternative where the data is transferred to safeguards authorities seems the most attractive since it enables a timely detection of any inconsistencies in measurement results or C/S signals, provided that the interpretation of the data can be carried out within the timeliness goals.

8.7.2 Data security

Data authenticity
For the safeguards authorities to be able to use the data from a remote piece of equipment they need to be assured that it originates from the correct device and that it has not been changed during transfer or is a copy of previous data. In other words, the authenticity and integrity of the information must be guaranteed. The integrity is attained through a signature over the data that allows detection of alterations, and timestamps prevents replays of old data [12]. An encryption algorithm in the device performs the authentication. The safekeeping of the encryption keys with the safeguards authorities is necessary for the authentication scheme to be credible and reliable. Furthermore, the data-collecting device (for example a camera or a sensor) should be secured by a tamper indicating containment and a seal so that all access to the device is monitored [35].

Data confidentiality
For the operators to send any information over unsecured transmission lines they need to know that the data only will reach safeguards inspectors so that possible commercial, technological and industrial secrets remain safe. This can be accomplished through encryption of the information to be transferred and authentication of the receiver. (In this sense, authentication refers to the assurance that the receiver is the one intended. This could be attained through a password or a unique object such as a key.) [12]

8.7.3 Data interpretation

The safeguards for the encapsulation plant, the transport between the encapsulation plant and the repository and the repository itself will generate a vast amount of data, which the safeguards authorities will analyze. The information is in form of measuring results, images from surveillance cameras, logs etc. These data are compared to data from the fuel factory and to operators' declarations of irradiation history etc. aiming to reveal any inconsistencies. This time consuming job can be facilitated in two ways, or the two combined: Data reduction and automated data interpretation.

Data reduction
This technique is relevant for data from surveillance devices. If the devices are set to record events at fixed intervals a large part of the information will not be of relevance for safeguards. Techniques to detect only images where a change occurs or where an event has triggered surveillance could be used. These could reduce the amount of data to be reviewed significantly [12].

Automated data interpretation
Sensors, measuring equipment and inspectors continuously collect data from the safeguards system. The safeguards authorities need to perform analyses on these data to gain the

information and detect interesting events. Normally, these analyses are carried out off-line on stored data. Since the amount of information is very large this procedure creates backlogs of unanalysed data, which makes the timely detection of any anomalies or inconsistencies vis-à-vis the operators' declarations more difficult. A new field in data handling is evolving to cope with this type of situation: Data stream management systems, DSMS [36]. The data stream (in this case the data from the different sources; sensors, measuring equipment, monitoring equipment and inspecting activities) is processed and then stored. The processing is depending on the continuous query and returns an answer in the form of an outgoing stream. If applied to safeguards, the continuous query would be to compare every data with operators' declarations and with the other data concerning the nuclear material at hand to discover any inconsistencies. The model to use for comparison with the data stream is composed of the operators' data including the characteristics of the nuclear material, and planned operations and transports [37]. When an anomaly is detected in the data stream a human operator could be alerted by the DSMS [36].

By using a computerised system the human effort to review and analyse all data from safeguards activities could be minimised, which makes the data interpretation process more cost effective.

One obstacle to this approach is the transformation of the data into a format that the DSMS can understand. For instance, the photograph of an ID number must be processed by a pattern recognition algorithm to read the number prior to it becoming available for analysis in the DSMS. Some information may be unreasonably difficult to formalise, perhaps for example imaging from a surveillance camera. In that case it could be fused to the results outside of the DSMS to further secure the correctness of the stream answering the query [38].

8.7.4 Data preservation

A safeguards objective is to preserve safeguards relevant information and documentation for as long as the nuclear material in the repository is under safeguards. This could imply that the information of the repository should be accessible 100 000 years from today. There is no technique proven to preserve data for such long time span, so some updating of the documentation will probably be necessary. Physical storage media could be retained for long periods, but they deteriorate over time and could be destroyed in a malicious attack.

Digital storage of information carries a different set of difficulties. The storage of data is connected to a certain technology (see figure 8), for example a document created in Word 2.0 not fifteen years ago cannot be read using the word processing programs available today. Also the storage media like disks and tapes deteriorates. This means that a constant updating of storage media must be withheld. The handling of the problem with obsolete incompatible source data and technology (hardware and software) could be done in two ways: Either the format of the data files could be updated, or the technology altered so that it can handle the "old" format.

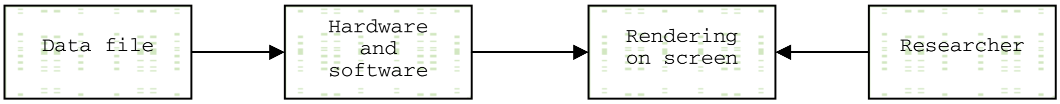

Figure 8: A model for the transformation of data files into accessible formats

Digital archive approaches based on extensible mark-up language (XML) have been developed to be readable even if the hard- and software is updated. Every data file to be stored is converted to an XML format (normalisation). When a future researcher need to access the information the XML object must be converted into an accessible format (transformation). The transformation process must be updated continuously to be compatible with future hard- and software [39].

An ideal approach to preserve safeguards relevant data should not be requiring maintenance to make access to the information possible. Moreover it should be stored in a media that could last an entire repository lifetime. Since these requirements cannot be reasonably met today, there is a need for compromises and redundant storage systems.

8.7.5 Joint database for safeguards authorities and operators

In Sweden today, data about operations and fuel properties are stored in several formats and on several types of media by the operators. Transcripts of this information are sent to the safeguards authorities for auditing and storage. The information consists of, for example, declarations from the fuel factory on initial enrichment and declarations from the operators on the number of cycles the fuel has been irradiated and the isotopic concentrations in the fuel. The information is sometimes calculated and sometimes the data is verified by measurements. Consequently, the confidence levels of the accuracy of the data differ. To facilitate the data handling a joint database for the safeguards authorities and operators could be established, containing information on the properties of items (meaning fuel assemblies, and later, disposal canisters). With all relevant information stored in one place the data handling could be made more effective.

The database should be updated continuously with additional information and new items. A system of ranking the information on the basis of confidence levels could be implemented. For instance, data verified by measurement is, in principle, more reliable than calculated data and should therefore have higher status. Authentication and secure transfer of data is of great importance in this implementation (see section 8.7.2). A system of access must also be established; it may be argued that only the safeguards authorities should be allowed to update the database, but the operators should also be granted access to the information.

9. Preliminary proposal on options for Swedish safeguards of the back-end of the fuel cycle

This chapter presents three options, developed as a part of this degree project, for safeguarding the future encapsulation plant and repository for spent nuclear fuel in Sweden. The options have been derived from the range of available safeguards techniques described in chapter 3 and the prerequisites regarding the safeguards authorities' requirements (see section 8.1). The options are designed to fulfil safeguards requirements by maintaining the continuity of knowledge on the nuclear material designated for emplacement in the repository. The obtaining of the needed information prior to the fuel being encapsulated is prioritised (see section 8.3.1) as well as considerations about possibly incomplete documentation of the fuel characteristics and history.

It should be clear from the discussion made so far that the SKB needs either to verify the fissile content of the fuel assemblies or to ensure that the encapsulation technique used, under no circumstances, allows for a state of criticality. In addition, the decay heat is an important safety parameter that is governed by fuel parameters such as burn-up, cooling time etcetera that, for that reason need to be determined or verified. These needs of the SKB coincide with the interest of safeguards authorities to obtain detailed information about the operating history of fuel assemblies, which also can be verified from the same parameters. Thus, several parameters have significance from the operators' point of view as well as the safeguards authorities'. This opens up the possibility for the authorities to perform measurements in connection with those carried out by the SKB or even use the SKB's measuring results (on condition that the measuring equipment and data handling are approved by the safeguards authorities).

The safeguards authorities' requirements make up the prerequisites of the possible safeguards approaches that could be implemented in the back-end of the fuel cycle in Sweden. These requirements may not be implemented in the form that they are presented in section 8.1 but can serve as guidelines to the future safeguards criteria. Three options for Swedish safeguards including the encapsulation and repository are suggested and discussed in sections 9.1, 9.2 and 9.3. In section 9.4 the safeguards that are common for all options are described and finally a summary of the various options is presented in section 9.5 so as to facilitate comparison.

9.1 Option 1

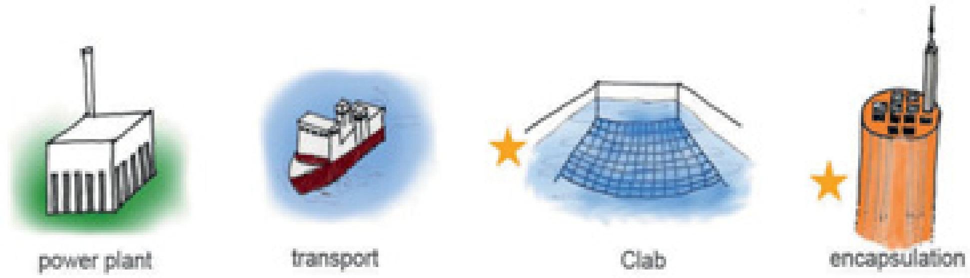

Figure 9: Option 1 with measuring stations (marked by stars) at Clab and in the encapsulation plant

It is advantageous to verify or determine relevant fuel parameters as early in the process as possible. Such a strategy gives the authorities an opportunity to obtain safeguards relevant information at a time reasonably close to the operative phase of the fuel cycle. Early measurements will also be helpful in the process to resolve possible errors in the accountancy: It is most certainly easier to find the reason for an error if it is discovered sooner than later.

The concept for option 1 assumes two measuring stations (see figure 9):

I. One measurement is performed at Clab; here this station is called MS1. As described in section 8.3.1 the SKB needs to verify some fuel characteristics for operational reasons, preferably by measurement since all information is not always accessible and can sometimes be considered dubious. These verifying measurements can in principle start as soon as possible in order to prepare for the continuous operation of encapsulation and emplacement in the repository later on. This measurement station should be located in the storage pool at Clab for the possibility to start measurements on the fuel assemblies already in storage. When operations start in the encapsulation facility it would be advantageous to have finished the measurements of these fuel assemblies. If so, the measuring station will be used solely on fuel assemblies arriving to Clab from the NPPs. The moving of fuel assemblies inside Clab to and from the measuring station will probably imply a need for a surveillance system, in order to track all movements.

II. Re-verification of fuel properties may be necessary as a result of an inconclusive or negative C/S result (or in order to take into account the mere possibility of such scenario). For the sake of being able to perform this re-verification another measuring station, here called MS2, is envisaged shortly before encapsulation in the encapsulation facility. The results of MS2 will thus act as a receipt that the continuity of knowledge has been maintained between the measurements of MS1 and MS2.

If any inconsistencies are discovered at MS2, the fuel assembly in question will not be allowed to continue to encapsulation [8]. This statement identifies an important issue of logistics: Where should the fuel assemblies be stored awaiting investigation? One possibility is to return them to an especially assigned area in Clab, preferably physically separated from the intermediate storage areas. Another solution is to include a buffer storage pool into the design of the encapsulation facility so that no fuel is allowed to travel in the reverse direction of the regular fuel handling.

The transfer of responsibility of the nuclear fuel from the power plants to the SKB is suggested to take place when the fuel enters into the Clab building, which means that the current border of responsibility prevails.

Option 1 does not facilitate a continuous operation in the encapsulation plant since a measurement is performed almost directly before encapsulation. If the measuring equipment malfunctions the entire encapsulation operation is halted. This situation could be relaxed if parallel measuring equipments are used as described in section 8.3.2.

Summary
Characteristics of option 1: The option

- fulfils the safeguards authorities presumed requirements on the kept continuity of knowledge, provided that dual C/S is applied between MS2 and encapsulation and onwards, on the canister until it is emplaced in the repository;
- includes consideration of the possibility of erring or missing accountancy by the early measurement at MS1;
- incorporates the operator's need for information into the approach which makes the option less intrusive on operations since the information acquisition, to some extent, is a part of the operation;
- provides a high detection probability of any diversion of nuclear material due to the use of two measuring stations;
- implies a need for a storage area for fuel assemblies where the measuring results of MS2 requires an investigation by the safeguards authorities; and
- requires parallel measuring equipment at MS2 for a non-intrusive capability.

9.2 Option 2

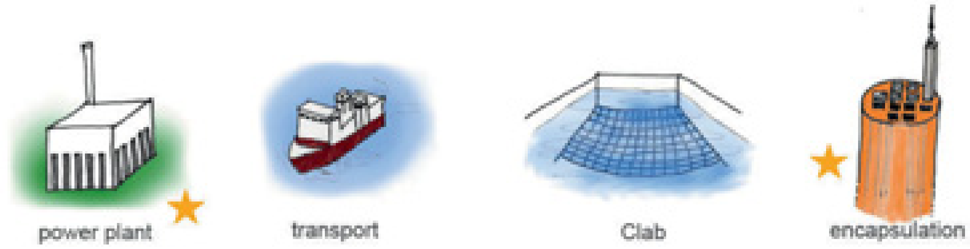

Figure 10: Option 2 with measuring stations (marked by stars) at the power plant sites and in the encapsulation plant

In this alternative a verifying measurement of the spent fuel is performed at every nuclear power plant prior to the shipment to Clab (see figure 10). This means that no unverified material or erroneously documented material will leave the area of responsibility where the fuel is irradiated and accounted for. The concept of a measuring station at each power plant presently implies that ten separate measuring stations must be maintained and operated. This is neither an efficient nor economical use of available resources, so an alternative with only one measuring station at the sites of Oskarshamn, Ringhals and Forsmark, respectively should be considered.

Option 2 would most certainly require construction efforts or allocation of space for measuring equipment on each site.

Even though a lot of the fuel to be encapsulated will already be identified and verified through the measurement at the power plants there will still be thousands of metric tons of spent fuel in Clab that never has been verified through an NDA measurement. As compensation a measurement will be performed shortly before encapsulation at MS2. The fuel that has already been verified at the nuclear power plant sites will undergo a second measurement here. Thus, the safeguards authorities can verify that the continuity of knowledge has been maintained during the storage in Clab. Furthermore, this is an opportunity for the SKB to perform the measurements required for their operation such as decay heat measurements if the measurement results from the first NDA measurement are judged too old.

As in option 1, a plan for the storage of fuel assemblies with incomplete accountancy at MS2 must be formulated.

The main advantage of option 2 is that the SKB eventually only will deal with correctly documented and well-verified spent fuel assemblies. In this case it may be reasonable for the SKB to take over the responsibility of the fuel already on the transport ship Sigyn since the nuclear power plants have in one aspect already taken full responsibilities on their part. The change of areas of responsibility does, however, require legislative action.

Summary
Characteristics of option 2: The option

- fulfils the safeguards authorities presumed requirements on the kept continuity of knowledge, provided that dual C/S is applied between MS2 and encapsulation and onwards, on the canister until it is emplaced in the repository;
- incorporates the operator's need for information into the approach which makes the option less intrusive on operations since the information gathering is a part of the operation to some extent;
- implies a need for a storage area for fuel assemblies where the measuring results of MS2 requires an investigation by the safeguards authorities;
- provides a high detection probability of any diversion of nuclear material due to the use of two measuring stations;
- facilitates the clarification of inconsistencies or errors in the accountancy by performing an early verifying measurement in the same facility that produces the accountancy;
- requires legislative actions if it is deemed advantageous to move the transference of responsibility between the nuclear power plants and the SKB;
- is resource demanding since new constructions at the nuclear power plant sites are necessary, along with the multiple measuring stations (one on each site); and
- requires parallel measuring equipment at MS2 for a non-intrusive capability.

9.3 Option 3

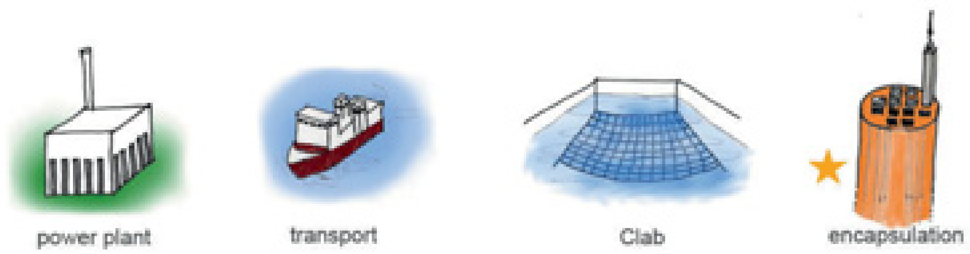

Figure 11: Option 3 with a measuring station (marked by star) in the encapsulation plant

A third alternative would be to only perform one measurement (see figure 11). Since it is of utmost importance to maintain the continuity of knowledge between the last verification and the emplacement in the repository, this measurement should be carried out as late before encapsulation as possible. An alternative with a single measurement is cost and resource efficient, but the problem with occurrence of incorrect accountancy is more prominent. If the only NDA verification is performed after the intermediate storage at Clab any possible errors in the accountancy will remain unnoticed for decades. As the measuring station is involved in a continuous operation it could, as in both the other alternatives, seriously disrupt the operation when malfunctioning. This is not compatible with the goals of non-intrusiveness and must be handled, possibly by the use of parallel measuring stations as discussed in section 8.3.2. As in options 1 and 2 a plan for the situation, where the measurement results needs to be investigated, must be constructed. For example, this could be handled by the provision of a storage area for the fuel assemblies awaiting investigation. The division of responsibility for the spent fuel between the power plants and the SKB would remain as it is at present.

Summary
Characteristics of option 3: The option

- fulfils the safeguards authorities presumed requirements on the kept continuity of knowledge, provided that dual C/S is applied between the measuring station and encapsulation and onwards, until the emplacement in the repository;
- is cost and resource efficient;
- reduces the intrusion on operations relative to options 1 and 2 since only one measuring station is used;
- incorporates the operator's need for information into the approach which makes the option less intrusive on operations since the information gathering is a part of the operation to some extent;
- provides a lower detection probability of diversion than options 1 and 2 since one less measuring station is used;
- is inconsiderate of the implications of old unverified accountancy;
- implies a need for a storage area for fuel assemblies whose measuring results require an investigation by the safeguards authorities; and
- requires parallel measuring equipments for a non-intrusive capability.

9.4 Safeguards measures common for all options

In the described options some important parts of a complete safeguards approach has been left out since these are the same for all three options to a large extent. The lacking safeguards that must be included for a credible safeguards system are design information verification, containment and surveillance, monitoring of the closed repository and the handling of obtained data.

Containment and surveillance is an important safeguards measure since an evaluation of the maintenance of the continuity of knowledge can be based on the performance of the C/S system. The continuity of knowledge for nuclear material designated for disposal in a geological repository is of paramount importance: If the continuity of knowledge of the spent fuel is lost it cannot be regained, which places high demands on the performance of the C/S system. In section 8.4 a credible approach for the use of C/S is described. After the last NDA measuring station before encapsulation dual C/S should be applied to minimise the loss of continuity of knowledge and to reach the IAEA safeguards criteria for geological repositories. For the sake of maintaining the continuity of knowledge it may be appropriate to use a fingerprinting method that marks each disposal canister with a unique and inimitable fingerprint of some physical property. This would help to increase the credibility of the C/S system since the results of the C/S system could be checked. For illustration, if the C/S system has recorded movement of a canister from one buffer storage to another, the fingerprint on the canister can be investigated to make sure that it is the same canister that is now in the new area and that it has not been switched during transport.

The DIV approach for all three options will be conducted using the procedures described in section 8.5. The features of the encapsulation plant does not compose any new challenges for DIV, considerably more complex facilities such as reprocessing plants have been under DIV without difficulties. For the repository however, a new situation is at hand: The construction will continue after operations have started, the “wall” thickness can be considered infinite, the facility is underground implying that nearby activities cannot be seen from above ground and the original design may have to be changed during construction due to previously unnoticed geological features. These circumstances imply that a credible DIV approach must continue throughout the operational phase of the repository. (See section 8.5)

Monitoring of the closed repository can be carried out using a combination of the techniques of satellite, seismic and environmental monitoring as described in section 8.6.

A proper data-handling scheme is crucial for the safeguards authorities for them to carry out an independent verification of the accountancy and to assure that the information is genuine. This area is somewhat developed in section 8.7.

9.5 Remarks on the various options

The characteristics of the options described in section 9.3 have, as demonstrated in table 1, different strengths and weaknesses. The choice of option to implement in the Swedish safeguards system will be based on which traits are judged to be the most important by the safeguards authorities.

Characteristics	*Option 1*	*Option 2*	*Option 3*
Cost and resource efficiency	2	1	3
Non-intrusiveness	2	2	3
Detection probability of diversion	3	3	2
Considers implications of old, doubtful accountancy	3	2	1
All pertinent information can be acquired	Yes	Yes	Yes
Requires storage for assemblies being investigated	Yes	Yes	Yes
Requires parallel measuring equipments	Yes	Yes	Yes

Table 1: Comparison of the options 1-3. The grading is relative between the options meaning that the best option of each characteristic is rewarded the grade 3 and the other two are graded on their relative performance compared to this option.

A first evaluation should appreciate the option’s ability to fulfil the safeguards requirements set by the authorities. Presently, such an evaluation is not possible to carry out to a full extent since neither the national nor the international safeguards authorities have formulated the safeguards requirements for spent nuclear fuel in geological repositories. Judging by the generic criteria (see section 8.1) that have been issued so far options 1, 2 and 3 are all able to comply with these criteria, provided that the chosen NDA techniques and C/S systems are able to reach the required standards. Thus, according to this line of reasoning, all three options are feasible for implementation in the Swedish safeguards system. However, as argued in the following section, it may be reasonable to pose national safeguards requirements that are more stringent than those of the IAEA.

9.5.1 A need for higher demands?

The criteria with relevance for safeguards for the back-end of the fuel cycle formulated by the IAEA are quite gentle. For example, a partial defect level of 50 % may be regarded as a lenient demand when the nuclear material will become inaccessible for re-verification.

Furthermore, in a situation where the anticipated declared information is doubtful or missing, the requirements presently do not state that a certain verifying function should be able to output a non-trivial result. However, such ability is desired and the requirements should be accompanied with additional requirements on accuracies and other relevant statistical quantities.

For a credible safeguards system the SKI may feel obliged to sharpen these demands for the Swedish situation. If so, these expanded demands would be the basis for comparison of the three options described in sections 9.1-9.3. These sharpened requirements could consist of, for example

a. re-verification by NDA measurement soon after transport to Clab since a lot of handling is done on the fuel from the time that it leaves the storage pool at the power plant until it has arrived at Clab combined with the vulnerability of marine transport is making the transportation a credible diversion path;
b. specifications regarding the continuity of knowledge by, for example, assigning statistical features to this concept;
c. a demand on a “one way” flow of nuclear material from Clab to the encapsulation plant in order to facilitate monitoring of the material flow;
d. demands on information handling: The proposition of a joint database in section 8.7.5 implies that information should be evaluated for relevance and then entered into a database. Demands may be placed on verification of the information by measurements prior to the introduction into the database;
e. a partial defect level of one fuel pin instead of 50 % of the pins; and
f. specifications C/S, both on device level as well as the system level. These specifications should include features such as performance, assurance, detection probabilities and failure probabilities;

The points a., b., c. and d. all have implications on the options 1-3. Points e. and f. have relevance for the choice of measuring and C/S technology but not on the choice of option for measuring system. The addition of these sharpened requirements to the generic safeguards requirements is illustrated in table 2.

The additional requirements presented in table 2 places higher demands on the different options, which change the result of the comparison. For a full comparison all characteristics must be evaluated for relevance and all authorities' requirements must be known. However, the results give an idea of the performance of the three options.

Characteristics	*Option 1*	*Option 2*	*Option 3*
Cost and resource efficiency	2	1	3
Non-intrusiveness	2	2	3
Detection probability of diversion	3	3	2
Considers implications of old, doubtful accountancy	3	2	1
Possibility of one-way flow between Clab and encapsulation	Yes	Yes	Yes
Re-verification after transport to Clab	Yes	No	No
Early verification of information (for database)	Yes	Yes	No
All pertinent information can be acquired	Yes	Yes	Yes
Requires storage for assemblies being investigated	Yes	Yes	Yes
Requires parallel measuring equipments	Yes	Yes	Yes
Ability to reach specifications for the continuity of knowledge	3*	3*	1*

*Table 2: Expanded comparison of options 1-3. Grading as in table 1.*This grading is difficult to carry out since the specifications do not exist at present. However, with two measuring stations as in options 1 and 2 it is easier to maintain the continuity of knowledge than in option 3 that only includes one station.*

9.5.2 Summary: Preliminary comparison of options 1-3

Section 9.5 has so far compared the three options of safeguards approach for the back end of the Swedish fuel cycle. The comparison has been divided in two parts, based firstly on the international authorities requirements presumed to be in force, and secondly on extended requirements that could be posed by the Swedish safeguards authority, the SKI. These two foundations for comparison and evaluation are not very firm since neither is formally decided yet. Moreover, the characteristics presented in tables 1 and 2 have not been evaluated for their relevance in relative order to the safeguards system, which might make the comparison unjust. However, all characteristics are judged to be of relevance per se so a preliminary comparison could be presented at this stage. Option 3 is singled out in this comparison as insensitive to a possible need for an early verification of operators' declaration, which may make it less suited for implementation in the safeguards system despite the advantages in form of its non-intrusiveness and economical use of resources.

The options 1 and 2 are difficult to separate at this stage. The primary difference is the location of measuring station 1 (see sections 9.1 and 9.2) which has an implication on the use of resources and the timing of the measurements. The use of resources is deemed to be smaller in options 1 since the first measurement will be carried out at one station compared to three in option 2.

The issue of timing could be judged as important in the possible future safeguards requirements on information handling. In option 1 the measurements could in principle start at any time, which would shorten the time passed between the creation of the operators' declarations and their verification. In contrast, this time will be minimised in option 2 as the declarations will be verified relatively soon after the creation and this situation is judged to facilitate the clarification of any possible errors in the accountancy. However, the thousands of tons of spent fuel already in interim storage in Clab will remain unverified by measurement until it reaches MS2 before encapsulation, which could be decades ahead. In the light of this fact, the advantage of option 2 becomes less prominent.

What option of the three that is most suited for implementation in the Swedish safeguards system is yet to be decided. As mentioned, a final evaluation of the presented options cannot be carried out before the safeguards authorities have decided on the formal requirements for the safeguards of the back end of the Swedish nuclear fuel cycle. Hence, the initiative in the progress towards an implemented safeguards approach is presently with the authorities.

10. Summary and conclusion

In Sweden today, the process towards a construction and operation of an encapsulation plant and a repository is progressing. The SKB is continuing their work on designing the facilities and evaluating them for safety and operation ability; the application for construction of the encapsulation plant is to be submitted in the summer of 2006 and of the repository in late 2008 according to plans. In order to grant permission to the SKB to start constructing these facilities the SKI needs to be sure that they can implement safeguards in a credible, effective and non-intrusive way, in them. To be certain of this the SKI must define what is necessary for a good safeguards system, and what information they need to obtain. The SKI has initiated a process that will lead to a formulation of its requirements regarding safeguards for the encapsulation plant and the repository in order to perform this evaluation of the facilities and this process will take place even though the IAEA has not yet formulated its requirements.

Presently, the IAEA will not issue specific requirements regarding safeguards at the encapsulation and final disposal. Such requirements will probably follow the generic requirements that are valid for all forms of safeguards, and the requirements are not expected to be more stringent, especially not under the Additional Protocol that is in force in Sweden [14]. The SKI, in the capacity of the national safeguards authority, may regard these demands as too lenient and may formulate stricter requirements for the Swedish safeguards system.

In this work, three options for a safeguards approach have been presented (see sections 9.1-9.3). The development of the options has considered required functions of a credible safeguards approach with the specific features of a geological repository in mind. A preliminary comparison based on the presumed requirements of the safeguards authorities is carried out in section 9.5.2. It was concluded that option 3 is inadequate if it is required that the operators' declarations of the spent fuel should be verified through measurement at an earlier stage than directly preceding encapsulation. The distinction in performance between options 1 and 2 is less obvious and a complete comparison of the two options is a too time consuming task to be performed in the scope of this work but at this stage it is judged that both options constitute feasible approaches for safeguarding the back-end of the fuel cycle.

During the process of investigating the technical means to perform safeguards, the compilation of the outlines for a safeguards system and the creation and comparison of the three options some areas that needs further research has been identified. These are

- Data handling: Investigation of adequate long-term storage of information relevant for safeguards needs more effort, as well as the possibility of automated data interpretation. A success in automated data interpretation could lessen the human effort of reviewing data significantly, with smaller costs as a result. Also, the area of pattern recognition should be addressed within research efforts in order to take into account diverse sources of information that combined with today's measures potentially could create an unprecedented level of C/S performance.

- Verification on pin level: A measurement able to verify the integrity of a fuel assembly on pin level would increase the credibility of nuclear safeguards.

- A method for "fingerprinting" sealed disposal canisters: A method that can unambiguously identify a canister based on physical properties would raise the credibility of the C/S systems by facilitating tracing of the items.

- Quantified evaluation of C/S performance and continuity of knowledge: The ability to quantify the results of an evaluation of C/S systems and the continuity of knowledge would strengthen the credibility of safeguards authorities' conclusions.

- Development of a plan of action for the case where operators' declarations are dubious or even missing, and where errors in the accountancy cannot be resolved, for example due to that errors occurred several decades before their discoveries.

11. Acknowledgements

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12. References

[1] Webpage: http://www.iaea.org/About/history.html, May 2005

[2] IAEA: Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/140, 1970

[3] A. Håkansson: *A Primer to Safeguards and its Instrumentation*, Uppsala University, 2004

[4] IAEA: *Model Protocol Additional to the Agreements between the States and the International Atomic Energy Agency for the Application of Safeguards*, INFCIRC 540 (Corrected), 1997

[5] P. Goldschmidt: *Meeting the challenges of the new safeguards environment, Proceedings*, ESARDA 24th annual meeting, Luxembourg, 2002

[6] J. Cooley: *Integrated safeguards – current status of development and plans for implementation*, Proceedings, ESARDA 23rd annual meeting, Belgium, 2001

[7] Webpage IAEA Country Nuclear Power Profiles, Sweden: http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2003/CNPP_Webpage/countryprofiles/Sweden/Sweden2003.htm, January 2006

[8] Private communication, M. Eiborn, Swedish Nuclear Power Inspectorate (SKI), May 2005

[9] IAEA: *The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, INFCIRC/153, 1972

[10] *IAEA Safeguards Glossary 2001 edition*, Nuclear Verification Series No. 3, IAEA/NVS/3, 2002

[11] C. Willman et al., *Nondestructive assay of spent nuclear fuel with gamma-ray spectroscopy*, Annals of Nuclear Energy, to be published, 2006

[12] IAEA: *Safeguards Techniques and Equipment 2003 edition*, Nuclear Verification Series No. 1 (Revised), IAEA/NVS/1, 2003

[13] B.W. Moran, *Design considerations for acceptable safeguards approaches for final disposal of spent fuel in geological repositories*, SAGOR Activity 8, IAEA STR-312, 1997

[14] Private communication, R. Fagerholm, IAEA, November 2005

[15] R. Carchon, *Limitations of safeguards NDA techniques and challenges for the future*, Proceedings, ESARDA 27th annual meeting, Great Britain, 2005

[16] IAEA: *The Text of Agreement between Belgium, Denmark, The Federal Republic of Germany, Ireland, Italy, Luxembourg, The Netherlands, the European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, INFCIRC/193, 1973

[17] J. Myatt et al., *Design Information Verification (DIV)*, SAGOR Activity 3, IAEA STR-312, 1997

[18] IAEA: *Advisory Group Meeting on Safeguards Related to Final Disposal of Nuclear Waste and Spent Fuel (AGM 660)*, STR-243 (Revised), 1988

[19] O. Okko, *Safeguards for the geological repository at Olkiluoto in the pre-operational phase*, STUK-YTO-TR 208, 2004

[20] Swedish legislation, Act on nuclear activities, 1984:3

[21] SKB: *Fud-program 2004, Programme for research, development and demonstration of methods for handling and final disposal of nuclear waste, including societal research*, 2004

[22] Private communication: P. Grahn, Swedish Nuclear Fuel Management and Waste Co (SKB), October 2005

[23] Treaty establishing the European Atomic Energy Community (Euratom), 1957

[24] Commission regulation (Euratom) no. 302/2005 concerning Euratom treaty safeguards reposting requirements, 2005

[25] Private communication, R. Fagerholm, IAEA, October 2005

[26] J. Rautjärvi, *Preliminary concept for safeguarding spent fuel encapsulation plant in Olkiluoto, Finland*, STUK-YTO-TR 187, 2002

[27] Private communication, R. Carchon, IAEA, October 2005

[28] Workshop result from the SKI workshop on Handling, Verification, Characterisation and Identification of Spent Fuel Prior to Final Disposal, Oskarshamn, October 2005

[29] IAEA: *Report of the Consultants Group Meeting on Safeguards for the Direct Final Disposal of Spent Fuel in Geological Repositories*, STR-305, 1995

[30] Private Communication, R. Fagerholm, IAEA, January 2006

[31] Private Communication, A. Håkansson, Uppsala University, December 2006

[32] S. Jacobsson et al., Nuclear Technology, Vol. 135, No. 2, 2001

[33] Webpage ESARDA: http://esarda2.jrc.it/about/index.html, February 2006

[34] H. Forsström, S.E. Larsson, *Use of operator and safety data for safeguards*, SAGOR Activity 4, IAEA STR-312, 1997

[35] Private communication, B. Richter, FZ Juelich, October 2005

[36] M. Ivanova, *Scalable Scientific Stream Query Processing*, Acta Universitas, Uppsala, 2005

[37] Private communication, D. Lindgren, Swedish Defence Research Agency (FOI), November 2005

[38] Private communication, E. Jungert, Swedish Defence Research Agency (FOI), November 2005

[39] H. Heslop, *An approach to the preservation of Digital Records*, National Archives of Australia, 2002

Table 1. Potential applications of containment, surveillance, and monitoring systems

Location	Diversion activity	Detection activity	Detection equipment
Conditioning plant and geologic repository			
Cask Transfer	Divert transport to cask-handling facility	Detect detour and delay in transport	Global positioning/ tracking system
	Removal of cask from transporter or opening of cask on transporter	Detect removal or opening of cask	Digital camera providing surveillance of cask on transporter
	Swap dummy for cask	Detect cask swap	Unique cask identifier (e.g., ultrasonic bolt, weld seal, reflective/fluorescing particle tag, electronic tags)
	Removal of cask lid	Detect that cask was opened	E-type seal, bolt seal, Vacoss seal, weld seal
	Removal of cask bottom by cutting	Detect that cask was opened	Ultrasonic weld signature, reflective/fluorescing particle tag across welds
	Swap dummy for assembly or can	Detect item swap	Radiation monitor, weight pad
Cask storage	Move cask within storage area	Detect cask movements	Digital camera, movement sensor
	Remove cask from storage area through transfer door/gate	Detect movement of cask through door	Weight pads, radiation monitor, motion detector, hard-wire or RF item monitor/identifier, digital camera
	Remove cask through roof, over fence, through wall, etc.	Detect removal of cask	Hard-wire or RF item monitor/identifier, digital camera
	Swap dummy for cask	Detect cask swap	Unique cask identifier (e.g., ultrasonic bolt, weld seal, reflective/fluorescing particle tag, electronic tag)
	Removal of cask lid	Detect that cask was opened	E-type seal, bolt seal, Vacoss seal, weld seal
	Removal of cask bottom by cutting	Detect that cask was opened	Ultrasonic weld signature, reflective/fluorescing particle tag across welds
	Swap dummy for assembly or can	Detect item swap	Radiation monitor, weight pad, digital camera

Table 1 (cont.)

Location	Diversion activity	Detection activity	Detection equipment
Conditioning plant			
Conditioning Plant Building Perimeter	Move cask/shielded container within conditioning building	Detect cask/container movements	Digital camera, motion detector
	Remove cask/shielded container from building through transfer door	Detect movement of cask/container through door	Weight pads, radiation monitor, motion detector, hard-wire or RF item monitor/identifier, digital camera
	Remove cask/shielded container through roof, wall, etc.	Detect removal of cask/container	Hard-wire or RF item monitor/identifier, digital camera, radiation monitor
	Remove shielded container from building through other doors, windows, etc.	Detect removal of shielded container with spent fuel	Radiation monitor, digital camera
	Swap dummy for cask	Detect cask swap	Unique cask identifier (e.g., ultrasonic bolt, reflective/fluorescing particle tag, memory chip)
	Removal of cask lid	Detect that cask was opened	E-type seal, bolt seal, Vacoss seal, weld seal
	Removal of cask bottom by cutting	Detect that cask was opened	Ultrasonic weld signature, reflective/fluorescing particle tag across welds
	Swap dummy for assembly or can	Detect removal of assembly or can from cask	Radiation monitor, digital camera
Conditioning Facility Hot Cell Perimeter	Remove diverted spent fuel through transfer tunnel	Detect movements of spent fuel	Radiation monitor, crane/dolly monitor, digital camera
	Remove spent fuel through hatches, windows or ducts of hot cell	Detect removal of spent fuel	E-type (or other) seal, radiation monitor, digital camera
	Remove spent fuel in "empty" cask	Detect presence of spent fuel	Digital camera, radiation monitor, weight pad
	Remove spent fuel in nonfuel or waste container	Detect presence of spent fuel	Radiation monitor

Table 1 (cont.)

Location	Diversion activity	Detection activity	Detection equipment
Conditioning Plant Hot Cell Operations	Pull nonfuel pins from assembly and leave fuel pins	Detect removal of nonfuel pins	Digital camera, radiation monitor, item count
	Swap dummy for assembly, can, or pins	Detect swap of items	Digital camera, radiation monitor
	Cut pins free from assembly (nonconsolidation)	Detect undeclared activities	Digital camera, equipment monitor
	Cache spent fuel dummies and collect/cache spent fuel pellets or pins in undeclared container	Detect undeclared materials	Digital camera
Operating Repository			
Repository Underground Facility	Substitute vitrified HAW for spent fuel	Detect reduced fissile content	Active neutron radiation monitor
	Remove from emplacement location	Detect removal from emplaced location	Digital camera, Vacoss (or other) seal, radiation monitor, memory chip (using emplacement rails as transmission lines)
	Remove from closed drift into repository	Detect opening of bulkhead	Digital camera, seal, radiation monitor
	Remove assembly from cask	Detect opening of cask	Digital camera, radiation monitoring, seal
	Process in underground facility	Detect underground processing	Fission gas detector, environmental monitoring
	Remove through declared tunnel	Detect removal of spent fuel	radiation monitor, movement monitor, camera surveillance
	Remove through declared shaft	Detect removal of spent fuel	Hoist monitor, radiation monitor, movement monitor, camera surveillance
Closed repository			
Repository perimeter	Excavate tunnel or borehole into repository	Detect tunneling or drilling activities	Satellite surveillance, aerial surveillance, visual surveillance, seismic array monitors

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