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ANNI FRITZELL
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UPPSALA UNIVERSITY
DEPARTMENT OF NEUTRON RESEARCH
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ANNI FRITZELL*
KLAAS VAN DER MEER†

** Department of Physics and Astronomy, Uppsala University,*
BOX 516, SE-75120 Uppsala, Sweden

†Belgian Nuclear Research Center SCK.CEN

ABSTRACT

The Swedish strategy to handle the spent fuel from the nuclear power plants is the direct disposal in a geological repository. The safeguards regime covering all nuclear material in the state will be expanded to cover the new repository, which will require a novel safeguards approach due mainly to the inaccessibility of the fuel after disposal. The safeguards approach must be able to provide a high level of assurance that the fuel in the repository not diverted, but must also be resource efficient. An attractive approach with regards to use of resources is to monitor only the access points to the repository, i.e. the openings. The implementation of such an approach can only be allowed if it is shown to be sufficiently secure. With the purpose of determining the applicability of this “black box” approach, a diversion path analysis for the Swedish geological repository has been carried out. The result from the analysis shows that all credible diversion paths could be covered by the black-box safeguards approach provided that the identified boundary conditions can be met.

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1 Introduction

As the Swedish nuclear fuel cycle is extended with the addition of an encapsulation facility and a geological repository for the final disposal of spent nuclear fuel, the safeguards system surrounding all nuclear installations in the state must expand to include the new facilities. The technical objective of safeguards as implemented by the IAEA is

> *"The timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection"* [1].

The incorporation of this objective into the safeguards approach for a new facility implies that the applied safeguards measures should cover all credible diversion paths. A reasonable starting point for the development of a safeguards approach is therefore a diversion path analysis.

From a safeguards perspective, a geological repository is significantly different from other nuclear facilities. The major difference is that the spent fuel is inaccessible for verification once it is placed in a disposal room. This means that the continuity of knowledge (CoK) cannot be restored should it be lost. Continuity of knowledge denotes the assurance that the known properties of a fuel item relevant for safeguards (e.g. its mass or fissile content) has not changed. Normally, the CoK can be restored with a verification if there is a suspicion that it is lost. After the backfilling of the disposal tunnels in the repository it is not feasible to gain access to the spent fuel for verification purposes. Therefore, safeguards efforts should concentrate on the maintenance of the CoK after the final verification before emplacement in the disposal tunnels.

The safeguards approach for the geological repository should thus provide a high level of assurance that the safeguards-relevant fuel-item properties remain unchanged after final verification. However, other boundary conditions apply to the implementation of safeguards in the facility. The safeguards approach should be resource efficient and as non-intrusive on facility operations as possible. These limitations make a safeguards approach where the repository is viewed as a "black box" attractive. With such an approach, the main safeguards concern is to verify that all nuclear material that goes in, remains in the confines of the repository. Monitoring should be applied to all access points of the repository such as shafts and the transport ramp, but not in the tunnel system.

Although resource efficient and non-intrusive, the black-box approach may only be implemented if it will ensure the CoK of the spent nuclear fuel emplaced in the repository. A basic requirement in this context is that all diversion paths should be credibly covered by safeguards measures. The purpose of this paper is to provide a diversion path analysis for the Swedish geological repository and use it to determine the suitability of the black-box safeguards approach.

2 Diversion of nuclear material

Diversion is defined as

> *"the undeclared removal of declared nuclear material from a safeguarded facility; or the use of a safeguarded facility for the introduction, production or processing of undeclared material"* [2].

The objective of a diversion is expected to be the acquisition of nuclear material for the construction of nuclear weapons. The nuclear material available in a geological repository is the plutonium content of the spent nuclear fuel. The diverted plutonium must be separated by reprocessing of the spent fuel in order to be usable as the nuclear component of a weapon.

2.1 Objectives

The amount of nuclear material needed to complete a nuclear weapon is defined as a significant quantity (SQ), and as mentioned in the introduction, the detection of diversion of one SQ is the technical objective of IAEA safeguards. The significant quantities are listed in table 1. As an example of the fissile content of spent fuel, a spent PWR fuel assembly contains approximately 4 kg plutonium or 0.5 SQ [3]. A BWR fuel assembly contains half as many fuel pins (around 100) as a PWR assembly, thus containing around 0.25 SQ. The final disposal canisters are planned to contain 4 PWR assemblies or 12 BWR assemblies. Accordingly, the canisters contain two or three SQ of nuclear material, respectively.

2.2 Strategies

The diversion of one significant quantity of nuclear material from the geological repository requires the diversion of one disposal canister (contains more than one SQ), two PWR or four BWR fuel assemblies or 400 fuel pins. To acquire an SQ by diverting a full canister requires only one diversion act but

Plutonium	8 kg, total element
Uranium-233	8 kg, total isotope
Uranium-235 (≥20 % enrichment)	25 kg, total isotope
Uranium-235 (<20 % enrichment)	75 kg, total isotope
Thorium	20000 kg, total element
Natural uranium	10000 kg
Depleted uranium	20000 kg

Tab. 1: Significant quantities of nuclear material [2]

the probability of detection would be quite high. In contrast, the diversion of individual assemblies or fuel pins requires several diversion acts but each act would have a lower probability of detection. The diverting state would have to balance the number of acts against the detection probabilities. The diverter would probably try to conceal the diversion acts from detection. The following are some examples of concealment strategies that could be used:

- Falsification of records and reports. An empty canister could be declared as full while the fuel declared to be in it is diverted.
- Containment and surveillance measures could be defeated. For example, the seal on a container could be removed followed by withdrawal of the material and the replacement of the seal so that the container appears untouched.
- The nuclear material could be replaced by dummy items reproducing the appearance, the physical properties and/or the radiological properties.

3 Facility description

The diversion path analysis is based on the facility design and operation, which are described in this section. The location of the repository is not decided presently. The remaining candidate sites are Oskarshamn near the central intermediate storage for spent nuclear fuel, Clab, and Forsmark where the repository for low and medium active waste is located. Since the location of the repository is not determined, the final facility design has not yet been completed. However, the preliminary designs for the two candidate sites are issued [4, 5] and the descriptions are detailed enough for the purposes of this paper. Moreover, the two designs do not show significant differences. Therefore, a single diversion path analysis is judged to hold for both locations.

3.1 Prior to the repository

The final disposal process does not start with the geological repository, but in the intermediate storage, Clab. All spent fuel from the Swedish reactors is stored here to cool before final disposal. The fuel assemblies will be transferred from Clab to an encapsulation facility which is planned to be constructed in direct connection to Clab. In the encapsulation facility the spent fuel assemblies will be encapsulated in copper canisters enforced with cast iron inserts. Prior to the encapsulation, the fuel assemblies will be verified by measurement. After encapsulation, the assemblies cannot be verified individually.

3.2 Facility design

The geological repository will be situated around 500 m below ground in the granite bedrock. The repository level will consist of a central area and a disposal area. The central area includes eight rock caverns with different functions necessary for the operation of the repository such as a ventilation hall and a hall for lifts and the reception of visitors. There is also a station for loading masses of rock onto a skip that will be used to transport the rock residue from the tunnel excavations to the surface. A central place from a safeguards perspective is the reloading hall. In this hall the spent fuel arrives carried by a cask transport vehicle and is reloaded to the emplacement vehicle. The reloading hall is therefore the first location since the encapsulation plant where the canister is available for identification and other types of verification (see figure 1).

The central area is connected to the surface by a transport ramp that will be trafficked by dumpers, trucks and vehicles carrying transport casks containing the disposal canisters. A number of shafts will be constructed leading from the surface to the repository level. These are a lift shaft, a skip shaft and ventilation shafts. The shafts are described in figure 2.

From the central area there are tunnels connecting the repository area, see figure 3. In the area, concurrent excavation and filling of disposal tunnels will occur. The disposal tunnels will branch out from two parallel main tunnels. Excavation will be carried out from one main tunnel and the emplacement of disposal canisters in the other at each point in time, with an exchange of the two operations at regular intervals. The disposal canisters will be emplaced in vertical holes drilled in the floor of the disposal tunnels [4, 5].

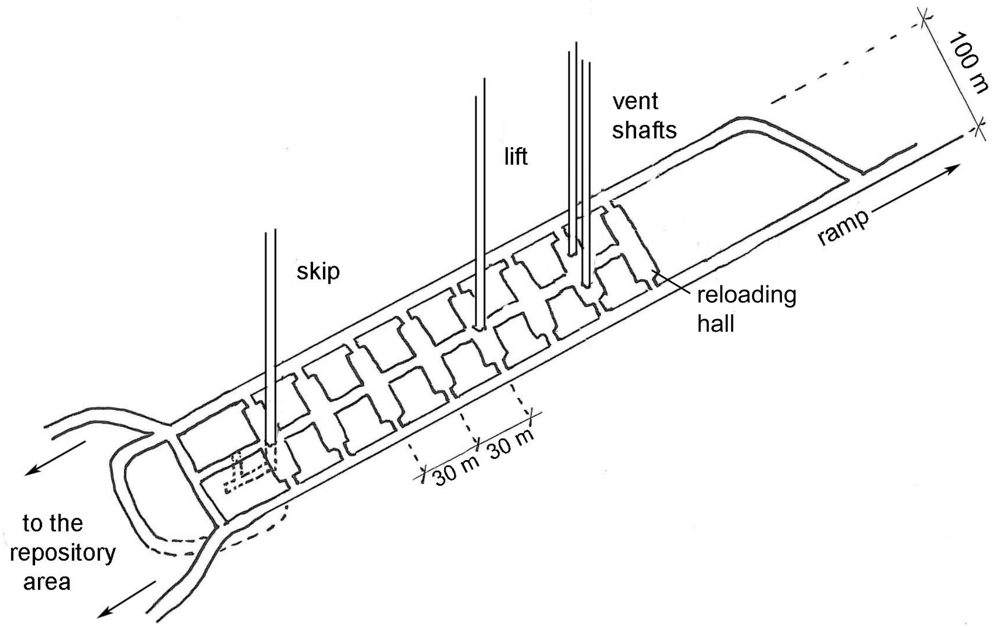

Fig. 1: The central area

3.3 Repository operations

The main operations in the repository concern the emplacement of disposal canisters and the excavations of disposal tunnels and tunnels connecting the parts of the repository. The excavation process does not include handling of nuclear material; nevertheless, it influences the prerequisites for the safeguards system. The following description of repository operations is preliminary and under development [4, 5].

The excavation will be performed using drilling and blasting techniques and the disposal holes will be drilled. The rock material will be transported by dumpers to the rock mass station where it is transferred to the skip.

The spent nuclear fuel encapsulated in disposal canisters will be transported into the repository through the ramp by a cask transport vehicle. The cask is taken to the reloading hall (the first hall of the eight in the central area, see figure 1) where it is collected by a shielded emplacement vehicle. The emplacement vehicle is driven to a prepared hole in a disposal tunnel where the emplacement is remotely conducted. A lid of pressed bentonite is placed on top of the canister to provide buffering and shielding. When

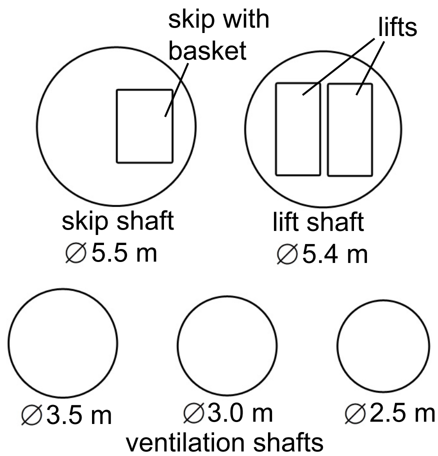

Fig. 2: Shafts connecting the surface and the repository level

all holes in a disposal tunnel are full the tunnel is back-filled by bentonite and crushed rock and sealed by a concrete plug. The final disposal process is schematically shown in figure 4. A flow chart for the spent fuel in its disposal canister is presented in figure 5.

4 The SAGOR diversion path analysis

The IAEA identified the special challenges of safeguarding a geological repository as early as the 1980's. In response, a multinational cooperation of many member states, including Sweden, was launched with the objective of identifying and recommending safeguards approaches for spent fuel at conditioning plants (such as encapsulation facilities) and at operating and closed geological repositories: the Programme for Development of Safeguards for the Final Disposal of Spent Fuel in Geological repositories (SAGOR). The results of the effort were presented in the SAGOR reports [3] in 1997.

As a part of the SAGOR programme a diversion path analysis was performed for the operating repository. The section including the diversion path analysis also presents the methodology used:

> *"A complete diversion path analysis would:*
>
> - *identify the potential points of diversion within the facility;*
> - *describe potential methods of concealment of the diverted fuel; and*
> - *identify potential routes available for diverting the fuel from the repository*

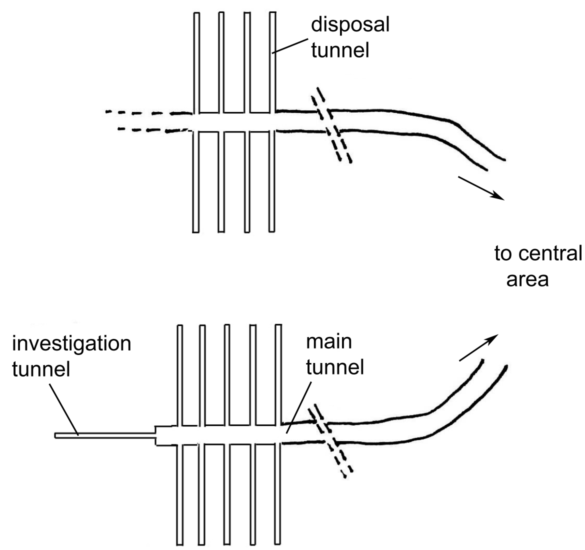

Fig. 3: The repository area

> *[...] In identifying potential diversion paths, strategies are examined in which a significant quantity of nuclear material may be diverted, in whole or in parts."*

The SAGOR report performed the diversion path analysis based on an assumed model facility created as a part of the programme. The model facility differs significantly from the Swedish repository. For example, it employs a waste shaft for the transport of disposal canisters into the repository while the Swedish plan is to use a ramp. Also, the model facility envisions a "retrieved container transfer facility" with the ability to open and inspect canisters in a hot-cell environment. Such a facility, not included in the Swedish design, would be very interesting from a safeguards perspective.

The diversion path analysis performed in this report follows the SAGOR outline in terms of fundamental diversion categories, but is based on the Swedish repository design and operations.

The description of concealment methods in the SAGOR reports is judged to be valid also for the Swedish case and is therefore not included in this report.

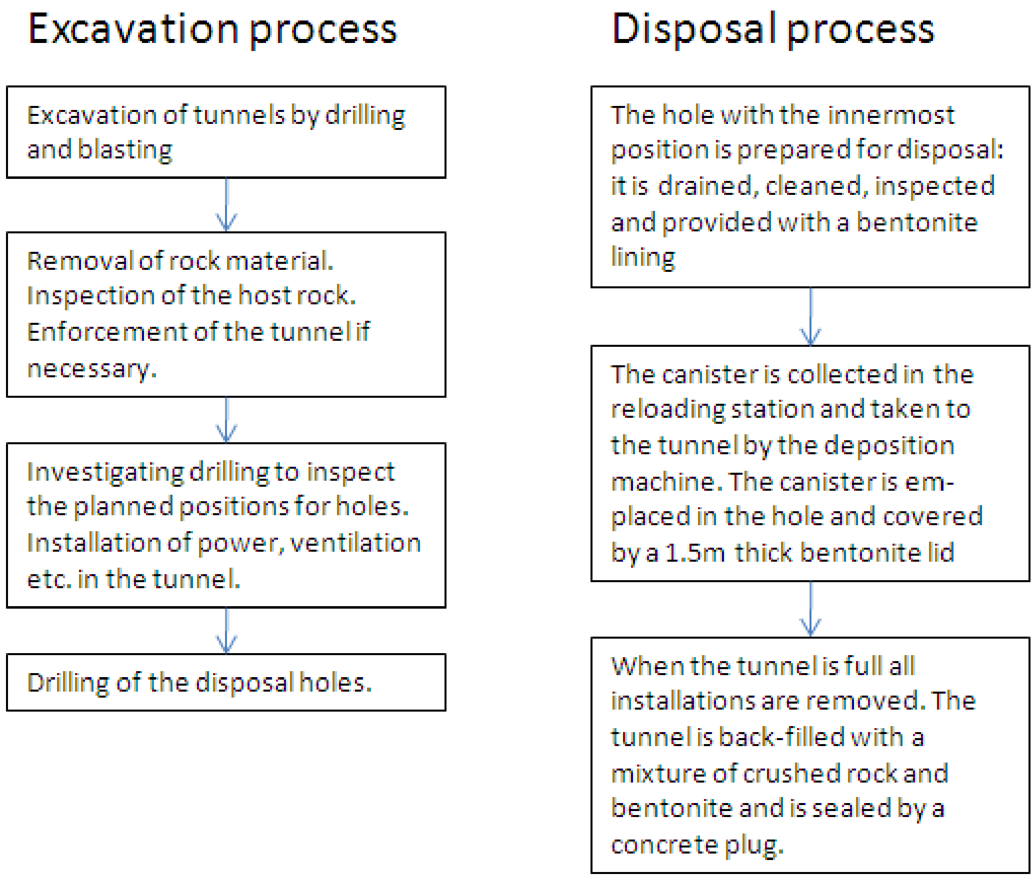

Fig. 4: A flow chart of the final disposal process

5 Diversion paths

5.1 Diverting a full transport cask from below ground

From below ground, a full transport cask could be taken up again by the vehicle used for transport of casks, or in another vehicle. However, the other vehicles used in the repository must be heavily modified in order to carry the full cask, which weighs 75-80 tons. The shafts reaching the repository level (skip shaft, lift shaft and ventilation shafts) are all wide enough for a transport cask, but none of them has enough installed hoisting capacity. A diversion through a shaft must therefore be preceded by installation of a strong hoist or by modification of the capacity where a hoist already exists. A transport cask could also be diverted to the surface through an undeclared tunnel or borehole.

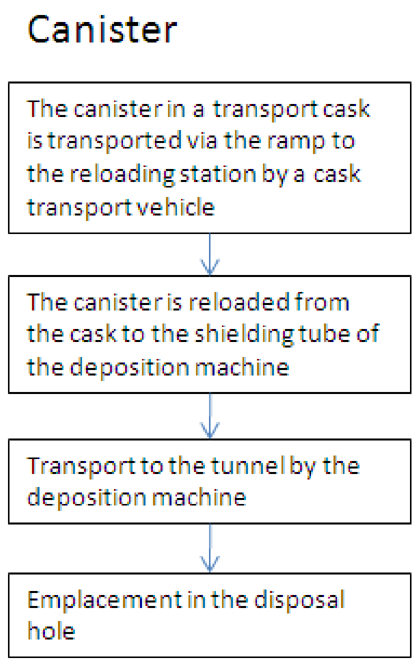

Fig. 5: A flow chart of the disposal canister

5.2 Diverting a full canister from below ground

A canister could be taken to the surface in a transport cask that is declared as “empty”. In this scenario, as well as for casks, the shafts could also be used, but with strengthened hoisting capacities as described above. Furthermore, an undeclared hole could be drilled down to the repository level from the surface and be used as an exit route for canisters, and finally it is taken into account that a vehicle used for transport of e.g. construction material could be used to transport canisters up the ramp. In this case it is envisioned that the canister is concealed by goods normally transported on such a vehicle. The vehicle must probably be modified to be able to carry the weight of the canister, which is 25-27 tons without additional shielding.

5.3 Diverting fuel from a breached canister from below ground

To divert fuel from a breached canister the construction of a hot-cell in the repository is required, with equipment installed to open a canister and handle the fuel assemblies. Should such an installation be carried out successfully and undetected, fuel assemblies or fuel pins could be taken out of the repository via the ramp or one of the shafts.

5.4 Diverting separated uranium or plutonium from below ground

If the uranium or plutonium in the spent fuel could be separated from the fission products and the transuranic elements, it could be removed from the repository in small packages without the need for much shielding. Significant amounts could probably be carried in a backpack. The separation of the fissile material however requires the construction and operation of a reprocessing facility underground.

6 Detection points

The detections points of a facility are all points where signs of diversion through the diversion paths described above, could be spotted. The detection points include

DP1 The ramp entrance

DP2 The reloading hall

DP3 The ventilation shafts

DP4 The lift and skip shafts

DP5 The disposal tunnel

DP6 The surface. This detection point refers to any surface point where fuel could exit the repository and that is not covered by any of the DPs 1,3 or 4. An example is an undeclared borehole.

DP7 The repository - this is not a “point” but the entire repository area where Design Information Verification, DIV, is essential in order to cover diversion paths including the opening of a canister and reprocessing inside the repository. DIV denotes activities carried out by the IAEA at a facility to verify the correctness and completeness of the design information as provided by the member state.

7 Strategic points

If safeguards measures were implemented on all detection points, some would be redundant. Redundancy increases the security of detection but at the same time, it is resource inefficient to employ more safeguards devices and activities than necessary. Therefore, a selection among the detection points is made in order to find the *strategic points*. A strategic point is

> *"a location selected during examination of design information where, under normal conditions and when combined with information from all strategic points taken together, the information necessary and sufficient for the implementation of safeguards measures is obtained and verified; a strategic point may include any location where key measurements related to material balance accountancy are made and where containment and surveillance measures are executed"* [2].

For the purpose of this report, the strategic points are of the most interest: could the detection points at the repository openings constitute a complete set of strategic points or is it necessary to monitor the spent fuel all the way to its emplacement hole? To cover the diversion paths described in this report (see section 5, *Diversion paths*) the following is judged to be a complete set of strategic points, provided that the boundary conditions defined in some cases, are met.

SP1 The ramp entrance. In the ramp entrance, radiation detectors could be used to detect attempts to take full casks or canisters out of the repository via the transport ramp.
Boundary condition: That no amount of shielding could reduce the radiation signal from a full canister below the detection threshold of the radiation detectors.

SP2 The ventilation shafts. Since no declared transports are expected to take place in the ventilation shafts a physical containment could be used to detect undeclared use of the shafts. A grid secured by seals could be an example of such containment, provided that it does not impair the ventilation function. Radiation detectors could also detect transport of spent fuel in the ventilation shafts.

SP3 The lift and skip shafts. Through the lift and skip shafts transports will be carried out as a part of normal operations. However, none of these transports will contain radiating nuclear material which allows radiation detectors to detect the illicit use of these shafts. Furthermore, an installation of enforced hoisting capacity is needed to divert a full canister, which DIV could be employed to detect.

SP4 The repository. As mentioned above, the repository as a whole is not a defined point. Nevertheless, the entire underground structure must be monitored in order to detect a possible installation for canister opening or reprocessing. In SP1-3 it is assumed that canister opening would be detected, and therefore the safeguards measures applied at the exits need only to be concerned with full canisters.
Boundary condition: The DIV regime must be comprehensive and capable of finding all hot-cell installations and reprocessing facilities. The time between DIV inspections must be shorter than the estimated time to complete such installations. Methods to find cavities behind walls like geophysical radar could strengthen DIV if they are shown to be accurate in the repository environment. The undeclared drilling of tunnels must also be detected by DIV. Seismic methods could be used with this objective if they are found to be capable of distinguishing between the declared drilling and blasting of new tunnels, and illicit excavations. Methods that could detect indications of reprocessing, canister opening and undeclared excavations exist and could be used to relax the demands on DIV. These are environmental monitoring that can detect reprocessing activities by the nitric gas release that is an inevitable result of reprocessing. Kr-85 detectors could discover canister opening by the fission gas release from damaged fuel pins, where those are present. Satellite imagery could detect for example masses of rock on the surface in the repository area that could be an indication of excavation. The DIV efforts should not be underestimated, and must be executed with care and thoroughness so that there is high assurance that undeclared structures would be detected in case of a diversion attempt.

The reloading hall is not included in the set of strategic points. It is nevertheless considered to be an important point for the safeguards system as a whole. The reloading hall is envisioned by this report to be used to detect diversion that has occurred prior to the repository by identification and possibly gross defect measurement and some method to detect canister breaching. However, for the detection of diversion from inside the repository, it is not judged as a strategic point.

The repository operations as suggested by the SKB are not fixed since the repository location is not decided. A design where the canisters are transported to the repository level by a waste shaft is not out of the question.

If it should be implemented, SP1 is changed from the ramp entrance to the waste shaft. The same boundary condition would apply except that the shaft diameter provides the maximum shielding thickness.

8 Conclusions and outlook

This paper has presented a diversion path analysis for the planned Swedish geological repository for spent nuclear fuel. The purpose of the diversion path analysis was to determine if the black-box safeguards approach, where only the access points of the repository is monitored, is a viable option for the safeguarding of the repository. The approach would be disqualified if a diversion path was found whose coverage would require monitoring of the spent fuel in the tunnel system of the repository. No such diversion path was encountered by the analysis. Hence, it can be concluded that no prohibition of the black-box approach is found, provided that the boundary conditions in section 7 *Strategic points* are fulfilled. In particular the necessity of DIV in the repository in order to verify that no undeclared reprocessing activities or hot-cells exists, is pointed out.

This report cannot declare that the black-box safeguards approach, or any other approach, covers all credible diversion paths. There is a limit to what the human mind can imagine in terms of what is technically possible, and what chains of events that could lead to a safeguards system failure. Therefore a formal systems analysis would be beneficial in order to find detection probabilities and vulnerabilities for different safeguards systems that may be overlooked by the system designers. Some work has been performed in this area (see for example [6]) and should be of interest for the IAEA and the safeguards authorities.

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