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DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

Swedish containers for disposal of spent nuclear fuel and radioactive waste

Tommy Hedman, Anders Nyström, Claes Thegerström *

Swedish Nuclear Fuel and Waste Management Co (SKB), PO Box 5864, 10240 Stockholm, Sweden

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Abstract The purpose of a disposal is to isolate the radioactive waste from man and the environment. If the isolation is broken, the leakage and transport of radioactive substances must be retarded. The package is one of several barriers, used to achieve these two main functions. For short-lived, low and intermediate level waste four standard containers of steel and concrete are used. Spent fuel will be placed in a canister consisting of a pressure-bearing insert of cast nodular iron and an outer corrosion barrier of copper before it is deposited in a deep geological repository. In particular, the development of a high integrity copper canister for the isolation of spent nuclear fuel is described in this paper. ***To cite this article: T. Hedman et al., C. R. Physique 3 (2002) 903–913.***

radioactive waste packages / spent fuel canister / deep geologic repository / encapsulation / sealing of canister / testing of canister

Le concept suédois pour stockage définitif des déchets nucléaires

Résumé Le but d'un site de stockage profond est de pouvoir isoler les déchets radioactifs de l'homme et son milieu environnant. Si le processus d'isoler ces déchets est, pour une raison on une autre, interrompu, les substances radioactives devraient être retardeés. Le conteneur est l'une de plusieurs barrières qui fonctionnent de façon à isoler les déchets et dans le cas échéant retarder le transport des nuclides radioactifs. Pour les déchets de faibles et moyennes activités, quatre conteneurs standardisés en métal et en ciment sont selectionnés. Les combustibles usés sont placés dans un conteneur en fonte pour fournir une résistance mécanique, le tout sera en suite placé dans un conteneur en cuivre qui résiste à la corrosion. Le conteneur sera placé dans un stockage profond qui est en cours d'être sélectionné en Suède. Cet article est particulièrement centré sur la mise au point des conteneurs. ***Pour citer cet article : T. Hedman et al., C. R. Physique 3 (2002) 903–913.***

conteneurs des déchets radioactifs / conteneur pour les combustibles usés / stockage profond dans une formation géologique / mise en conteneur / soudage des conteneurs / control des conteneurs

* Correspondence and reprints.
E-mail address: claes.thegerstrom@skb.se (C. Thegerström).

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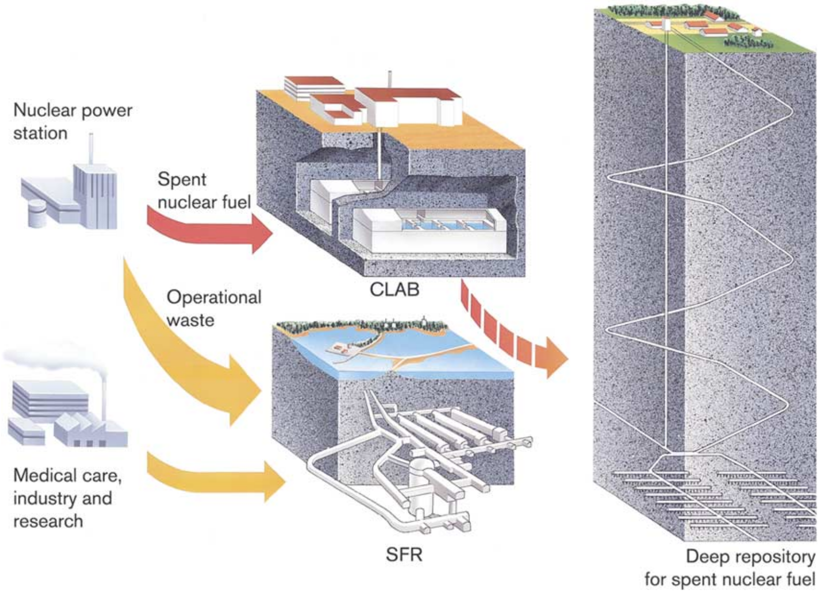

Figure 1. Swedish system for radioactive waste.

1. Introduction

In the beginning of the 1980s the Swedish nuclear power industry, by law, was given responsibility for managing and disposing of all radioactive waste from its plants in a safe manner. The owners of the nuclear plants jointly formed SKB (the Swedish Nuclear Fuel and Waste Management Company) for this purpose. To ensure funding of the work the Nuclear Waste Fund was also established, based upon a fee on all electricity produced by nuclear power.

So, the Swedish management system for radioactive waste is the result of a gradual development and expansion for more than 25 years. The work is performed by SKB in close collaboration with universities, scientific/technical institutes and consultant firms in Sweden and abroad.

The present Swedish system includes a specially built ship for transport, a final repository for different types of operational waste (SFR) and a central interim storage facility for spent nuclear fuel (CLAB), Fig. 1. However, three important components of the spent fuel management system are lacking: a plant for encapsulating the spent fuel in canisters, a factory for fabricating canisters and a deep geological repository where the encapsulated waste can be disposed of in a safe long-term manner. SKB plans to start the initial operation of a deep geologic repository in the year 2015 and the regular operation in about 2023 [1].

2. Containers used or planned to be used

The purpose of a disposal is to isolate the radioactive waste from man and the environment. If the isolation is broken the leakage and transport of radioactive substances must be retarded. To achieve these two main functions of a repository the waste must be protected by barriers of which the package is one. The packages must also be designed taking into account aspects such as physical protection, radiation protection and transportation. The waste itself, its form and its content of activity, are of course also important factors.

There are some general principles used when designing the Swedish containers for radioactive waste. One is to use standards, set up by authorities and international organisations. Since these regulations are created to prevent radiation damage and to valid for the loads to which the container is exposed, it is natural for us to fulfil these requirements. Another principle is to use tested and reliable material in the container.

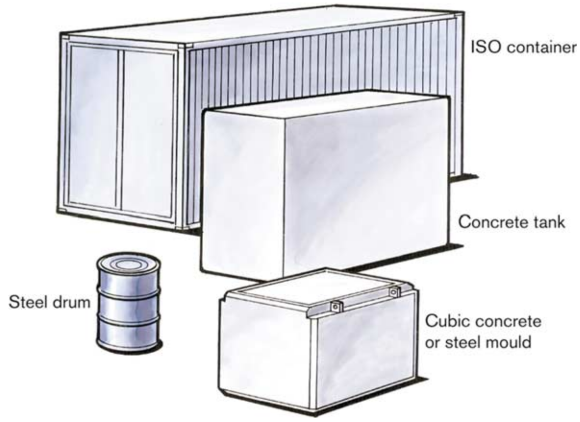

Figure 2. Waste packages used in SFR.

A third principle is to have routines and techniques to control the containers. A quality control system is necessary in order to avoid the use of defect containers.

2.1. Containers used for low- and medium-level waste

In SFR, the Final Repository for Operational Radioactive Waste, in operation since 1988, four standard containers (Fig. 2) are used for storing short-lived, low and intermediate level waste [2].

Cubic concrete moulds with a side of 1.2 m where the thickness of the walls is between 10 and 35 cm, are one type of container used. The insert of the mould can be varied depending on the content. The mould is, among other things, used for ion exchange resins. Moulds in the same size are also constructed in steel. The material is carbon steel that has been painted with epoxi to prevent corrosion. The steel mould is used for waste, solidified in concrete or bitumen. Solidified waste could also be placed in steel drums with a diameter of 0.6 m and a height of 0.9 m. The material is epoxi painted carbon steel or stainless steel. The drums can be placed on plates or in boxes four by four, for better handling inside the SFR facility. For dewatered waste reinforced concrete tanks are used. The tanks have a base area of 1.3×3.3 m and a height of 2.3 m.

Besides these four specially built containers, standard ISO-containers are used for solid low-level waste, which is packed in a primary package. The containers are produced with a strong steel frame covered with corrugated sheet iron and are available in different sizes.

2.2. Canisters planned for encapsulation of spent fuel

Before the spent fuel is emplaced in a deep repository it will be encapsulated in canisters. The canister for spent fuel, designed by SKB, consists of an outer corrosion barrier of copper and a pressure-bearing insert of cast nodular iron, Fig. 3. The canister holds 12 BWR-assemblies or 4 PWR-assemblies. Filled with fuel, the weight of the canister is about 25 tons. The Swedish nuclear programme requires about 4 500 canisters. Several fabrication methods have been and will be tested and a canister laboratory has been built in Oskarshamn to develop and test sealing and inspection techniques.

3. The development of durable canisters for final disposal of spent nuclear fuel

The studies concerning suitable canister concepts for long-term isolation of spent fuel in Swedish bedrock started in the 1970s. Already at an early stage copper was identified as a potentially very suitable material [3] due to its thermodynamic stability and corrosion resistance in reducing groundwaters, such as those found in the deep bedrock. Over the years the canister concept has been gradually changed and refined to optimise the canister design to the requirements set by operation and long-term storage conditions.

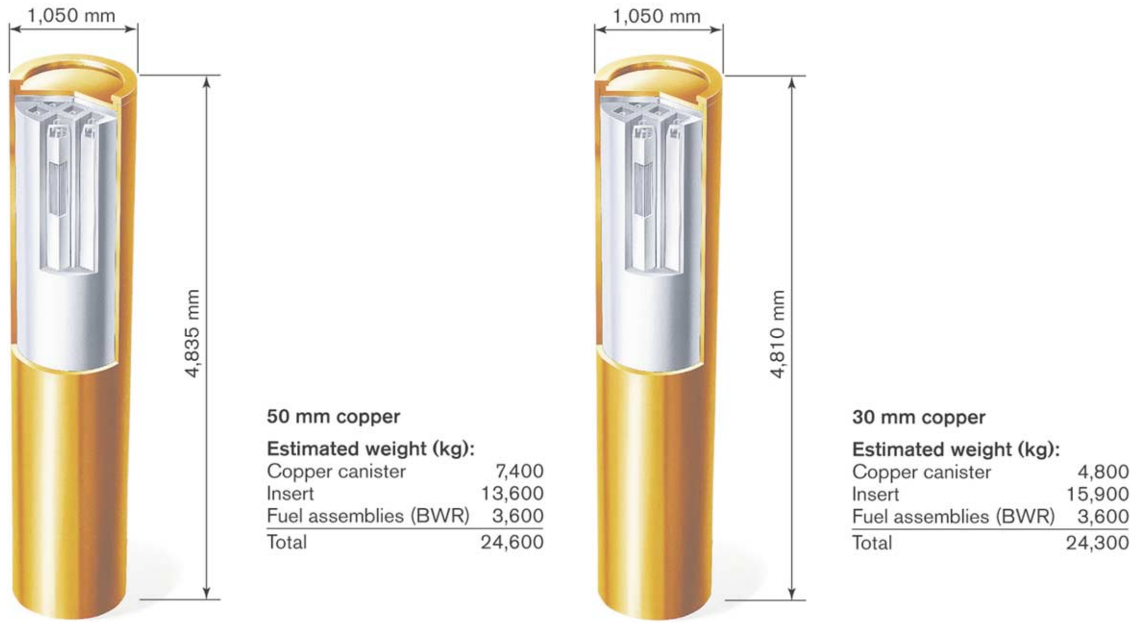

Figure 3. Planned design of the Swedish spent fuel canister.

3.1. Requirements

The primary function of a deep repository is to isolate the waste. The canister provides direct isolation, but the buffer and the rock are also needed for the canister to fulfil its isolation function. If this isolation should be breached, the deep repository will retard the transport of radionuclides from the fuel. The canister, the buffer and the rock work in conjunction to provide this. Besides these long-term safety requirements, there are requirements related to design, fabrication and handling of the canister [4].

To achieve isolation the canister must be leaktight on emplacement and it must be resistant to the chemical environment and withstand the mechanical loads anticipated in the deep repository. The chemical resistance means that the outside of the canister must neither be affected by corrosive substances in the groundwater nor by other harmful substances introduced during construction of the repository. Moreover, the canister must not corrode internally as a consequence of harmful substances that may remain or be formed in the canister. The mechanical loads, to which the canister is exposed, are caused by pressure from the groundwater and the swelling bentonite. Future glacial periods and rock movements can also cause mechanical stresses.

To ensure the retarding function, the canister must influence the chemical properties of the buffer and the rock as little as possible. The heat flux and radiation dose to the near field must, therefore, be limited. The canister material must not affect the rate of dissolution of the fuel or the radionuclide transport through buffer and rock. The canister design must also ensure that criticality may never occur.

The canister must meet the requirements made in connection with both normal and abnormal operating conditions during handling. This means that predicted accidents during handling must not lead to unacceptable radiation doses or releases of radioactive substances to the environment. It must be possible to transport, deposit and, if necessary, retrieve the canister from the deep repository in a safe manner. Another requirement is that it must be possible to serially fabricate canisters to the specified quality. Additionally, it must be possible to encapsulate BWR and PWR fuel as well as damaged fuel assemblies in canisters with the same overall dimensions.

3.2. Design

Canister design proceeds stepwise by compilation of basic premises, property requirements and design requirements. At the same time, practical trials are conducted with fabrication and sealing of canisters. In the reference design, Fig. 3, the canister consists of a pressure-bearing insert of spheroidal graphite iron (nodular iron) with a steel lid. The insert's lid is screwed on with a bolt in the centre. The spacing between the fuel channels in the insert is 50 mm and the minimum distance from the fuel to the outside of the insert is 40 mm. The insert is surrounded by an outer corrosion barrier of copper. In the reference canister the thickness of the copper shell is set to 50 mm. Between the copper tube and the copper lid the canister has a horizontal weld surface. Lid and tube are planned to be joined together in vacuum by electron beam welding.

To give the canister its required corrosion protection the thickness of the copper shell must be at least 15 mm [5]. Compilation of design requirements will give the final design, including copper thickness, of the canister.

3.3. Fabrication

In recent years, continued fabrication trials with copper canisters and cast iron inserts have been conducted on a full scale with good results [6]. Three methods have been used for full-scale fabrication of copper tubes, roll forming, extrusion and pierce and draw processing.

Using roll forming, two copper plates are rolled to tube halves that are welded together by electron beam welding. The two longitudinal welds can be regarded as a disadvantage. Using this method the tubes must also be stress-relief-annealed to ensure shape stability. Since 1998 the test fabrication has been focused on seamless tubes where extrusion and pierce and draw processing have been used. Extrusion means that a preformed copper ingot is squeezed through a die in one step. Pierce and draw processing is performed in two steps. First, the ingot is preformed into a blank with a centre hole and a retained bottom. In step two the finished tube is produced by repeated drawing through a die.

Both reference canisters, with 50 mm copper thickness, and canisters with a 30 mm copper shell have been test fabricated. A possible future focus on wall thickness of 30 mm may be favourable for the application of roll forming and longitudinal welding. The current development of friction stir welding could also be favourable for longitudinal welding of copper tubes.

The cast inserts have been trial-fabricated in both cast steel and spheroidal graphite iron. The channels for the fuel assemblies were formed by square steel sections, welded together into a cassette and placed in a mould. The space between the cassette and the mould is then filled with molten iron. The trial castings have shown that spheroidal graphite iron has several advantages compared with cast steel. The risk of defects is lower since spheroidal graphite iron has better castability. This also means that the inserts can be cast with an integral bottom, which is not possible if cast steel is used.

Copper lids and bottoms are made by hot-forging of continuously-cast round bars, followed by a machining to a blank that is dimensioned so that it can be finally machined either to a lid or a bottom. The fabrication trials have shown that a homogeneous and defect-free material is obtained in the finished components.

3.4. Sealing of the canister

Development work on welding techniques at TWI (The Welding Institute, Cambridge, UK) and at the SKB Canister Laboratory in Oskarshamn is aimed at developing techniques and welding parameters to achieve a stable process with high reliability so that the sealing weld meets the durability and strength requirements.

To join canister and lid, electron beam welding (EBW) can be used. EBW is a fusion welding method. The work-piece is bombarded with a powerful stream of electrons with high kinetic energy. When the electrons hit the work-piece, local heating occurs and the material melts. The method has several advantages: Thick work-pieces can be welded, the process takes place without contact with the work-piece, no filler material is required and the welding parameters are reproducible and can be programmed. Fusion welding of thick unalloyed copper entails certain difficulties due to high thermal conductivity of the material and the low viscosity of the molten metal. In order to develop EBW in thick copper, SKB started a development project at TWI in 1982, and a machine designed for welding copper canisters was developed and is now in use at the SKB Canister Laboratory.

Friction stir welding (FSW) is an alternative method of joining copper. In FSW a specially designed rotating tool is used. It is equipped with a central probe that is pressed down between the joint surfaces. When the tool rotates and moves along the joint, heat is generated, and under proper conditions the metal becomes soft and formable and the parts are joined together.

The welding method or methods that will be used in the final process of fabricating and sealing canisters will have to be qualified.

3.5. Testing the canister

Most of the practical work of developing methods for Non Destructive Testing (NDT) is done at the SKB Canister Laboratory. The whole weld is radiographed to detect volumetric discontinuities (pores). A linear accelerator with a maximum photon energy of 9 MeV and a dose rate of 1.8 $kG{\cdot}h^{-1}$ is used as radiation source. The system has sufficient basic performance to penetrate copper of the thickness in question. The dose rate is also sufficient to provide an acceptable examination time and negligible influence on the radiograph results by the radiation from the canister with fuel. The detector system is digital with a resolution of 0.4×0.4 mm.

The presence of discontinuities that lack volume, for example incomplete penetration, is investigated by ultrasonic inspection using a phased array technique. An ultrasonic array made of composite material is placed above the top surface of the canister lid. Multichannel electronics are capable of beam-steering, in particular, focusing, steering and scanning. During focusing the beam is concentrated in the weld. Steering enables inclining the beam close to the outer wall. A scan that moves the beam along the canister radius eliminates mechanical movement and increase inspection speed. Beam steering is performed electronically both in emission and the reception by introducing phase difference (delays) between the individual array elements.

Methods for eddy-current testing are being developed to detect near-surface discontinuities. In eddy-current testing, a coil induces a weak eddy current in the weld. Discontinuities cause measurable changes in the secondary field created by the eddy current. In order for eddy current testing to be performed, the top of the weld must first be machined off so that the canister surface is smooth.

The results of the NDT are evaluated by means of destructive tests where the actual sizes of the discontinuities are compared with the measured results.

The testing methods that will be used in the final process of fabricating and sealing canisters will have to be qualified. Two important milestones can be distinguished in the qualification. The first one will be reached when SKB apply for a license to build an encapsulation plant, tentatively planned for 2005. At this point a plan for NDT qualification will be issued describing the necessary steps prior to commissioning of the encapsulation plant. The second milestone is the commissioning of the plant when SKB has to qualify the NTD methods, equipment and personnel.

3.6. Encapsulation process

Fig. 4 shows the planned process for encapsulation. Empty canisters are transported from the canister factory in special transport cases. At arrival they are checked before being allowed to proceed into the encapsulation process. The existing fuel elevator in CLAB is used to transport fuel from the storage pools in CLAB to pools in the encapsulation plant. The identity of the fuel is checked, burnup and decay heat is measured and the assemblies are transloaded into a transport canister. The filled transport canister is lifted

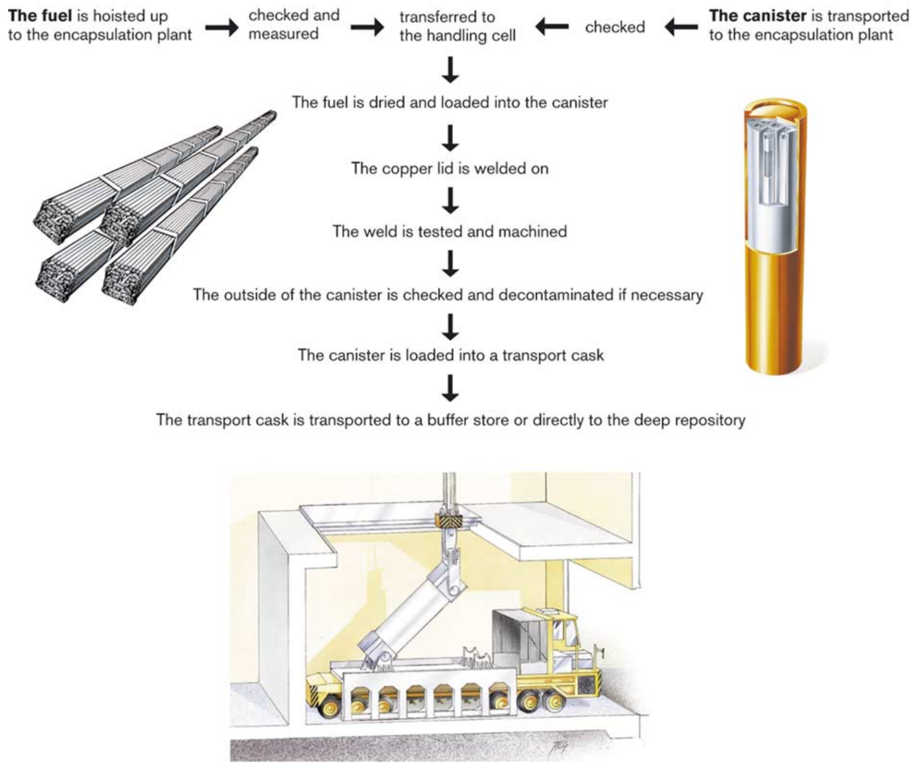

Figure 4. The different steps in the process for encapsulation of spent nuclear fuel.

over to a handling cell where the fuel is dried by hot air. When the fuel is dry, the assemblies are placed in a disposal canister, which is docked to the handling cell. The disposal canister is mounted in a shielded transport frame. A steel lid is bolted onto the insert of the full disposal canister. The framed canister is taken to a station where the steel lid is checked and the joint surface for the copper lid is inspected. At the next station the canister is docked to a welding chamber. The air in the chamber is evacuated so that a vacuum is also created in the gap between the copper canister and the cast insert. The copper lid is placed on the canister and sealed by welding. Machining and non-destructive testing of the weld takes place in separate stations. Then the canister is transferred to a position where it is lifted up from the transport frame and placed in the next station. Smear tests are taken and the canister could be decontaminated if necessary. In the final operation the canister is lifted over to a transport cask. The cask, containing the canister, is taken from the encapsulation plant to the deep repository or to a store for full transport casks.

3.7. Canister handling

The transportation system required to transfer filled and sealed canisters from the encapsulation plant to the deep repository will be based on the same principles as today's system for shipments from the nuclear power plants to CLAB. To satisfy the safety requirements, the canisters will be transported in special transport casks. The main purpose of the casks is to shield the ionizing radiation from the fuel. The transport casks can thereby be handled by the personnel without any extra radiation protection measures. Safety against damaging of the canisters is provided primarily by the transport casks, which can withstand, with ample margin, the stresses, which can reasonably be expected to arise in the event of an accident, even a serious one. The transport casks must be approved in accordance with the international requirements made in the IAEA's recommendations.

The process of the canister deposition is planned to be carried out in a radiation-shielded environment. SKB have studied different methods for this and decided that the canister shall be completely surrounded by a radiation shield until the process is finished. The radiation shield can then be parked above the deposition hole and moved only after the canister has been deposited and covered with bentonite blocks that shield the radiation. Calculations have shown that an approximately 50 cm thick overpack of highly compacted bentonite provides adequate radiation protection under normal conditions.

3.8. Canister processes in a sealed repository

A number of processes will with time change the initial state of the closed deep repository. Some of these processes can influence the canister and its isolating and retarding function. To understand these processes and to determine the risk for damage in the repository system they are carefully described and analysed, for example in the latest safety analysis from SKB, SR 97 [7]. Processes that might influence the canister integrity and performance may be related to radiation effects, thermal or mechanical effects or chemical effects such as external or internal corrosion.

The radiation-related evolution includes radioactive decay in the fuel, the radiation to which this gives rise, and the distribution and attenuation of the radiation in the fuel, the canister and the buffer. Our conclusion when analysing this process is that the radiation-related evolution of the repository does not include any processes that have bearing on the isolating capacity [8]. One important question about the radiation-related evolution is if the conditions in a damaged canister can possibly cause a self-sustaining fission process. Here it is important to study fuel types, burnups and hydraulic conditions inside the canister. Analyses show that fuel from the Swedish nuclear power plants can be disposed of in the canisters with good margin to criticality, even if the canisters should be filled with water if credit is taken for the burnup of the fuel. The heat generated by the radioactive decay is transported by conduction within the insert and the canister and, to a large extent, by radiation between these two parts. The thermal evolution of the repository does not include any processes that affect the isolation capacity of the canister. The requirements that the surface temperature of the canister must not exceed 100 °C, can always be met with the necessary safety margin by choosing a suitable spacing between deposition holes or by adjusting the fuel content of the canisters.

Mechanically, the insert and the canister must withstand external loads. These loads include the hydrostatic pressure, the swelling of buffer, changes in the geosphere (stress changes, rock movements and possible fracturing) and movements caused by buffer or backfill swelling. The canister is subjected to mechanical loading via the buffer in the form of groundwater and buffer pressure. If the pressure on the canister surface is evenly distributed, the canister can take a load of approximately 80 MPa. This is far above the sum of swelling pressure, 7 MPa, and groundwater pressure at a depth of maximum 700 m, 7 MPa. In order to be able to judge the consequences of rock movements, the strength of the canister has been calculated (in SR 97 [7]) for a postulated displacement of 0.1 m lasting 30 days along a horizontal fracture. The results showed that this movement does not lead to immediate canister failure. With pessimistic assumptions, however, the possibility cannot be ruled out that creep deformation in the copper shell after such a rock movement could lead to failure of the copper shell in a time perspective of tens of thousands years.

An important chemical process is external copper corrosion. Under currently known conditions at the deep repository level, the canister is expected to remain intact for a very long time, much longer than the 100 000 years stipulated in the design premises. If water enters the canister, the cast iron insert will corrode anaerobically, since the groundwater is oxygen-free, with hydrogen generation and magnetite formation. A magnetite layer will build up on the iron surface and the corrosion rate is expected to be around 0.1 $\mu m \cdot y^{-1}$. Stress corrosion cracking (SCC) may also occur in both the canister and the cast iron insert. In SR 97 [7], SKB observes that that there is no evidence that SCC could occur in the repository environment, but the possibility cannot be entirely ruled out. The ongoing research on SCC of copper in the repository environment will therefore continue with both laboratory experiments and field experiments in the Äspö Hard Rock Laboratory.

4. What is coming next?

4.1. Development program

Even if the main issues concerning canister design, fabrication and control are solved, there are some areas where further development and also demonstration is required. Some of the development programs for the next years are mentioned here.

The work with full-scale trial fabrication of all canister parts will continue. The Swedish Nuclear Power Inspectorate (SKI) has declared that SKB must demonstrate availability of the methods for serial fabrication and inspection of canisters before an application for construction of the encapsulation plant is given to the authorities [9]. Thus, a sufficient number of canisters must have been fabricated and inspected and shown to satisfy stipulated requirements.

Continued fabrication of seamless copper tubes will primarily be done using the two methods extrusion and pierce and draw processing [9]. The work will be focused on showing that full-scale copper tubes can be fabricated by means of this methods and satisfy applicable requirements. Manufacturing trials with other methods will also be carried out in parallel. Important aspects are optimizing material yield, process parameters and inspection methods.

Experience from the trial fabrication of all canister parts will be applied to the further development of the factory. The work of researching and establishing acceptance criteria and testing methods will make it possible to specify and modify equipment for non destructive testing and other quality inspection more precisely. A more thorough evaluation of modified machinery and testing equipment will be made in cooperation with potential suppliers. This will provide opportunities for a more precise analysis of the factory's layout and investment costs.

Projects regarding further development of electron beam welding, are planned to be completed in early 2004. The goal is to develop processes and equipment for sealing both 50 and 30 mm thick canisters in a way that provides the requisite properties of the weld while satisfying production requirements as regards production rate and reliability. For friction stir welding the work is focused on further development of tools and of process parameters. It is also important to develop technology for monitoring and control of certain process parameters. A completely new machine for friction stir welding is planned to be installed in SKBs Canister Laboratory. The purpose is to be able to try out the technique for the sealing of canisters in a similar manner as with electron beam welding.

The development of non destructive testing will continue for several years. Methods and techniques will be developed for canisters sealed with both EBW and FSW.

4.2. Applications for permits for siting and construction of the encapsulation plant

Encapsulation of the fuel should start approximately one year before the deep repository is put into operation. With reference to the timetable for execution, construction of the encapsulation plant should therefore commence before the deep repository. However, it is not appropriate to start construction before the safety assessment for the deep repository has been completed and reviewed.

The work of planning and designing the encapsulation plant is proceeding in five stages. First, a conceptual design study of the plant is carried out. Then a basic design stage is carried out as a basis for an application for a permit to build the encapsulation plant. With reference to SKBs siting work and overall timetable, the application for a permit should be submitted around 2005. The application will include a facility description, a preliminary safety report and an environmental impact statement. While the authorities process the application, the general engineering documentation needed to begin building the plant is produced. In the next stage, which proceeds during the time the plant is being built, detailed engineering is carried out. When the encapsulation plant is finished and commissioning is in progress, the design work is concluded by final documentation of the building layout and designs. Start of operation of the encapsulation plant is planned for the year 2014.

Further information related to this article can be found in [10–31].

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Discussion

Question from J.M. Kindelan

I would like to ask Mr Thegerström for details about the calendar for work on the copper canisters after 2005?

Reply of C. Thegerström

The schedule is to further develop the fabrication and welding methods during 2002–2005 so that a license application for an encapsulation plant can be sent to the authorities 2005. Construction of the encapsulation plant is planned for the period 2007–2013 and the first hot canister is planned to be produced 2015.

Commentary from J.P. Martin

At CREN we are constructing the LHC which has a very high luminosity. As the packets of protons cross, there are multiple elementary collisions. The radiation intensity will be considerable, and we need to study the resistance of the vacuum chambers, magnets, the accelerator cavities, and above all the detectors. We have never in the past come across such a situation in particle physics.

Question from C. Deviller

What role do you forsee for reversibility as security in long-term storage?

Reply from C. Thegerström

There is no legal requirement in Sweden for retrievability. However, retrieval is technically possible and reversability of the deposition sequence is necessary in case a canister has to be retrieved for technical reasons during deposition. After closure of the full repository retrieval is still feasible in technical terms but it would require a major undertaking and a special operation including rather high costs.