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Encapsulation and handling of spent nuclear fuel for final disposal

1 Welded copper canisters
2 Pressed copper canisters (HIPOW)
3 BWR Channels in Concrete

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SVENSK KÄRNBRÄNSLEFÖRSÖRJNING AB / AVDELNING KBS

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ENCAPSULATION AND HANDLING OF SPENT NUCLEAR FUEL FOR FINAL DISPOSAL

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This report concerns a study which was conducted for SKBF/KBS. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

A list of other reports published in this series during 1983, is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17) and 1982 (TR 82-28) is available through SKBF/KBS.

Encapsulation and handling of spent nuclear fuel for final disposal

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LIST OF REFERENCES

Reference A	Sandersson A, Szluka T F, Turner J Feasibility Study of EB Welding of Spent Nuclear Fuel Canisters Welding Institute Cambridge UK KBS TR 83-25, April 1983
Reference B	KBS - Final disposal of components with neutron induced activity - Radiation shielding calculations. (In Swedish) ASEA-ATOM PM KPC 83-20, Lars Carlquist
Reference C	Encapsulation of spent nuclear fuel - Safety analysis KBS TR 83-30, ES-konsult AB

SUMMARY

The handling and encapsulation of spent fuel for final disposal is dealt with in this report.

The handling and embedding of those metal parts which arrive to the encapsulation station with the fuel is also described.

For the encapsulation of fuel two alternatives are presented, both with copper canisters but with filling of lead and copper powder respectively. The sealing method in the first case is electron beam welding, in the second case hot isostatic pressing. This has given the headline of the two chapters describing the methods: Welded copper canister and Pressed copper canister.

Chapter 1, Welded copper canister, presents the handling of the fuel when it arrives to the encapsulation station, where it is first placed in a buffer pool. From this pool the fuel is transferred to the encapsulation process and thereby separated from fuel boxes and boron glass rod bundles, which are transported together with the fuel.

The encapsulation process comprises charging into a copper canister, filling with molten lead, electron beam welding of the lid and final inspection. The transport to and handling in the final repository are described up to the deposition and sealing in the deposition hole. Handling of fuel residues is treated in one of the sections.

In chapter 2, Pressed copper canister, only those parts of the handling, which differ from chapter 1 are described. The hot isostatic pressing process is given in the first sections.

The handling includes drying, charging into the canister, filling with copper powder, seal lid application and hot isostatic pressing before the final inspection and deposition.

In the third chapter, BWR boxes in concrete moulds, the handling of the metal parts, separated from the fuel, are dealt with. After being lifted from the buffer pool they are inserted in a concrete mould, the mould is filled with concrete, covered with a lid and after hardening transferred to its own repository. The deposition in this repository is described.

0 INTRODUCTION

The first KBS report dealing with final storage of spent nuclear fuel was published in 1978. The design studies presented in that report have been the subject of further investigations, the results of which are presented in this report.

The fundamental principles of the earlier study have been retained. The fuel is thus contained in copper canisters which are deposited in vertical holes in bedrock at a depth of 500 m. As in the earlier study, the canisters will be surrounded by bentonite.

Certain changes are presented. The fuel bundles are not dismantled before being placed in the copper canisters, thus eliminating the time-consuming dismantling work. At the same time, the wall thickness of the copper canister has been reduced, since careful investigations have demonstrated that a 100 mm thick copper wall is more than sufficient to provide intact protection for the fuel for a sufficient length of time. Copper has been removed from the inside of the canister, and space is therefore available for the same quantity of fuel as previously, in spite of the fact that the bundles are not dismantled.

Two different principles for encapsulating the fuel are presented. The first is based on the principles in KBS 2, whereby the canister with the fuel in it is filled with lead. A copper cover is then secured to the canister by electron beam welding. This method is described in more detail in Chapter 1.

According to the second principle, a copper canister is used but the lead is replaced by copper powder. The entire unit is then placed in a press and is subjected to hot isostatic pressing, which results in an end product in which the fuel is encapsulated in a homogeneous copper block and each fuel rod is then surrounded by solid copper. This alternative is presented in Chapter 2.

The choice of alternative will only affect apart of the encapsulation station (see Figure 0-1).

This report also specifies how fuel boxes and boron glass rod bundles are handled. This is another area that has been processed more accurately since the earlier report. This handling is dealt with in Chapter 3.

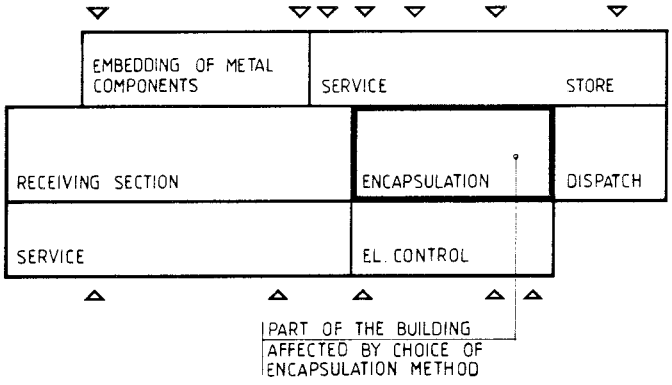


Figure 0-1. Encapsulation station. Key plan.

Spent fuel

The various types of fuel employed in Swedish light water reactors are described in Appendix 1. The appearance of the fuel is shown in Figure 0-2.

The CLAB central spent fuel storage facility is used for intermediate storage of the fuel. The fuel is then transferred to the final repository about 40 years after it has been removed from the reactors. During this decay period, the decay power will have been reduced, thus allowing for a suitable configuration of the canister and the size of the rock repository area, with a moderate temperature at the canister surface and in the rock.

At the same time, the radioactivity of the fuel will have decayed, thus allowing for more moderate dimensions of the radiation shields necessary for the various handling operations.

On arrival at the encapsulation station, the fuel bundles are placed in a buffer store in a pool. The buffer pool is used for evening out the loading during periods when transport may be affected by various disturbances, such as by ports being ice-bound.

Before encapsulation, the fuel bundles are assembled into units that are of suitable size for the copper canister. Eight BWR bundles or two BWR and two PWR bundles in each canister are considered in this study. The decay power of the individual bundles will vary somewhat due to their different burn-up, and the units are therefore made-up by selecting bundles in such a manner that the heat emission from the canister will be between 800 and 850 W. This selection is made when fuel is removed from CLAB and also when fuel is picked out of the buffer pool. Achievement of a suitable combination is facilitated by comprehensive documentation being available for each individual fuel bundle. The assembled fuel bundle encapsulation units are shown in Figure 0-2.

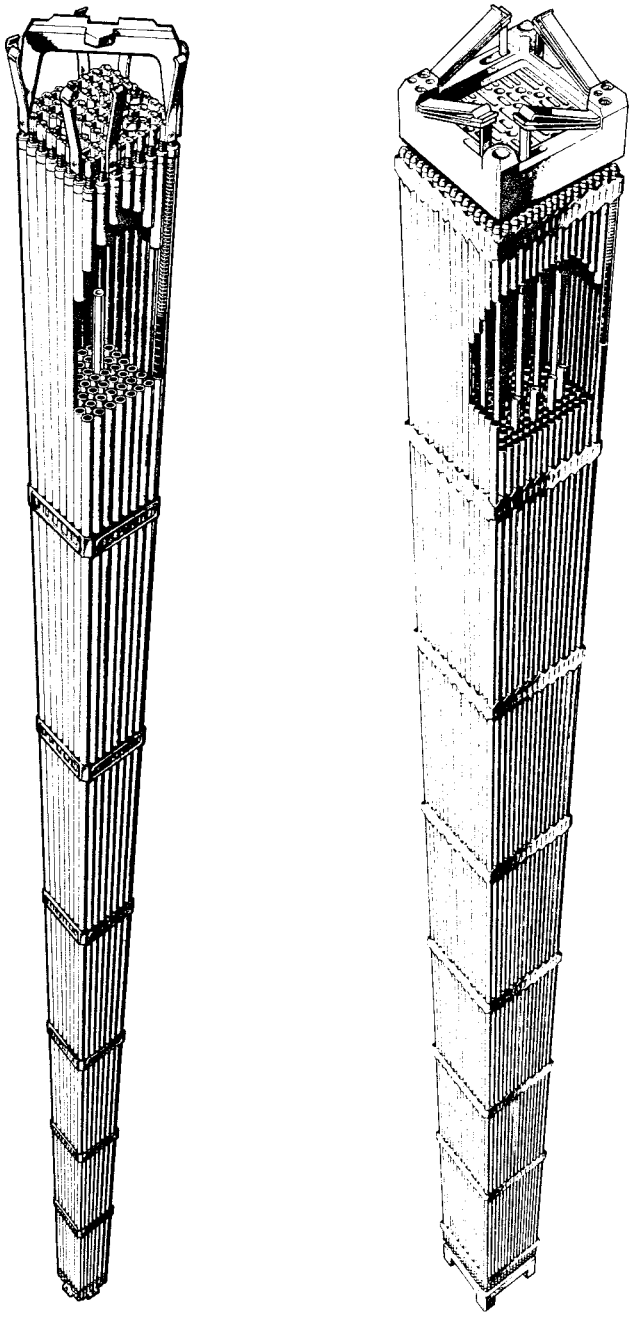


Figure 0-2. BWR and PWR fuel bundles.

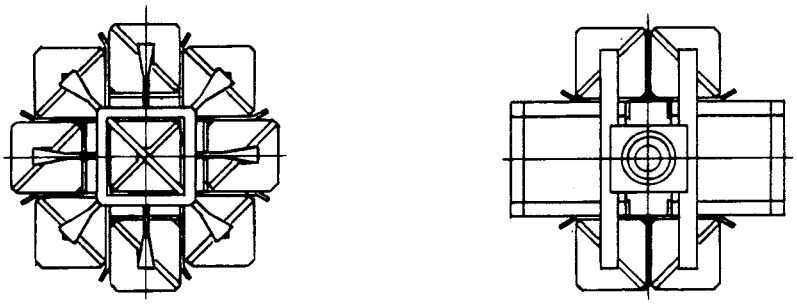


Figure 0-3. Bunches with 9 BWR (left) and 2 PWR + 4 BWR fuel bundles.

The number of copper canisters will be about 4400, of which 2800 will contain BWR fuel and 1600 will contain BWR and PWR fuel.

The size of the copper canister is such that it could accommodate nine BWR bundles or two PWR and four BWR bundles, as illustrated in Figure 0-3. This would give a somewhat higher heat emission than the one mentioned above why parameter studies to be carried out at a later date will demonstrate whether the greater fuel amounts are acceptable.

The BWR bundles are transported in their boxes to the encapsulation station. In the work of assembling the fuel into encapsulation units, the BWR fuel is lifted out of the boxes. The boxes are transferred to a separate cell for embedding into concrete. The boron glass rod bundles of the PWR fuel are lifted out of the fuel bundles. They are also transferred to the separate cell for embedding into concrete.

The geometry of the individual fuel bundles is maintained during the encapsulation process. During storage in water, the fuel is arranged in a geometry which is similar to that employed in the fuel pools at the nuclear power plants. This provides a very wide margin to criticality, even assuming an enrichment corresponding to that of new fuel.

When it is assembled into encapsulation units, the fuel is arranged in a new geometry. The limited quantity of fuel in each unit and the relatively widely-spaced arrangement of the fuel in this geometry also provide a very wide margin to criticality.

Fuel damage has so far proved to occur only to a very limited extent, and the individual cases of damage consisted of minor holes in the fuel cladding. No special measures are therefore likely to prove necessary during the encapsulation process.

However, the copper rack can accommodate an extra tube in which any broken rods can be located. In addition, space is available for a copper can in which the waste from sludge extraction from the pools can be collected. Such fuel residues are thus encapsulated together with the fuel.

Handling of the waste

The design of the component equipment is based largely on investigations carried out earlier or on investigations and project design work carried out in parallel with the preparation of this report. The material has been re-worked and adapted to the demands made on coordination between different plants, depth of storage, quantities of waste, etc.

The handling procedure in the various processes has been studied in a similar manner and a comprehensive study has been carried out, including by simulation, for designing and verifying the incoming material flows with regard to practical attainability.

The encapsulation station, in which the waste is received and encapsulated before deposition, is the dominating building on the site. A number of facilities are provided around this building for the encapsulation and deposition functions. These consist of buildings for the storage of materials, for producing concrete and bentonite, for the needs of the personnel, etc. and a transport system of roads and railway tracks.

The transport procedures to the encapsulation station are assumed to be as follows. The waste is transported by sea from CLAB to a harbour in the vicinity of the selected deposition site. The transport units are unloaded from the ship by means of a self-propelled hydraulic truck and are lifted onto railway wagons by means of a crane. They are then transported by rail to the encapsulation station, where they are unloaded by means of a crane.

The encapsulation of the waste is described in the following chapter. Two encapsulation methods are presented for the spent fuel. The procedure of casting lead around the fuel in the canister and then securing a cover by electron beam welding is described under the heading "Welded canister" (Chapter 1). The procedure for hot isostatic pressing of the fuel together with copper powder in a canister to produce a canister of homogeneous copper right up to the fuel rods is described in Chapter 2 "Pressed canister". Chapter 3 "BWR boxes in concrete" shows how BWR boxes and PWR boron glass rod bundles are handled and embedded into concrete moulds which are dispatched to their separate repository.

The handling during the encapsulation of spent fuel is largely the same in both methods.

Fuel from CLAB is received in the receiving section of the encapsulation station, where it is lifted out of the transport casks and is placed in a buffer pool.

The fuel bundles are assembled into encapsulation units in racks that differ slightly for welded and pressed canisters. In the case of the welded canister, the rack must have a lead-filling pipe which simultaneously serves as the central frame holding the rack together and as a mounting for lifting. In the case of the pressed canister, the frame of the rack must allow the copper powder to flow freely and fill all cavities in the canister.

The differences between the two methods start after the rack with the fuel has been lifted into the encapsulation cell.

When the canister leaves the encapsulation cell, it must first be monitored. The welded canister is checked by ultrasonic examination of the welded joint. The pressed canister is checked by weighing and measuring the volume and by visual inspection of the external seal weld.

Further handling, transport to the deposition site and the deposition procedure are the same for both types of canister.

1
WELDED COPPER CANISTER

In the processing station, the spent fuel is received and encapsulated, and the boxes and PWR boron glass rods are embedded. The design of the plant is shown in Figure 1-1. The layout of the plant is presented in Appendix 2.

1.1
Functional description

Spent fuel arriving in transport casks from CLAB to the encapsulation station is encapsulated in copper for further transport down to the final repository.

As shown in Appendix 2, the plant can be divided functionally as follows:

* Arrival and receiving section in which unloading is carried out. This section contains:

  - Arrival hall and sluice for admission of a railway wagon carrying the transport cask.
  - Active workshop for repairs to the transport casks.
  - Storage area for three transport casks for use as a buffer.
  - Flushing pits for internal flushing on arrival and also for external flushing on dispatch (for flushing away the pool water).
  - Cask and unloading pools in two parallel lines, each for one cask and cover.
  - Buffer pool with space for fuel for about three months of encapsulation work.
  - Lock pool for transfer of the fuel to the encapsulation section.

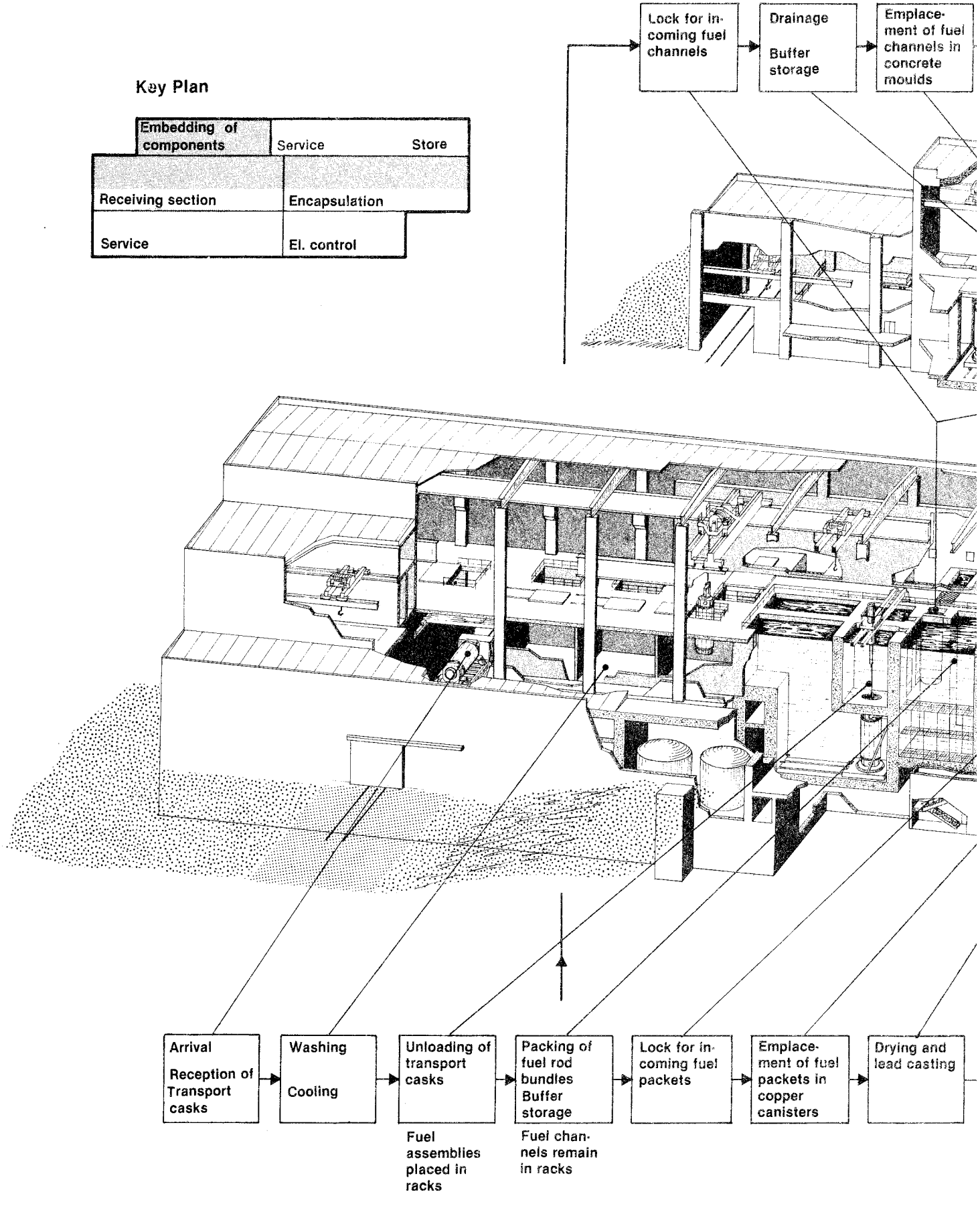
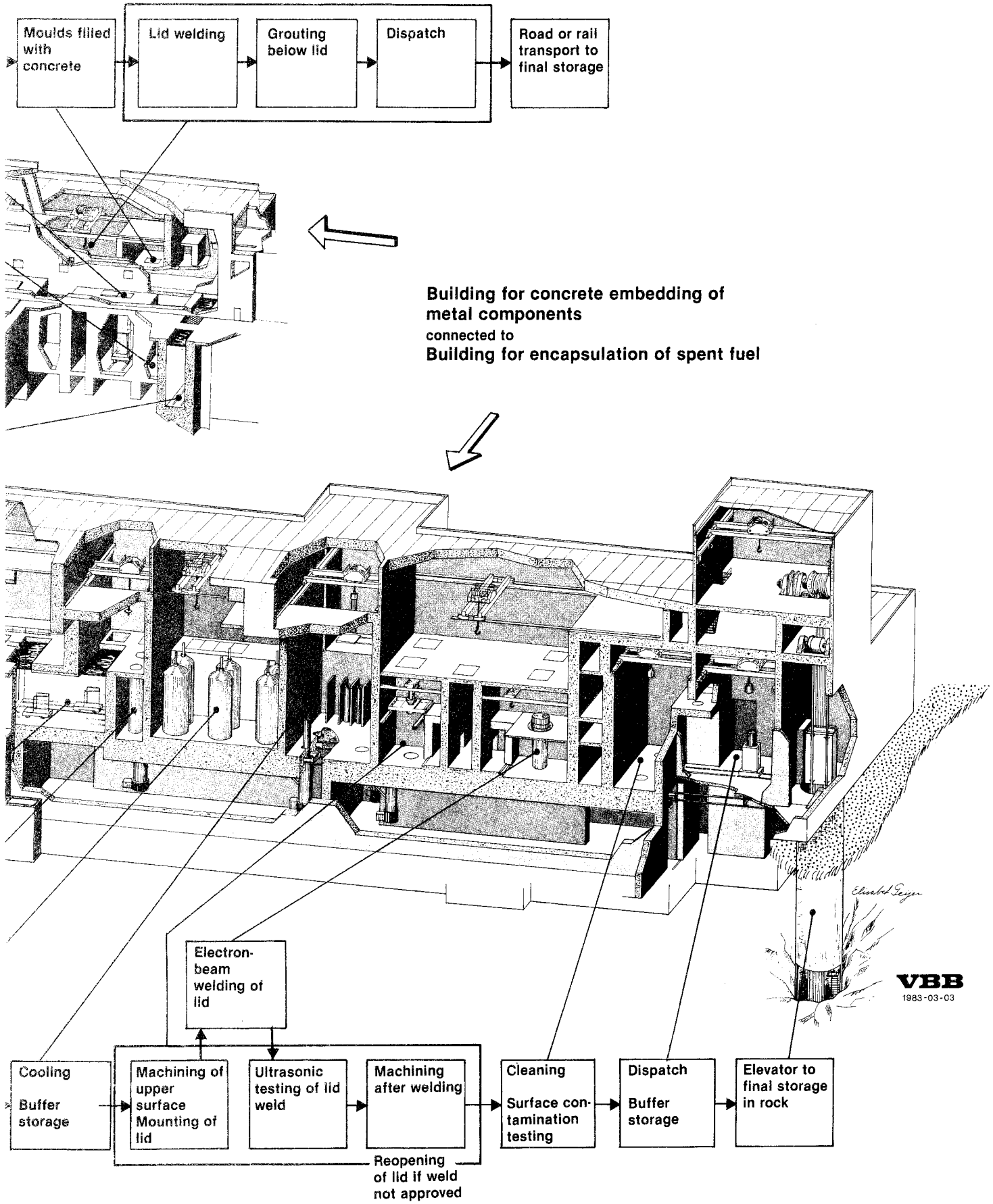


Figure 1-1. Encapsulation station with process scheme


Moulds filled with concrete
Lid welding
Grouting below lid
Dispatch
Road or rail transport to final storage
Building for concrete embedding of metal components
connected to
Building for encapsulation of spent fuel
Electron-beam welding of lid
Cooling
Buffer storage
Machining of upper surface Mounting of lid
Ultrasonic testing of lid weld
Machining after welding
Reopening of lid if weld not approved
Cleaning
Surface contamination testing
Dispatch
Buffer storage
Elevator to final storage in rock
VBB
1983-03-03

* Encapsulation section designed as a hot cell, i.e. completely inaccessible to personnel during operation. This section contains an admission cell, a casting cell, a cooling cell, a machining cell and a welding cell. Transport between the cells is carried out by means of wagons running in a transport culvert below the cells. The encapsulation section has two parallel processing lines, which allows for continuous work even if a stoppage should occur on one of the lines.

  The cooling cell/transfer cell is equipped with a sluice through which empty canisters can be admitted.

* Dispatch section comprising a room for monitoring and washing of the outer surfaces of the canister, a buffer store and an elevator room. Equipment for wiping tests and washing is provided for surface inspection. The buffer store is provided with a track for the wagon belonging to the elevator, which transfers the canisters to the repository.

* Casting section for core components, located adjacent to the receiving section. This is in communication with the buffer pool, to allow boxes and boron glass rod bundles to be transferred. It includes an arrival and dispatch section for concrete canisters and equipment for filling with concrete and sealing of the concrete lid.

* Service section located predominantly adjacent to the encapsulation and dispatch sections. The service section contains a buffer store for copper canisters, lead melting equipment and general services rooms. The transport wagons for the canisters can be admitted into the service section through the decontamination rooms. Access to the elevator room can be gained via the service section. The service section opens onto an external storage area and a loading quay.

* Auxiliary systems section located adjacent to the arrival and receiving section. The auxiliary systems section contains the cooling and clean-up systems and systems for compacting and solidifying the waste from the station itself.

* Electrical and control section with stand-by diesel-generator set.

* Entrance building which is completely separate but is in communication with the electrical and control section by means of elevated walkways. One end of the entrance building is occupied by the superstructure for the central shaft down to the final repository. The entrance building also contains office and common rooms, cafeteria, etc., as well as changing rooms and entrance and exit monitoring for the personnel employed above and below ground.

1.2 Cask handling in the receiving section

The transport cask arrives on a railway wagon at the arrival hall of the encapsulation station. This is where the outside surfaces of the cask are flushed. The wagon is then transferred to the sluice compartment, where the shock absorbers and mountings of the cask are removed.

The cask is placed in a washing pit, where it is washed to reduce the contamination of the pool water. Hoses are connected to it for discharging transport water, if any, and for flushing the internals of the cask. The cover retaining bolts are removed but the cover is left in position.

The cask is now transferred to a wagon in the cask pool, where the cover is removed. It is brought to below an opening to the unloading pool. It is tightened to the opening to prevent exchange of water, and the fuel elements are transferred from the cask to cassettes. BWR bundles are lifted in their boxes.

After the cover has been replaced, the cask is transferred to the flushing pit, where it is flushed and the cover is secured in position. The cask is then lifted back onto the railway wagon.

When the fuel moves on in the process the boxes remain in the cassettes and are transferred on another wagon to a separate cell. They are transferred to a concrete mould designed to accommodate 49 boxes. The mould is then filled with concrete. After the concrete has set, the mould is transferred to a transport vehicle for transport to its separate final repository. This is described in more detail in Chapter 3.

1.3 Assembly of the fuel into encapsulation units

This method of encapsulation consists of a copper canister with a fill of lead around the fuel and with a welded-on lid.

After removal from the transport cask, the fuel is moved into the buffer pool, where it is placed in a buffer storage area. The fuel bundles are transferred from the buffer store to a lock wagon, on which a unit suitable for the copper canister is assembled on a copper rack designed to accommodate either eight BWR bundles or two PWR and two BWR bundles. The copper rack is shown in Figure 1-2 and consists of a central casting pipe, a bottom grille and a top grille. The bottom grille maintains the bottom plate of the fuel bundles in position. The top grille has retainers that grip the top plates of the bundles when the bundles are moved in towards the top grille. The bundles are lowered into the rack at a slight slope and are straightened for engagement in the top grille when they have been lowered so that they rest on the bottom grille. This procedure avoids the top plates blade springs and guide pads gripping the adjacent bundle on the way down. The casting pipe is then used for lifting the unit. The lock wagon is moved into position under the admission cell of the hot cell section, where the unit is lifted up.

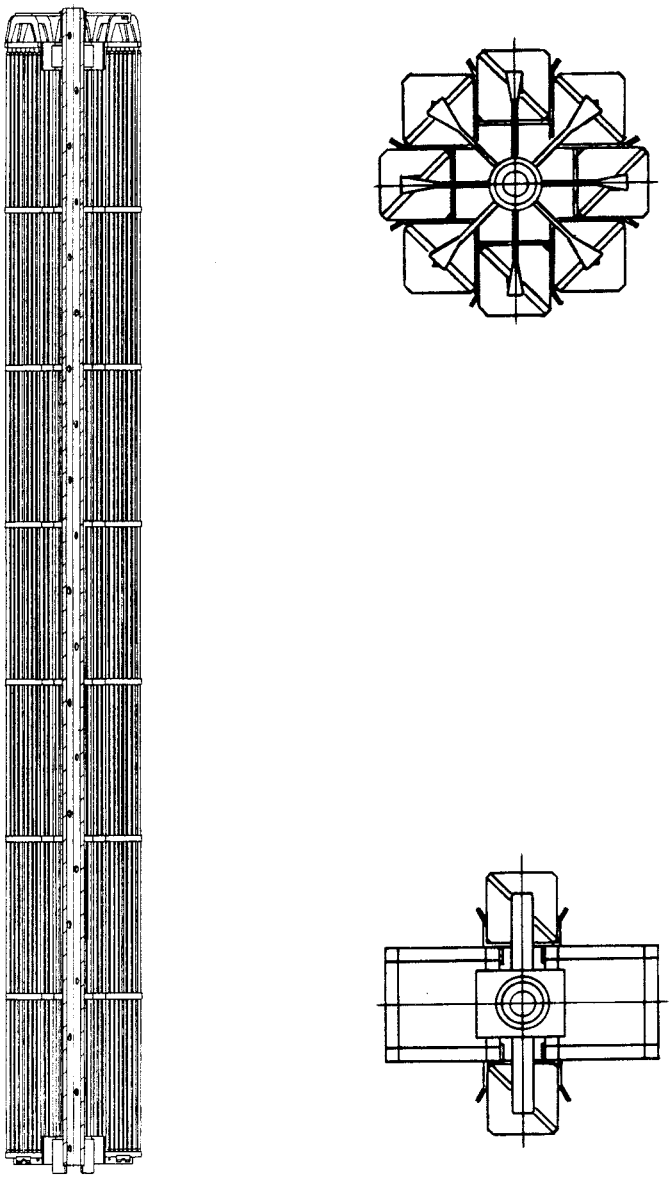


Figure 1-2. Copper rack with 8 BWR fuel bundles. Bunch with 2 PWR + 2 BWR bundles shown in lower section.

1.4 Encapsulation section

The encapsulation section consists of five cells.

- an admission cell with overhead travelling crane, used for transferring the fuel to the canister.
- a casting cell for filling the canister with lead. In this cell, six furnaces are connected to the lead melting equipment and the nitrogen cooling system.
- a cooling cell which can accommodate about ten canisters and which is provided with a sluice towards the canister store. This cell has an overhead travelling crane for moving the canisters.
- a machining cell provided with equipment for machining the cover seating surfaces of the canister. The cover is admitted through a sluice and is placed on the canister.
- a welding cell provided with electron beam welding equipment for welding-on the cover.

1.4.1 Handling in the encapsulation section

The handling is shown schematically in Figure 1-3.

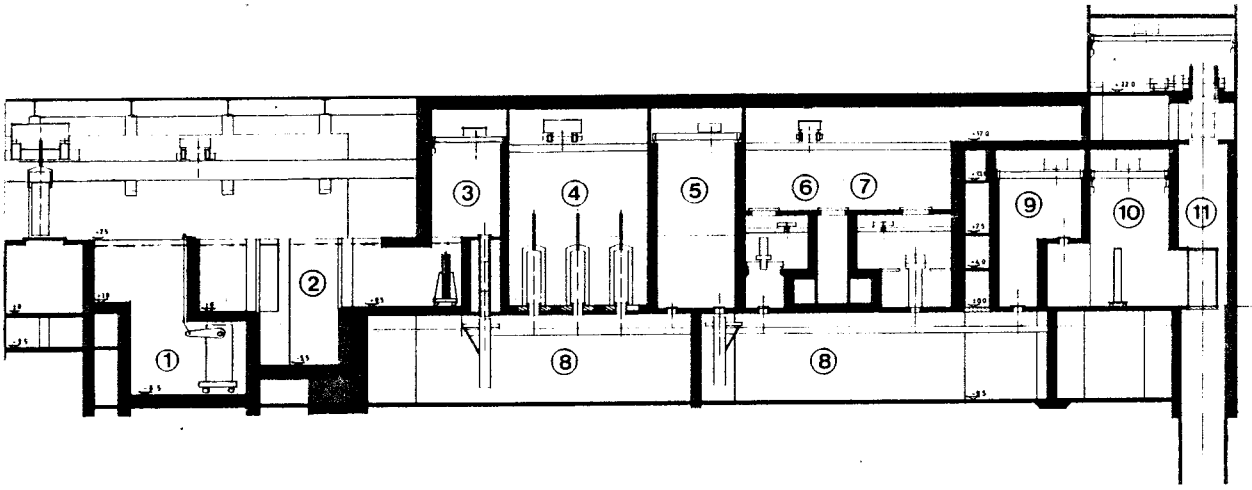
The copper rack, filled with fuel bundles, is transferred on the lock wagon to the admission cell of the encapsulation section, through a pool that also serves as a water trap between the lock pool and the casting cell. In preceding operations, the fuel was handled and stored under water at all times, with a water coverage that provided the necessary radiation shielding.

In succeeding operations, handling is carried out in air in remotely controlled cells, where radiation shielding is provided by thick concrete walls.

The copper rack is lifted by means of an overhead travelling crane from the lock wagon to the admission cell. Water is allowed to run off for a few minutes before the unit is lowered into a copper canister.

The canister is admitted into the cooling cell through a sluice and is placed on a transport wagon, using the overhead travelling crane provided in the cell. The transport wagon serves one of the two handling lines of the casting cell.

The design of the canister is shown in Figure 1-4. The canister is forged from a pure copper ingot and is subsequently turned to its finished outside dimensions. After boring of the cavity, the open end is turned to accommodate the cover.



1. Cask pool
2. Buffer pool
3. Lifting cell
4. Casting cell
5. Cooling cell
6. Machining cell
7. Welding cell
8. Transport ducts
9. Washing and monitoring
10. Buffer store for completed canisters
11. Lift to the final repository

Figure 1-3. Fuel and canister handling in the encapsulation part. Canister for welding

The transport wagon is used for transferring the canister to one of the three casting stations in the handling line. A casting station consists of a vacuum hood into which the canister can be admitted from the underside. The hood is contained in a furnace used for heating the canister and for controlling its cooling.

The canister is raised into the hood by means of a lifting device on the transport wagon. The canister then rests on the bottom plug of the hood, and this plug is lifted up together with the canister and is secured to the hood to provide an air-tight seal. The central casting pipe in the fuel rack is connected by means of an automatic coupling to a pipe for admitting the molten lead as shown in Figure 1-5.

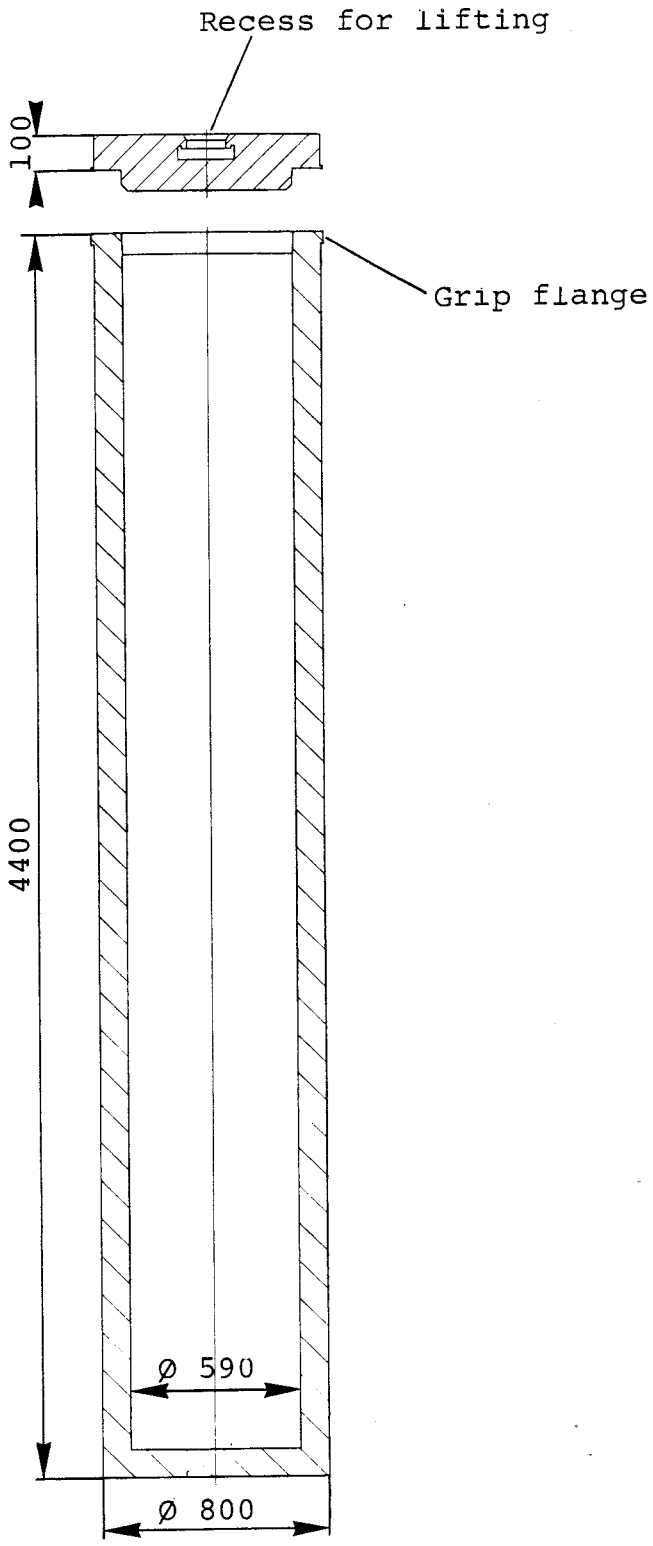


Figure 1-4. Canister for welding.

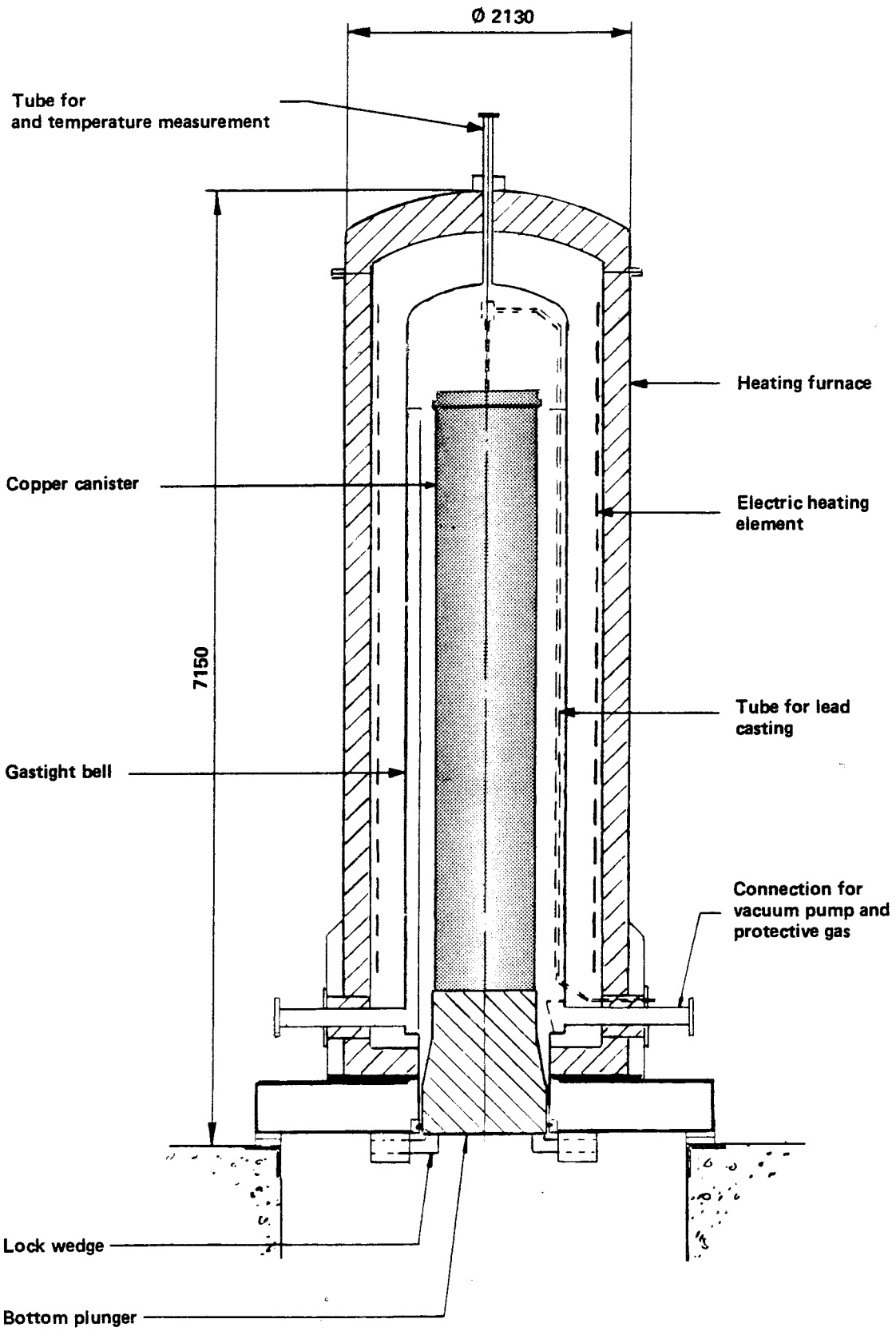


Figure 1-5. Furnace for lead casting.

The hood is evacuated or is filled with nitrogen and the canister is heated for 48 hours by radiant heat from the furnace and by the heat emitted from the fuel itself. This procedure dries the fuel in the canister. Heating is interrupted at 380 - 400°C and molten lead is pumped from a melting furnace outside the cell into the centre tube of the copper rack. This casting method is called rising gate and gives a homogeneous goods.

When the canister is being filled with lead, the rack with the fuel is subjected to a lifting force due to the fact that the density of the unit is lower than that of the lead. The lifting force is counteracted by the retaining force exerted by the lead-filling pipe. The admission of lead is interrupted on receipt of a signal from a level sensor. Lead is cast to a few centimetres above the seat for the bottom edge of the copper cover. The solidification process is controlled so that solidification will proceed from the bottom upwards, and shrinkage is made up by molten lead above the solidified lead.

The hood is now filled with nitrogen which is circulated in a closed circuit and is cooled in a heat exchanger. The canister is cooled in stages over a period of 48 hours down to approx. 150°C. When the lead has solidified, additional lead is admitted to compensate for the shrinkage.

The temperature process in the furnace is illustrated by Figure 1-6.

The function of the nitrogen is to prevent oxidation of the copper, lead and fuel during the period when the canister is at high temperature. The spreading of nitrogen and airborne activity in the cell is prevented by the hood being sealed.

After completion of cooling, the canister is transferred to a cooling cell by means of the transport wagon. The cooling cell serves as a sluice between the casting cell and the machining cell, and is also used for the admission of new canisters. In the cooling cell, the temperature of the canister will drop further down to approx. 80°C.

The overhead travelling crane of the cooling cell is now used for placing the canister on one of the transport wagons of the machining cell. These wagons serve the two handling lines comprising machining, welding and inspection stations.

The canister is moved to the machining cell, in which the excess lead and the projecting centre pipe are removed by machining, so that the top surface of the lead will be flush with the bottom edge of the canister cover. The seating surfaces for the cover are then also skimmed.

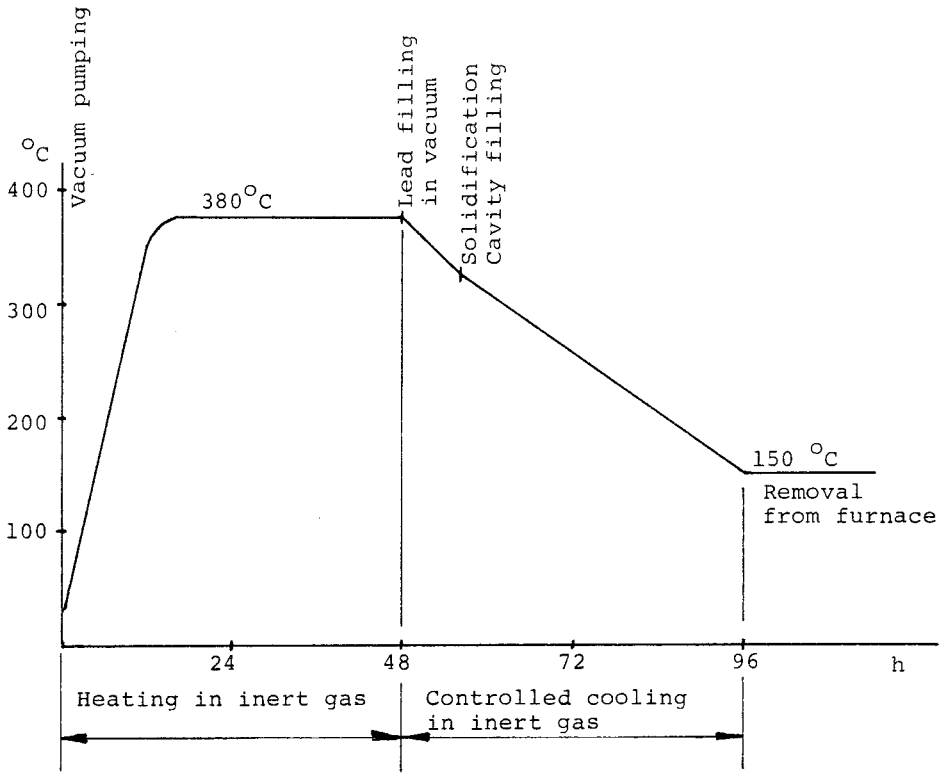


Figure 1-6. Furnace process.

The swarf from the machining and skimming is collected and is transferred to a melting furnace located in a separate room below the machining cell. The lead is recovered here and is then transferred to the system for filling the canisters with lead. The slag formed during melting may contain radioactive material from the fuel, and it is therefore separated and encapsulated in concrete moulds after cooling, in the same manner as the filter compounds from the station's own waste system. As an alternative, the slag can be collected in drums which, after filling with sand and sealing, are placed in a special position in a new copper rack.

The transport wagon then moves the canister to the welding cell, in which the lid is secured in position by electron beam welding. The weld is inspected by ultrasonic examination.

The finished and inspected canister is moved back to the machining cell, in which the flange that was used earlier as a lifting flange and as a guide for the electron beam is turned off. This station can also be used for opening sealed canisters found to be defective during inspection.

The finished canister (Figure 1-7) is then transferred to an elevator wagon used for transporting it down into the final repository.

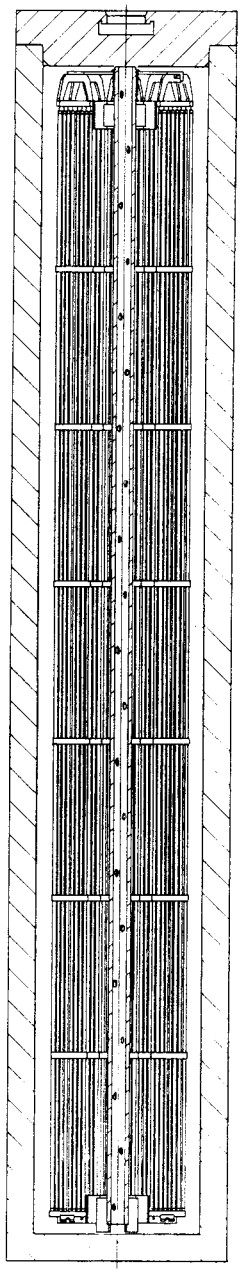


Figure 1-7. Finished welded canister.

1.4.2
Welding

The procedure and equipment used in welding are described in Reference A.

The contents of this reference can be summarized as follows.

It has been demonstrated that a simulated lid of 100 mm thickness can be welded by electron beam. The design of suitable mechanical manipulation equipment would not be expected to create any particular difficulties. Fully enclosing the canister in a vacuum chamber would probably simplify sealing arrangements and with a fixed electron column it would only be necessary to rotate the canister. A 100 kW beam would be sufficient to achieve in excess of 100 mm penetration irrespective of vessel size.

There is no doubt that vacuum and electron beam technology is currently sufficiently advanced to enable a viable equipment to be designed and built for the proposed full scale 4.5 m x Ø0.8 m canister.

1.5
Handling of fuel residues

Fuel residues that may be shaken loose from damaged fuel rods during handling in the encapsulation station is collected by sludge extraction and is transferred to a cyclone separator in a pool in the receiving section. Particles down to about 0.5 mm in size are collected here, and these particles are expected to comprise at least 99% of the fuel residues. From the cyclone separator the water from sludge extraction is transferred to a tank in which the fine-grained fuel spill is allowed to settle.

The fuel residues collected in the cyclone separator is poured into a copper can with a volume of approx. 1 litre. The bottom of the can is covered with a layer of sand. When the can has been filled, it is transferred to the admission cell, where it is allowed to dry. After all of the water has been evaporated, the fuel residues is covered with a layer of sand. The sand and the residues are then mixed by vibration and the mixture is compacted by a copper cover being pressed down onto the top surface by means of a piston. The sand is graded in such a manner that it will fill the spaces between the coarser fuel fragments and will ensure a high density of the compacted mixture. It will thus be able to withstand the high pressures to which it may be subjected in the final repository, without being deformed. After compacting, the edges of the can are bent onto the cover, thus fixing it in position (see Figure 1-8).

The copper can with the fuel residues is placed in the position provided for this purpose in the copper rack for fuel and is cast in together with the fuel.

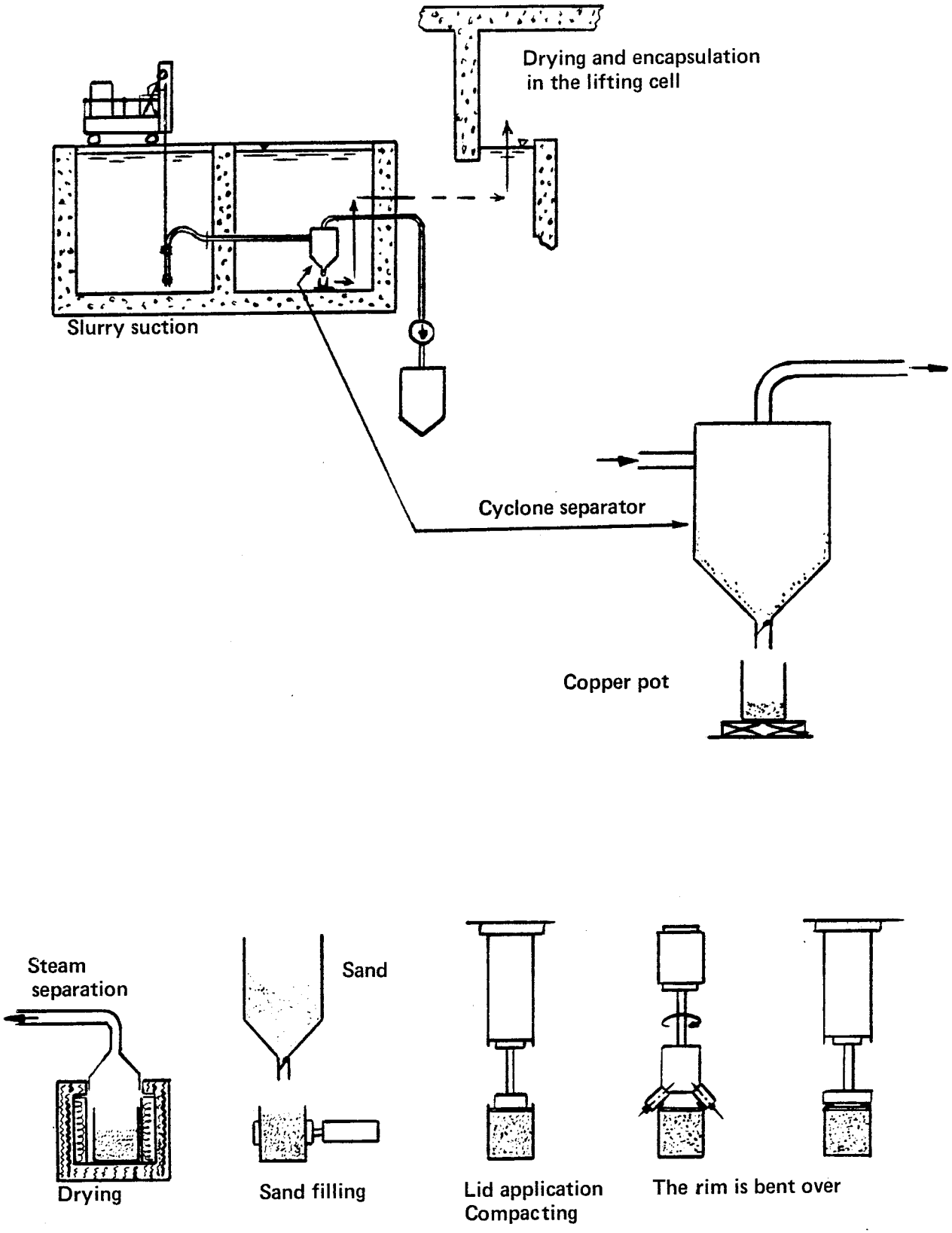


Figure 1-8. Handling of fuel residues.

After sedimentation in the collecting tank, the finegrained fuel spill is transferred in the form of a sludge to an evaporator. The dry material is collected into a copper can and is handled in the same manner as the coarser fractions described above. The water from the tank is discharged to the filters in the pool water clean-up system.

Only a few canisters will contain fuel spill cans. This assessment is based o the extensive experience gained in the handling of fuel. Less than 1 per cent of the fuel rods can be expected to be damaged, and even heavily damaged or even broken rods have demonstrated that the quantity of uranium dioxide that may drop out is very limited.

1.6 Handling in the dispatch section

From the welding cell, the copper canister is moved to the dispatch section that starts with an monitoring and washing station. The cleanliness of the surface is inspected by a wiping test. If necessary, the canister is washed and a new wiping test is taken. Efforts are made to keep the surface of the canister clean, so that radioactive particles will not be deposited on the handling equipment and in the underground tunnels. This is of no consequence as regards long-term storage, but it facilitates cleaning and maintenance during the operating period.

After inspection, the canister is transferred to the buffer store or is placed on the elevator wagon. The buffer store is used primarily when the elevator or deposition vehicle is out of service.

The elevator wagon is pushed into the elevator cage which is then lowered into the repository tunnels.

The operations in the discharge section are remotely controlled, but are supervised by closed-circuit TV and through radiation-shielded windows.

1.7 Auxiliary systems

The plant will include auxiliary systems for:

- cleaning of the transport casks
- lifting and transport
- ventilation
- space heating
- electric power supply
- drainage
- sludge extraction
- water treatment
- treament of filter and ion exchanger resins from the clean-up system
- water supply and compressed air supply

These systems are predominantly of conventional design. Practical tests have been carried out on the casting of lead around the fuel rods and on electron beam welding of copper to obtain verification that the technique oulined here is appropriate.

In order to restrict the disturbances in the event of failure of the external power supply and thus to increase the availability, the plant is equipped with its own stand-by diesel-generating plant to which certain process systems and also the personnel elevators are connected.

The room ventilation system in the process buildign maintains rooms with a higher risk of contamination at a lower pressure than rooms at which this risk is smaller. The supply air is filtered and conditioned to provide comfortable working conditions. The exhaust air is subjected to activity monitoring and is filtered, if necessary.

1.8 Other gods

The goods that will be handled at the encapsulation station are primarily spent fuel and boxes, although significant quantities of encapsulation materials and consumable will also be handled, and the most important items are as follows:

- 4400 copper canisters
- 4400 copper racks
- 533 moulds for boxes
- approx. 47000 tonnes of lead or 30000 tonnes of copper powder
- cement

In the same manner as the waste, the consumables will also arrive by rail.

1.9 Deposition of the finished copper canister

1.9.1 General

From the encapsulation station, the finished copper canister will be transferred by elevator down to the final repository. This is located at a great depth in the bedrock and consists primarily of a number of deposition tunnels, with holes drilled in the bottom of the tunnels. The copper canisters will be surrounded by bentonite and will be located in the holes as shown in Figure 1-9.

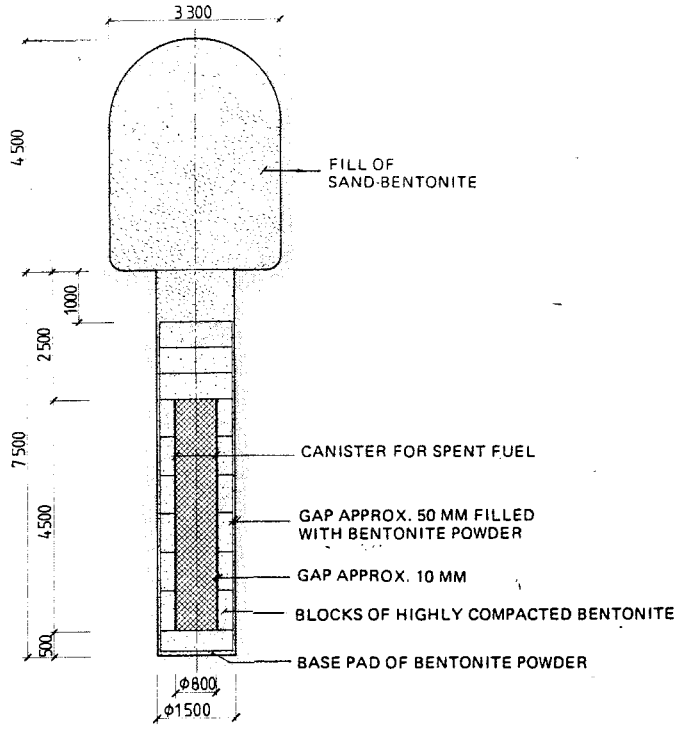


Figure 1-9. Deposition of waste canister.
The sealed final repository.

Figure 1-10 shows an example of the design of the final repository. The division of the repository into different areas (four in the figure) is dictated by adaptation to the fracture geometry of the rock and the demand that reception and deposition of the canisters must be separated from other activities in the repository, such as blasting and sealing.

1.9.2
Elevator transport down to the final repository

After the finished canister has been subjected to the last inspection, it is transferred to a transport wagon running on tracks in the discharge section of the encapsulation station. The canister is placed vertically on the wagon and is provided with a certain amount of radiation shielding downwards and to the sides. The material thickness at the top end of the canister is greater and no extra radiation shielding is therefore necessary.

A permanently mounted drive system outside the elevator moves the wagon into the elevator. A locking system inside the elevator then secures the wagon in position.

When the elevator has reached the bottom level, the wagon is withdrawn from the elevator cage, the canister is collected by the deposition vehicle, and the elevator with the wagon then returns to the upper level. In order to ensure that no canister will be left standing in the final repository in the event of operating disturbances, the canister is not lowered down into the final repository until the deposition hole is ready and has been lined with bentonite and until the deposition vehicle is in the receiving position.

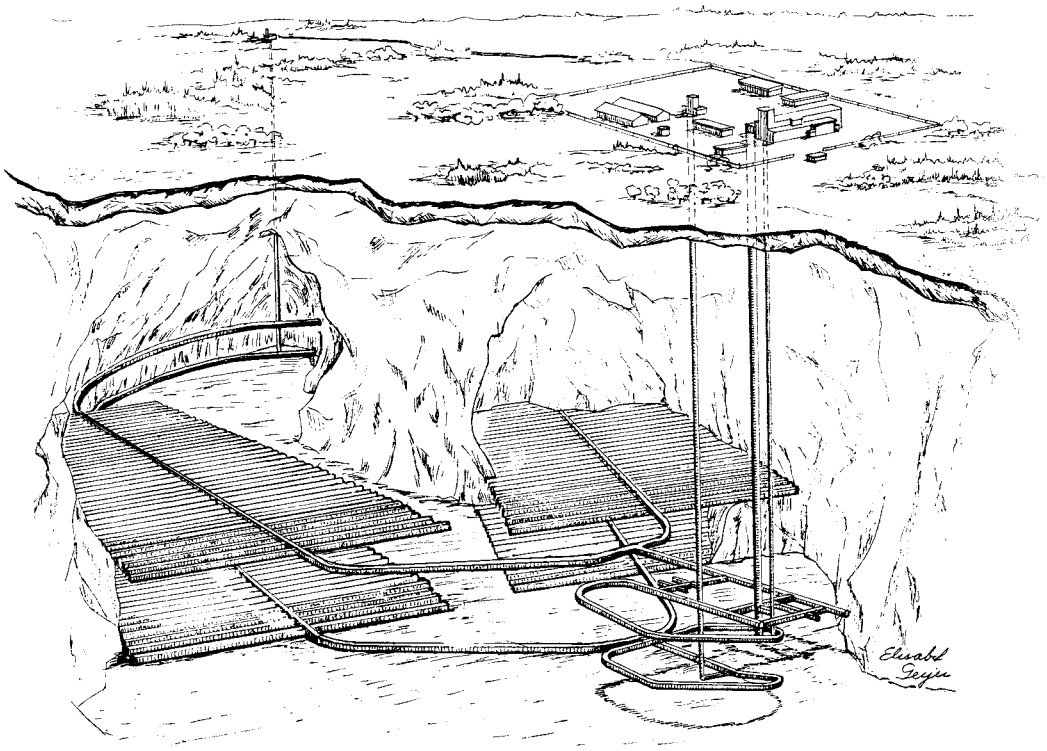


Figure 1-10. Final repository. Siting example.

The elevator is driven by a friction drive across a drive disc with a diameter of approx. 3 m and is guided in the shaft by permanent guides. The cables are designed with a factor of safety of 10 and the load is distributed onto a large number of cables. The cables are secured to the elevator cage by means of at least two mutually independent load-carrying systems. This also applies to the mounting of the counterweight.

The drive system is equipped with several independent braking systems, at least one of which acts directly on the cables. The building structure is designed to be capable of withstanding failure of the drive disc shaft. The building is also equipped with friction-type overtravel protection.

The shaft is equipped with a ladder for inspection and service and also for access if the elevator cage or counterweight should become jammed. If the elevator should contain a canister in the latter case, the radiation shielding of the elevator wagon permits access for fitting additional radiation shields.

1.9.3
Reception and transport of the canister in the final repository

Reception, transport and deposition of the copper canister are carried out by means of a specially designed deposition vehicle. Figure 1-11 shows an outline of the procedure. The vehicle is designed in a similar manner to an articulated truck. Due to the articulated steering, the manoeuvrability of the vehicle is very good, even in very tight turns, such as at the entrances to the deposition tunnels. The front of the vehicle is occupied by the propulsion machinery and the driver's cab. The rear section contains the following equipment:

- Radiation shielding drum. This drum surrounds the canister during transport and deposition and provides an effective radiation shield. The drum is equipped with lifting machinery, including the connecting devices necessary for raising or lowering the canister. The connecting device is guided towards the inside of the drum and grips the recess in the canister lid. During transport, the open end of the drum is shut off by a radiation-shielding steel cover fitted to the vehicle. The surface radiation dose rate on the cylindrical surface of the canister is below 60 mSv/h, which can be seen in Appendix 4. There also the dose rates at various distances from the canister can be found. A steel drum with a thickness of approx. 10 cm and a neutron radiation shield with a thickness of 10 - 15 cm will restrict the dose rates at the sides of the deposition vehicle to approx. 0.1 mSv/h (10 mrem/h).

- Boom. This is hydraulically operated and is used for manoeuvring the drum into various positions, ranging from horizontal (transport position) to vertical (lifting position) as shown in Figure 1-12. During the time when the boom is in operation, the canister is inside the drum, and maloperations can therefore be attended to manually.

- Support beam. This is equipped with two hydraulic outriggers which support the rear section of the vehicle in the lifting position. When the outriggers are lowered, the rear section of the vehicle can be moved in different horizontal directions within a limited area. This displacement is carried out hydraulically and with high precision, and is utilised for centring the drum over the canister (when collecting a canister) or over the deposition hole. Adjustment can be carried out with the drum in the raised position. Various transmitters incorporated into the bottom end of the drum are utilised as guiding aids.

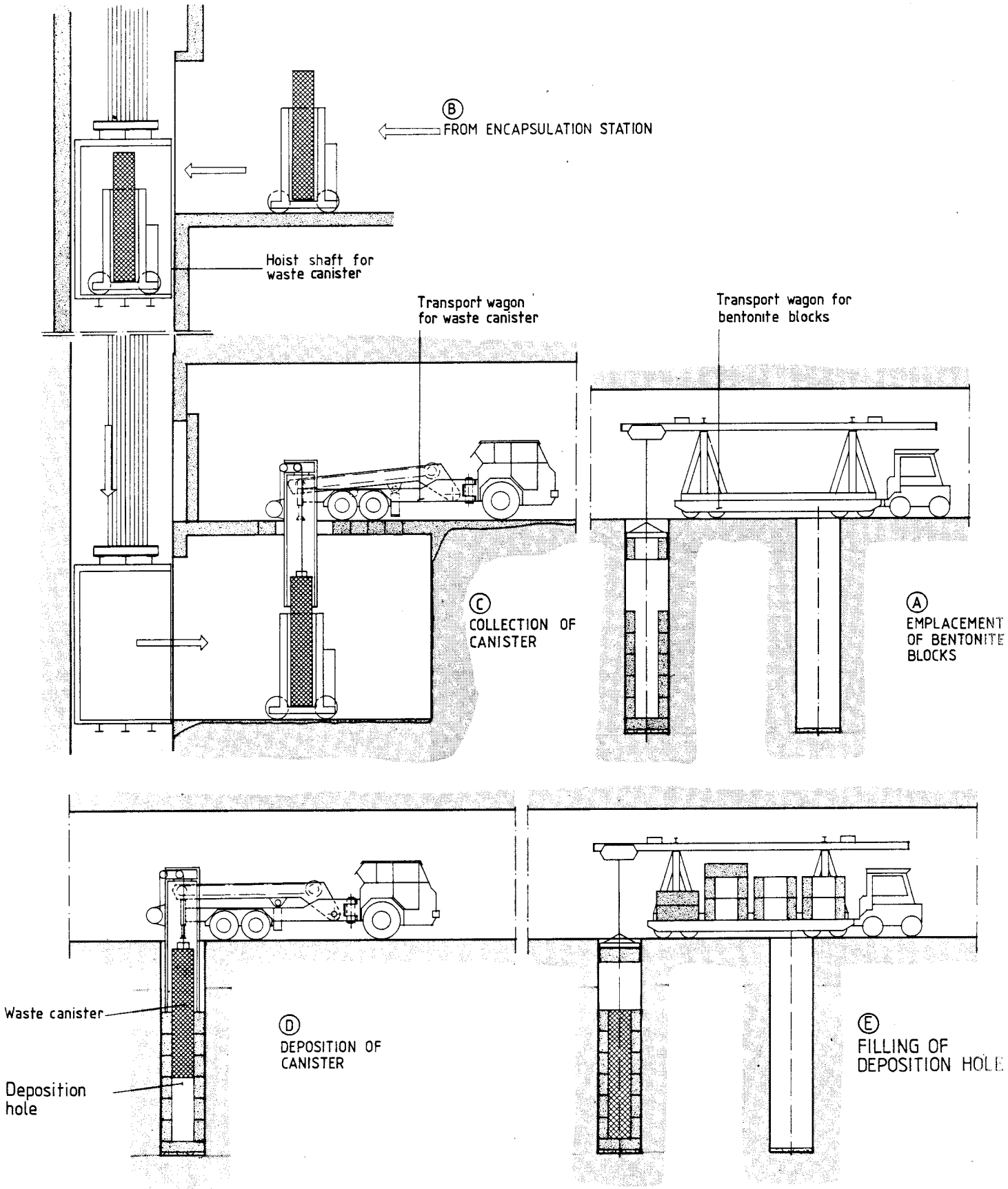


Figure 1-11. Handling of waste canister in the final repository.

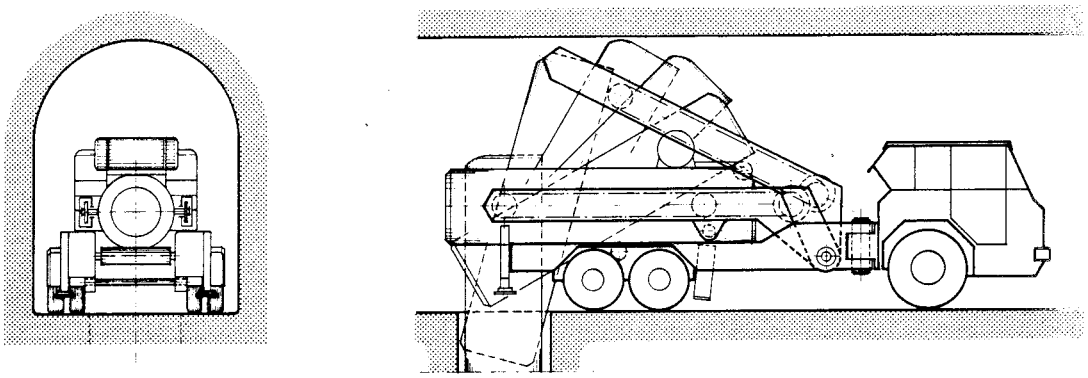


Figure 1-12. Deposition vehicle for copper canister.

As shown in Figure 1-13, the repository can be sectionalised into two completely separate parts by means of suitably located doors. This enables the handling of canisters to be separated from other activities, as mentioned earlier.

The deposition vehicle is a rubber-tyred vehicle and requires a smooth surface on which to operate. The floors of the central tunnels are therefore covered with asphalt, which is removed before sealing. Steel floor plates are provided along the entire lenght of the deposition tunnel in which activities are in progress. After completion of deposition, these floor plates are moved to the next tunnel.

1.9.4
Deposition

A thin concrete slab of approx. 3 x 2 m is cast on the tunnel floor before drilling of the deposition hole is started. The slab is removed before the deposition hole is sealed. The slab is primarily designed to provide protection against water running into the deposition hole, but will also serve as a support for the outriggers of the deposition vehicle.

Before deposition, the hole is prepared by bentonite blocks being lowered into it as shown in Figure 1-11. A dummy canister made of sheet steel is used for centring the blocks. The top bentonite block is provided with temporary edge reinforcements of steel, to protect the bentonite block against damage when the canister is lowered and to guide the canister. The guiding action is not mechanical but is achieved by the edge reinforcement being provided with transmitters that give readings on the guiding instruments on the radiation shielding drum. The edge reinforcement is raised with the drum by means of a number of electromagnetic lifting points, after the canister has been lowered into the hole.

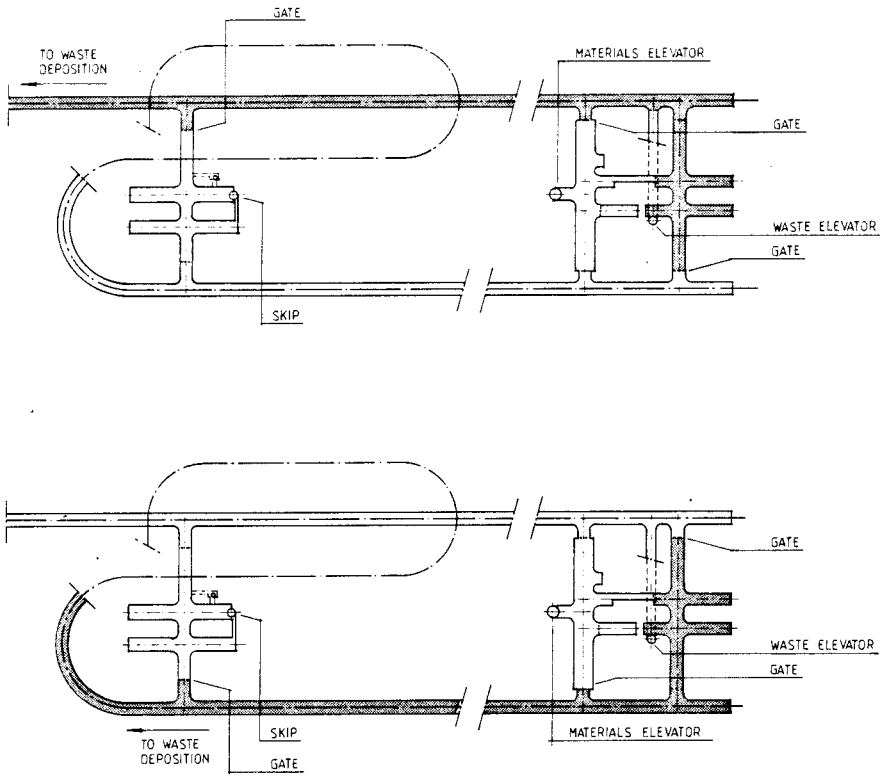


Figure 1-13. Final repository.
Partitioning system for the separation of waste handling from other activities.

When the vehicle arrives at the deposition hole, coarse alignment is carried out by the driver manoeuvring the entire vehicle. The outriggers are then lowered onto the concrete slab and the drum is raised while being simultaneously lowered into the hole. This enables the height of the tunnel to be utilised fully. When the drum is locked in the raised position, fine adjustment is carried out in the horizontal direction in accordance with the procedure described earlier, and the canister is then lowered. After the drum has been lowered a couple of metres down into the hole, the entire process will continue with satisfactory radiation shielding and manual action can be taken, if necessary.

When the deposition vehicle has returned, the canister is covered with a number of additional bentonite blocks, and the tunnel is then accessible without limitations due to radiation.

1.10 Mechanical strength of the canister

A study of the mechanical strength of the canister when it is subjected to pressure in the deposition hole is presented in Appendix 5.

2
PRESSED COPPER CANISTER

2.1
Introduction

Hot isostatic pressing of waste, from which the acronym HIPOW has been derived, was first suggested in 1976 for the efficient anchoring of long-lived radioactive waste in bodies very resistant to corrosion. The purpose has been to offer an alternative technology for efficient densification and containment of waste forms which are difficult to process in various respects.

Apart from the ability to fully densify powders at a relatively low temperature the process has also another important feature from an environmental point of view. The metal container with the waste products can be hermetically sealed at a comparatively low temperature. The heating up to the temperature for the final compaction is then done with a support of a high outside pressure in a gas tight container preventing any release of radioactive dust. This is a problem in conventional hot pressing, in sintering and also in waste glass fabrication. In these processes the high temperature process equipment is inevitably contaminated by fumes and dust while the HIPOW process offers a possibility to keep the high temperature equipment free from lasting contamination.

Small scale tests since year 1981 and larger scale tests in 1982 and 1983 imply the feasibility of the HIPOW process be used for encapsulation of spent nuclear fuel.

Because of the limitations of the hot isostatic press available at the laboratory, the tests were made by using seven simulated BWR fuel bundles with reduced length, 1.6 m. The simulated fuel contained all BWR components but the fuel pellets which mere simulated by steel rods.

2.2 Hot isostatic pressing

Hot isostatic pressing is a versatile and powerful technique to sinter, bond and densify particulate or porous materials to virtually completely pore free bodies. While the material is heated to the selected temperature, pressure is isostatically applied by a high pressure gas, usually argon, acting on all surfaces of a hermetically sealed container encasing the material to be processed. Temperatures of 50-70% of the material's absolut melting point are generally sufficiently high to yield fully dense compacts during this processing due to the tri-axial action of the high pressure gas. Typical pressure level is around 100 MPa and time at full pressure and temperature is 1-6 h depending on size and thermal conductivity.

Examples of current industrial production is the manufacture of high speed tool steels, of discs for jet engines of super alloy materials and eliminating of porosity in cemented carbide material and in castings.

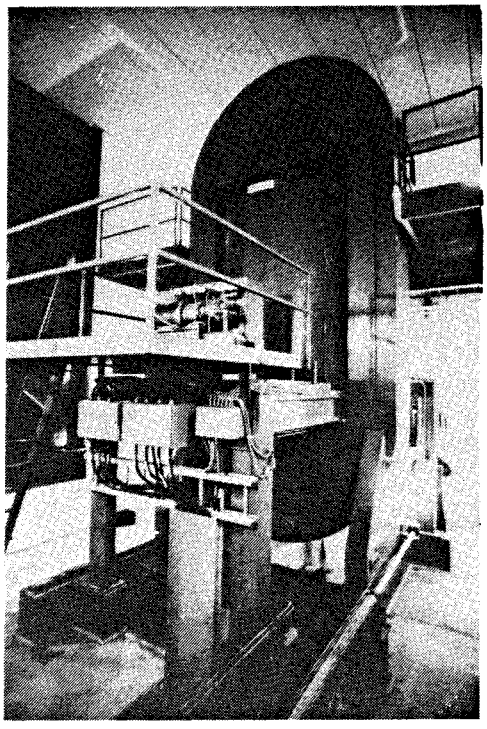


Figure 2-1

Hot isostatic press with appr. 2 m^3 work space at max 2000 bar pressure and 1260°C temperature. The press is of ASEAs QUINTUS^R-type with wire wound pressure cylinder and frame giving a very high degree of safety.

The equipment used, a hot isostatic press, consists of a furnace inside a pressure vessel with water-cooled walls (Figure 2-1). A suitable pressurizing gas, usually argon, is pumped into the pressure vessel while the furnace is electrically heated to the processing temperature. The high pressure gas acts isostatically on all external surfaces of the container. This is a very efficient hot pressing technique and can without difficulty be applied also on large bodies.

Hot isostatic presses may be loaded and unloaded either from the top or the bottom. In the case of press installations for high production bottom loading is often the most suitable. The charge is in this case standing on the bottom insulation of the furnace and transferred by a railbound manipulator. Preheating or cooling stations are often installed along such a manipulation line, which of course is remotely operated even in normal industrial production.

2.3 Copper

2.3.1 Copper material

Copper is a reddish coloured ductile metal and a very good conductor of heat and electricity. The most important copper ores are the sulfides, oxides and carbonates. But due to the precious properties of copper metal it also occurs native in some deposits. Copper does not react with water free from dissolved oxygen and for reducing conditions dissolved sulphide. The solubility of copper metal in water is also extremely low. In deep ground water where no free oxygen is present, copper is extremely corrosion resistent. The findings of very old native copper nuggets in nature also prove its corrosion resistance in a geological time scale.

In most cases produced copper has a thin shell of oxides on the surface. The oxides on the metal are formed when copper is stored in air at room temperature or in some cases during the manufacture. At elevated temperature copper oxidizes in air to Cu_2O and CuO but at temperatures below 400°C the formed oxides prevent a fast oxidation. Oxidation in dry air at room temperature is extremely slow but in moisture a shiny copper tarnishes gradually. As a consequence even high purity copper contains some oxygen and this is accentuated for copper powder storaged for long times in air.

Molten copper easily dissolves oxygen that reprecipitates as Cu_2O at cooling. Molten copper at a temperature of 1100°C can dissolve 0.5% oxygen in the liquid metal phase. In solid copper the solubility of oxygen is very low and diminishes with the temperature. At a temperature of 800°C the solubility of oxygen is about 3 ppm and at 500°C only 0.02 ppm. From the given values its is clear that even extremely pure copper contains a small quantity of a second oxide phase.

In order to give a good metallic bonding between copper blocks or powder at HIP, surface oxides must be removed, which can be done by washing in acid or by reducing the oxide to copper by means of hydrogen or some other reducing gas at elevated temperatures. Copper oxides can easily be reduced by hydrogen at temperatures above 250°C. The equilibrium between copper oxides and hydrogen is strongly tilted to formation of metallic copper and water vapour. Thus for a complete reduction of any copper oxide within copper only an equivalent amount of hydrogen is necessary. Further the reduction must be run at temperatures where the reaction rate is satisfactory.

The solubility of hydrogen in copper is very low and depends on hydrogen pressure and temperature. With a hydrogen pressure of 1 atm at 500°C copper will dissolve only 0.1 ppm hydrogen. Therefore pure copper will not be contaminated by treatment in hydrogen.

Many interrelated factors influence the reduction of copper oxides in copper by hydrogen. Surface oxides are easily reduced and then formed water vapour escapes. Hydrogen readily diffuses in solid copper and reacts with present oxides but the formed water can not readily escape by diffusion. It must either escape through formed fissures or it forms internal cavities in the copper body. It is therefore wise to use copper with a low internal oxygen content as a hydrogen treatment can result in some confined water in the material.

2.3.2 Copper powder

In all HIP of powder a high tap density is to be desired, as local and major deformation thus can be minimized. In this case a strange composite of fuel elements and copper powder is compacted and therefore exaggerated deformation of the fuel should be avoided in order to keep the fuel confined within the zircaloy tubes. A high tap density of copper powder can be obtained by mixing a coarse grade of 700-800/um powder with a fine grade of 100-200/um spherical powder. A powder density of up to 82% of theoretical was reached at tapping. Large and heavy containers might be difficult to tap efficiently and thus decreases the density, but on the contrary a high and heavy powder column might improve the tap density.

Solid copper compacted by HIP from powder has a high strength and ductility only if the used powder is free from surface oxides. However, it is difficult due to lack of a commercial market to get a copper powder with a high metallic purity and a low content of oxygen and phosphorus. Spherical copper powder is mostly produced by water or air atomization and thus oxygen content between 1000 and 2000 ppm is regularly found. HIP densified copper powder with surface oxides present gives a low ductile copper. However, surface oxides on copper powder can easily be removed by treatment in hydrogen at elevated temperature and thus normal mechanical properties are obtained of the densified materials.

By cooperation with Eckart-Werke, West Germany, a high purity argon gas atomized copper powder was obtained with a low oxygen content. The production was made in a pilot plant scale with batch size of 70-80 kg. The powder was spherical and gives a high tap density.

The powder quality used in the large scale encapsulation of fuel elements was a mixture of 60% coarse powder made from wire by cutting, type Alcan 23 HP, and 40% argon gas atomized spherical powder of type Ecka AK 91. The mixture gave a tap density of approx. 80% in the large canister.

2.4 Tests carried out

2.4.1 Tests with HIP

In total a large number of canisters in laboratory scale have been processed for test of different process and material parameters.

To test and demonstrate the embedding of fuel elements in copper, canisters in close to full scale have been processed. Two canisters with a diameter of 600 mm and a length of 1850 mm with a total weight of 4300 kg have been pressed. These canisters have been designed to contain seven elements of BWR-type. Components in such a canister are shown in Figure 2-2. The elements were placed in a copper container with a wall thickness of 60 mm. The space between the elements and the container wall was filled with copper powder, which also surrounded each of the fuel rods as well as any void inside the container. With three elements centrally and two on each side the inner diameter was 490 mm. The outer diameter of the thick-walled copper container was 610 mm. The end lids of 100 mm thickness and the joint between the lids and the container were made in stepped design. This increases the joint length and also decreases the tendency of the central deflection of the closure.

The pressed canisters were investigated where mechanical properties and metallurgical defects of HIPed material are set in relation to HIP parameters. Most suitable HIP parameters are 150 MPa in pressure and 500°C in temperature during 6 to 10 hours.

2.4.2 Mechanical properties

Test samples of HIPed powder have given strength and ductility in level with OF copper in annealed condition. Tensile tests of the HIPed joints have given slightly lower level than for the homogeneous material.

	Yield stress N/mm^2	Ultimate strength N/mm^2	Elongation %	Reduction of area %	Hardness
HIPed joint	86	197	32	25	56 HB
HIPed powder	103	229	45	63	81 HV_{10}

2.4.3
Metallurgical examination

The copper material in the thick-walled container and the end closures were forged from ingot. A polished surface from forged material is outside the joint free from pores or slag inclusions, Figure 2-3. Etching in 10% ammonium persulphate shows the microstructure of the forged material. The end closures show a crystal size of 500 to 1500/um turned-in with recrystallization twins which is normal for forged and heat-treated material, Figure 2-4. The pipe shows a crystal size of 200 to 500/um due to higher reduction in forging. A cold worked surface is favourable for the quality of the resulting HIP-joint. To get cold worked and cleaned surfaces for joining, the areas were brushed with a rotating copper brush. This worked the surface layer to fine grain size and after HIP a regular structure of fine grain size 2-5/um was obtained, Figure 2-5.

Copper powder compacted by HIPing is shown in Figure 2-6. Previously the mixing of two fractions of powder is explained. On an etched surface of HIPed powder the coarse grade was seen as round areas of 700/um with irregular crystals of 20 - 80/um size. Embedded in between these coarse grade granules are the fine grade granules which shows slightly lighter crystals of 5 - 20/um. On a polished surface small voids < 2/um were noticed. The copper oxide reduced by hydrogen has formed water. In case the formed water was inside a copper granule it can not easily leave the metal even during evacuation. This makes the copper compacted from powder sensitive for hydrogen embrittlement. One way of avoiding the hydrogen embrittlement is to start with powder of a very low internal oxygen content.

Handling and production of copper powder with a controlled low content of oxygen is due to the limited market but would be the shortest way to solve the problem.

2.4.4
Deformation of canister and embedded fuel during HIPing

Compaction of the copper powder and the canister surrounding the simulated fuel effects the internal distance between fuel elements. An uneven deformation of the fuel tubes, especially at the stiff end plates, was foreseen. At the gas filled fission gas plenum a stronger deformation was obtained but with a preserved void inside the spring.

In the compacted canister the elements were bent towards center line. The bending was regular and limited. Most peripheric elements had a relative bending of 12 mm. The relative bending decreases for elements in the center of the canister. Most bending of the fuel rods was found close to the end plates and decreased with distance from the ends. The spacers did not significantly effect the deformation of the elements. The zircaloy tubes were compacted to close contact with the simulated fuel. Figure 2-7. In the area of the fission gas plenum the zircaloy tube was compacted close to the spring but the spring was kept relatively undeformed, an advantage for internal confinement of the continued slow production of fission gas.

The HIPed canister (Ø 600 x 1800), Figure 2-8, was carefully measured after HIP. A shrinkage of 4% of the diameter along the length of the canister filled with powder was noted. The axial shrinkage was just 1% due to the higher axial stiffness. A central deflection of the top end plate was notable.

2.5 Discusson

The large-scale canisters confirm the function of the developed technology based on hot isostatic pressing. The powder material has, by using inert gas atomized powder, been densified to 99.7% of the density of high purity forged copper. Oxygen and hydrogen contents in the powder material are, however, higher than specified for OF copper. This seems not to effect the mechanical properties at room temperature. The pressed canisters are splitted both diametrically and axially to demonstrate the location of the embedded fuel elements (Figures 2-9 and 2-10). The good bonding between lid and forged canister has been controlled with ultrasonic tests. A failure would directly be indicated, why the ultrasonic test will be a reliable test method for HIPed canister.

Figure 2-2. Components used in a nearly full scale test. From the left: lids, seven non-active fuel bundles of BWR type, thick-walled copper container, thin-walled sheet container, copper powder and sheet lid with evacuating tube.

Figure 2-3. Polished surface of HIPed joint.

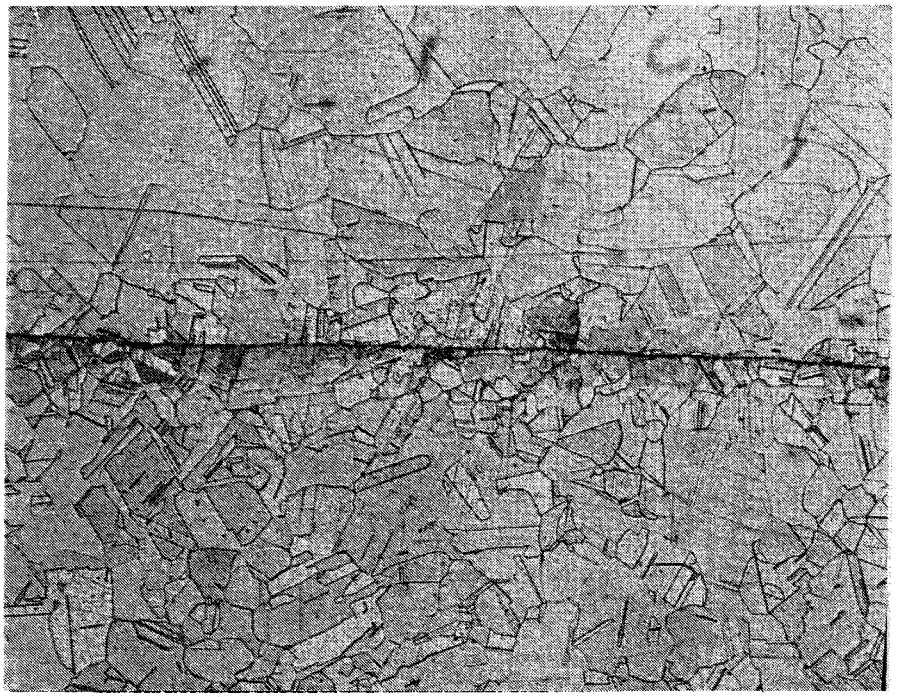


Figure 2-4. Etched surface of HIPed joint. The same area as in figure 2-3. Lid material on top and cylinder material under the joint. 50 x.

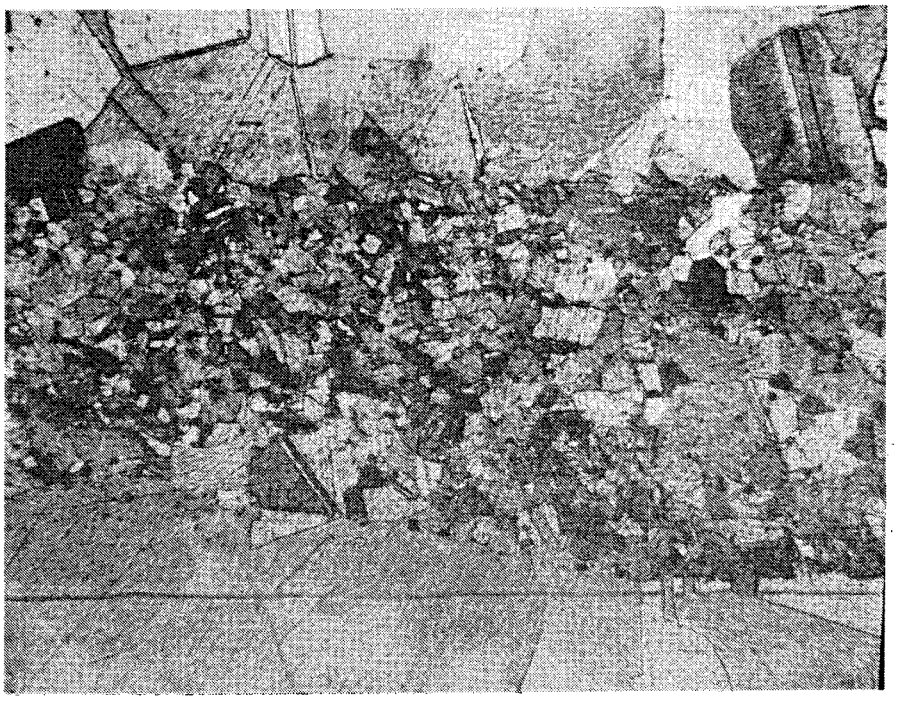


Figure 2-5. An etched area of a brushed joint. The brushing has made the structure fine-grained. 400 x.

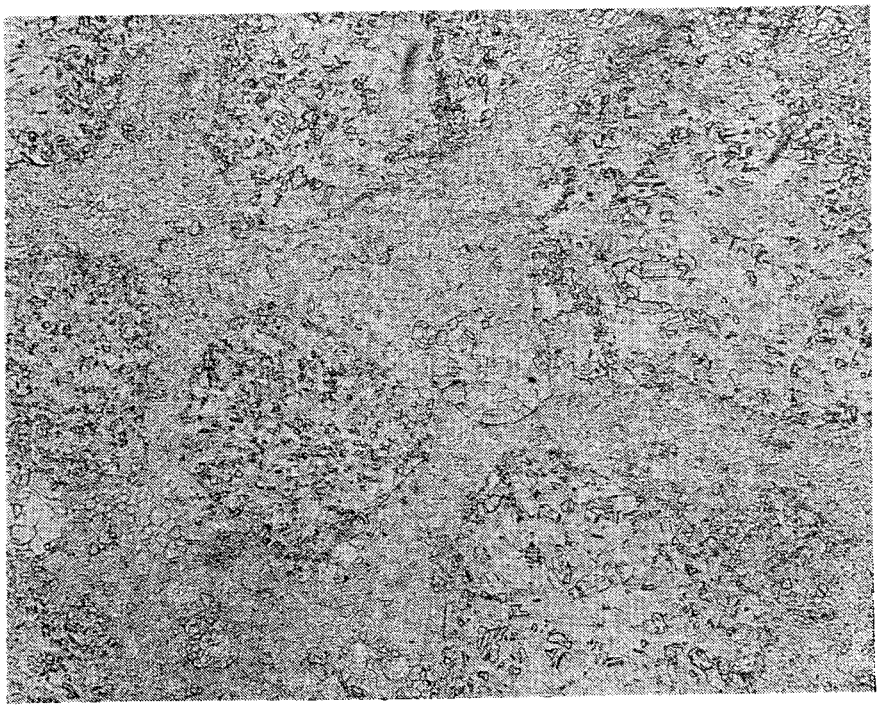


Figure 2-6. HIPed copper powder, mixed of a coarse and a fine grade of powder.

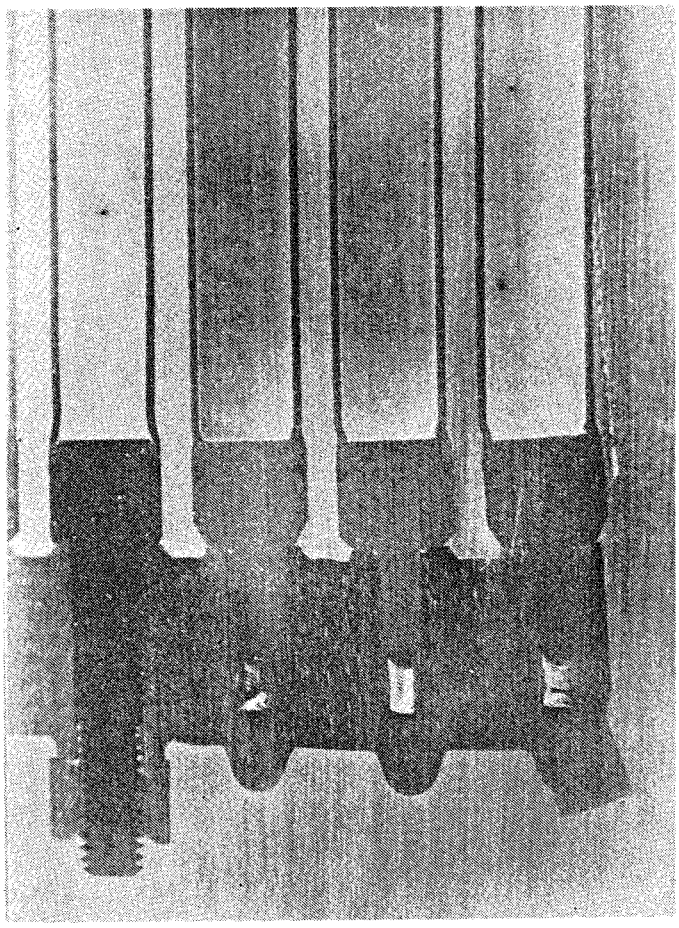


Figure 2-7. Fuel bundles embedded in copper.

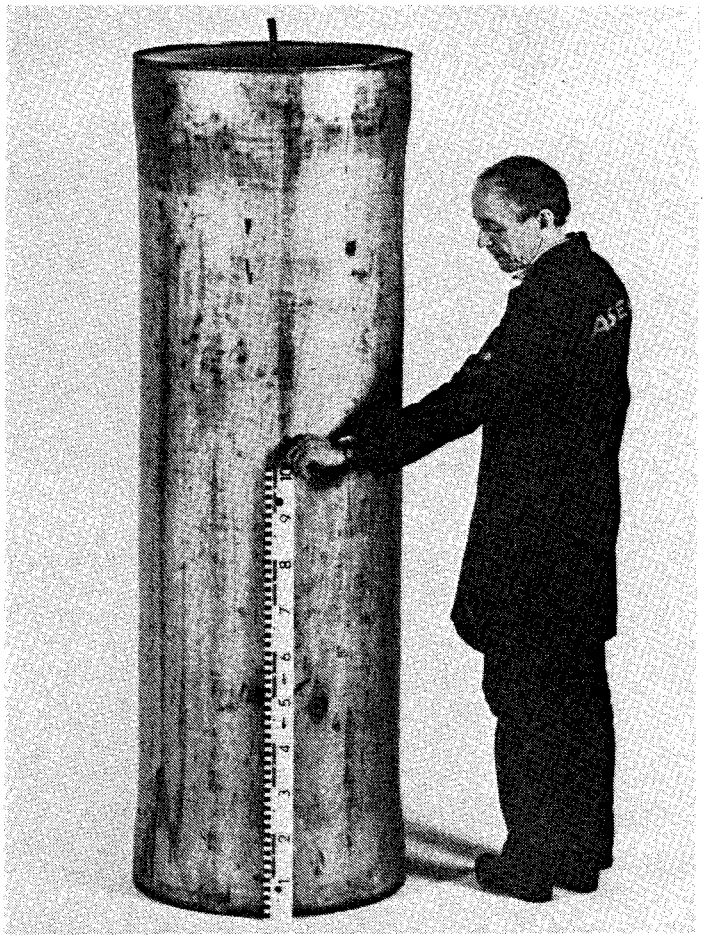


Figure 2-8. A HIPed canister with seven shortened simulated fuel bundles of BWR type embedded in copper. Dimensions Ø 600 x 1800 mm. Weight 4300 kg.

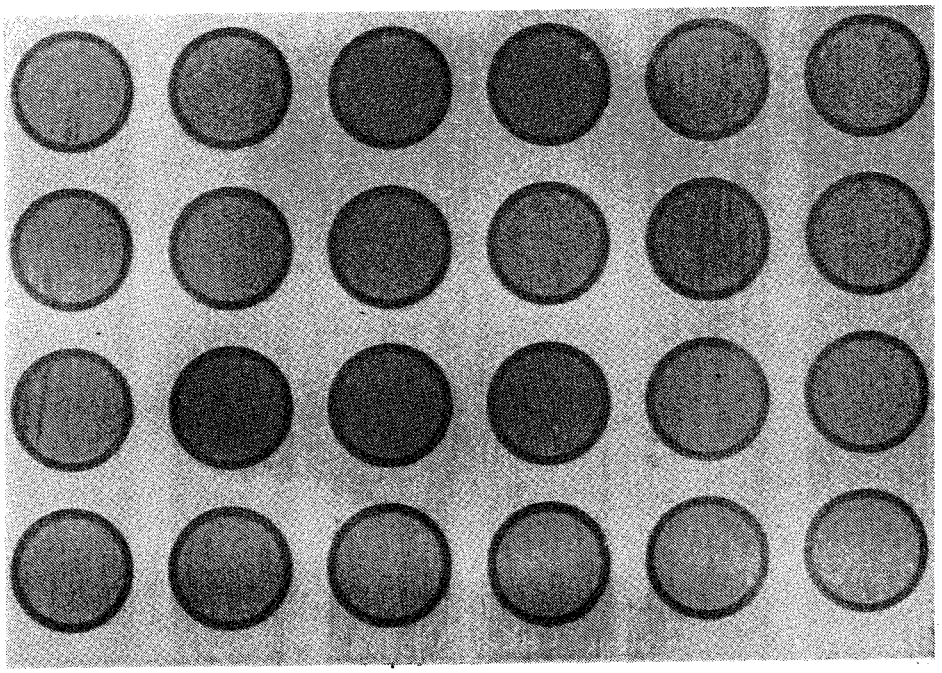


Figure 2-9. Non-active fuel rods embedded in copper.

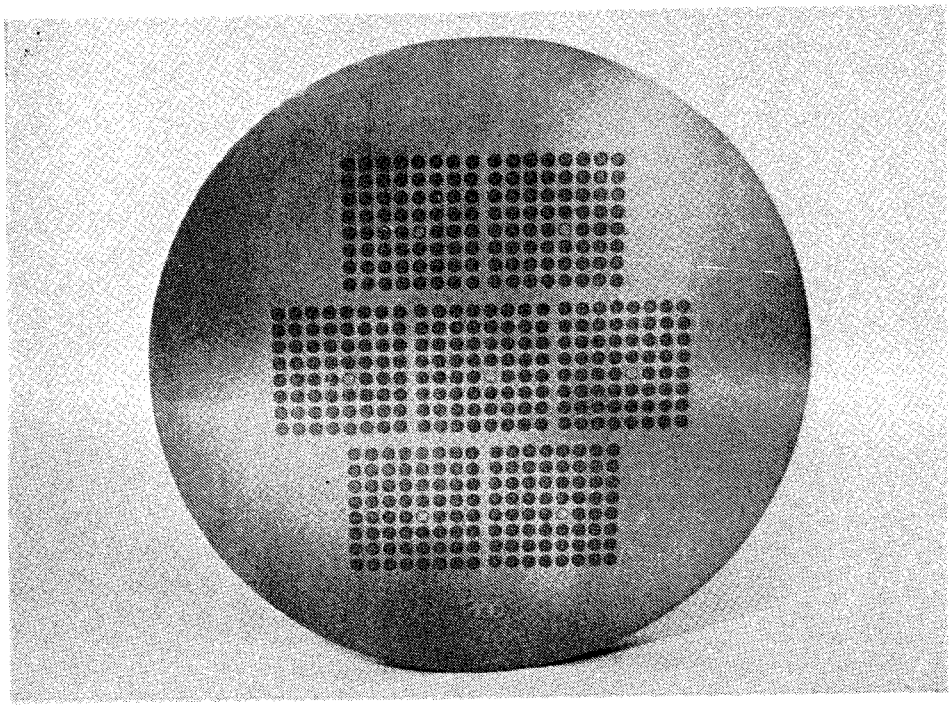


Figure 2-10. Diametric cut of a canister with fuel bundles embedded in copper.

2.6 The copper canister

A design of a copper canister is shown in Figure 2-11. This consists of a cast and forged cylindrical shell which is turned to the correct shape. The closure of the canister has three covers: a main cover, an inner sealing cover and an outer sealing cover. The thickness of the main cover is 200 mm. After isostatic pressing the material at the joint will also have the same thickness. The finished canister thus forms a solid copper shell with a thickness of at least 10 cm at all points around the contents.

The inner and outer sealing covers are seal-welded to weld lips in the cylinder material. The inner cover forms the seal during hydrogen conditioning of the copper powder. This conditioning is carried out to remove any oxide film on the copper powder, since such a film could otherwise prevent fusion of the powder into a homogeneous metal. The cover also serves as a seal if the fuel should produce leakage during pressing. A major gas leakage may impair the vacuum to such an extent that an unsatisfactory joint will be obtained between the cover and the cylinder. Although the probability of more than one or a few rods in the fuel content leaking is minimal and the gas emitted from such an amount is negligible, the cover has been introduced as an extra precaution to ensure a good end product. The sealing cover prevents any such leaking gas from reaching the joint surfaces of the main cover.

The outer sealing cover forms the pressure-tight layer when the press load is applied in the Quintus press. It also provides a seal during hydrogen conditioning of the joint surfaces between the cover and the canister.

2.7 The encapsulation process

The handling is shown schematically in Figure 2-12.

2.7.1 Assembly of the fuel bundles into encapsulation units

In the buffer pool, eight BWR bundles or two PWR and two BWR bundles are assembled in a rack into a unit that will fit into a copper canister. The rack consists of a bottom grille into which the bottom plates of the fuel bundles fit, a column that interconnects the bottom grille with a top grille and that transfers the lifting force to the bottom grille, and the top grille that holds together the top plates of the fuel bundles. The column may be in the form of a perforated tube or a number of tie rods.

Two types of racks are necessary, i.e. one for the eight BWR bundles and one for the BWR/PWR combination.

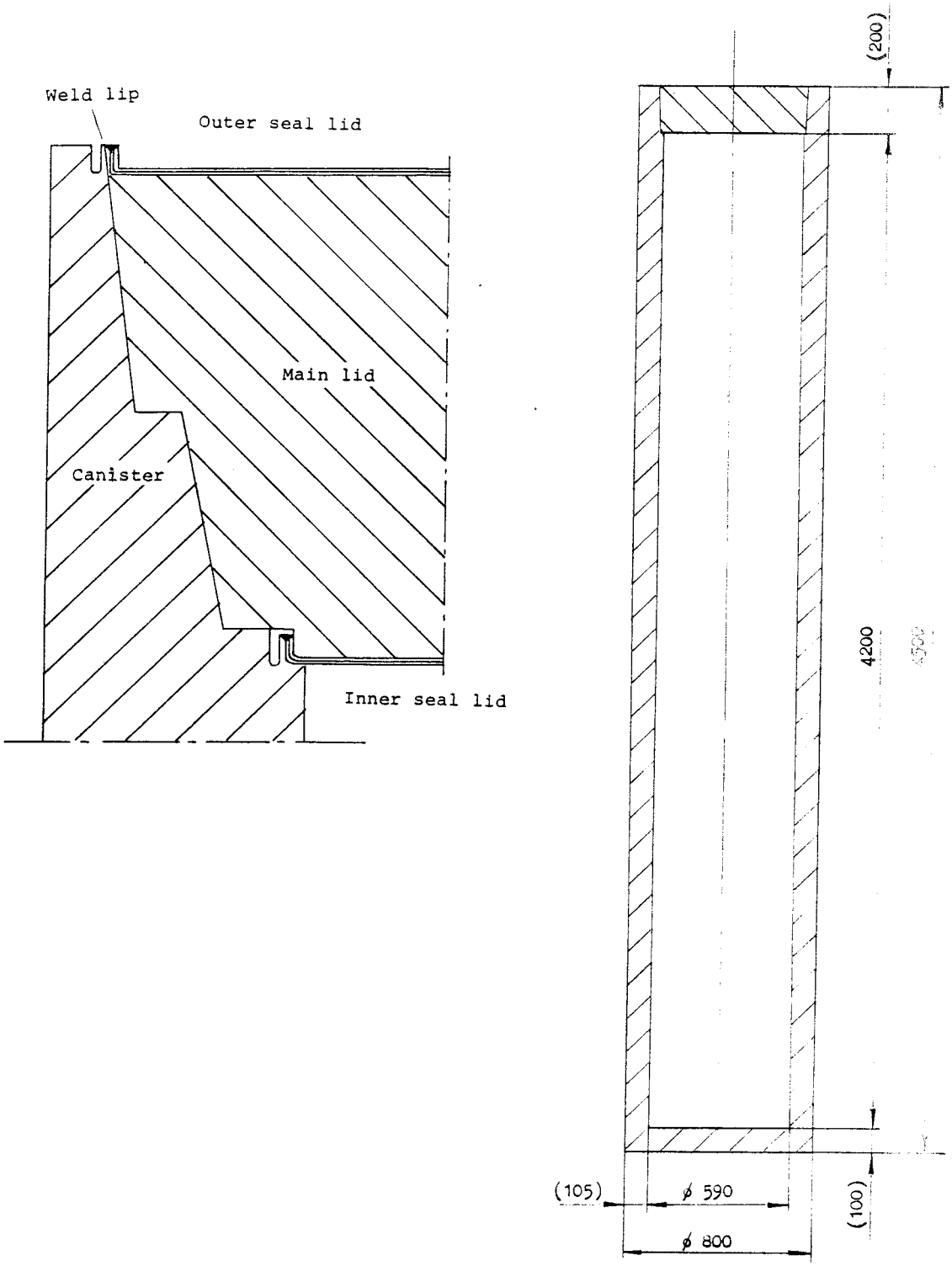
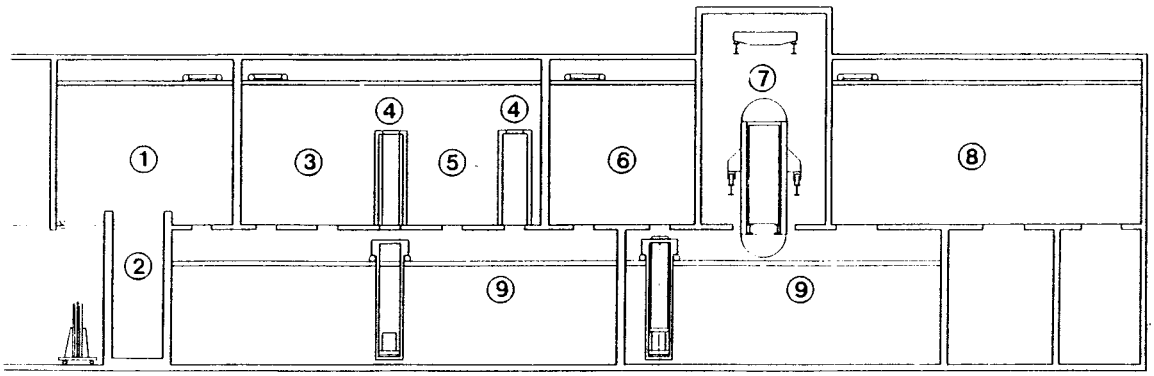


Figure 2-11. Canister for hot isostatic pressing with detail of lid joint.



1. Drying cell
2. Drying chamber
3. Copper powder storage. Application of inner seal lid
4. Hydrogen conditioning furnaces
5. Application of main and outer seal lids
6. Transfer cell
7. Quintus press for hot isostatic pressing
8. Exit and control
9. Transport ducts

Figure 2-12. Fuel and canister handling in the encapsulation part. Canister for hot isostatic pressing.

The rack is placed in a position which is designed so that the bottom plates will be guided into the correct position in the grille. The top ends of the bundles are moved towards the top grille and are snapped in position. The rack with the fuel is then placed on the lock wagon for transport into the encapsulation section.

2.7.2
Lifting the fuel out of the pool and drying

The fuel in its rack is lifted from the lock wagon into the drying cell by the overhead travelling crane of the cell. Water is allowed to run off the fuel, and the fuel is then transferred to the drying chamber.

The drying cell and the succeeding rooms used for the process up to the Quintus press are filled with an inert gas, preferably nitrogen. The advantage of this is that oxidation of the copper powder is avoided, which reduces or, in the best case, entirely eliminates the need for hydrogen conditioning of the powder. However, a conditioning stage for the powder in the canister has been included in the following description, although this stage may be excluded at a later date.

The fuel is placed in the drying chamber. The most important function of the drying process is to ensure that any water that may be contained in damaged fuel rods will boil away. Any such water may otherwise disturb the encapsulation process. It is also vital to the filling of the copper canister that no water drops or accumulations of water remain in the fuel bundles.

The decay power in the fuel is very low. It would take a fairly long time and would demand good insulation for the fuel to attain autogenously the temperature necessary for drying, e.g. 150°C. Electrical or gas make-up heat raises the temperature, and a circulating current of nitrogen removes the steam and any other gases. In order to avoid the spreading of activity, the drying chamber should be sealed with a cover. The gas flow circulates through a fan, preheater and drying chamber, and is then bubbled through a water bath for removal of any moisture and for cleaning. The water bath requires a clean-up system and a cooler. It is expected that one gas system will be provided for each drying chamber, with common cleaning.

The drying time should be about 24 hours. Three chambers may be used, which will provide a certain buffer function. However, a larger number of stations should not be employed, since this would lead to major rearrangements if the cell must be emptied for repairs.

Only one activity check is normally made for detecting any leaking rods. However, it should be possible to connect HEPA (high efficiency particulate air) filters into the gas circuit, if necessary.

The drying chambers will be equipped with flushing equipment and drainage. It should be possible to lift mobile brush equipment into the chamber by means fo the overhead travelling crane for brushing the drying chamber clean during flushing.

2.7.3 Charging the canister

An empty copper canister is moved to the transfer cell before the Quintus press and is placed on a canister wagon. By employing this procedure, the need is avoided for opening a sluice to the drying cell on every occasion. The transport passage includes two parallel tracks, each with its own wagon. The canister is then initially placed on a bottom plug designed to fit into the bottom of the furnaces for hydrogen conditioning. The wagon is moved into position under the drying cell.

The overhead travelling crane of the drying cell lifts the fuel into the canister.

The service area for the canister wagon is arranged adjacent to the charging station.

In order to avoid direct gas communication between the drying cell and further handling and thus to reduce the risk of the spreading of activity, the floor structure between the transport passage and the drying cell can be designed as an opening with a cover. The opening should be of such size and shape that, when the cover has been removed and the canister has been raised by means of the hoist of the canister wagon, only the inner surface of the canister will be exposed to the drying cell.

2.7.4
Filling with copper powder

The wagon is moved to a new station in the handling line, and the canister is then under the copper powder storage vessel. The storage vessel is equipped with a filling pipe with a valve. The valve may consist of a plug at the outlet from the storage vessel. In order to avoid spillage of copper powder, the filling pipe must project down into the canister. This may be carried out by raising the canister by means of the wagon hoist.

The powder level is monitored by closed-circuit TV in the equipment hall. A rough check of the copper quantity can also be made by weighing the storage vessel. Shaking gear raised from the floor below the wagon induces such vibrations into the canister that thorough filling will be assured. The bottom plug should be designed so that it will withstand the transmission of these vibrations to the canister.

The powder is produced in a plant located outside the cells. The powder is produced in an inert gas and transfer to the equipment hall is enclosed, so that oxidation of the powder will be avoided. Two grain sizes are used and are mixed before the powder is admitted into the copper canister in accordance with the specification (see Section 2.2).

2.7.5
Application of the inner sealing cover

In the next station, the canister is fitted with an inner sealing cover. The cover is in contact with the surface of the copper powder and connects to a weld lip in the canister. The cover serves as a barrier for the internal volume during hydrogen conditioning and as a seal when vacuum is raised. The sealing cover is equipped with a central evacuation pipe. It is collected by a pivoted arm in the equipment hall. The arm is telescopic and is equipped with a grapple which presses the cover into place. The cover is gripped by means of vacuum nozzles in a plate that centres the cover in relation to the weld lip. The outer shape of the plate corresponds to the seating surface for the main cover. When the plate is pressed down onto the weld preparation, the sealing cover will be in the correct position. The plate is provided with resilient supports that press against the top surface of the canister. Closed-circuit TV in the equipment hall is used for supervising the guidance and for carrying out any adjustments.

A pivoted arm serves both wagon tracks.

Welding of the cover is carried out in the same station. Welding equipment that is guided by the conical or cylindrical surface of the copper canister is lowered down onto the canister. As an alternative, the canister can be raised towards the welding equipment. The equipment includes a rotatable welding head that runs around the weld preparation. TIG may be used as welding method. No filler metal is necessary.

The welding equipment can also be used for re-welding if vacuum pumping reveals that the canister is not tight.

2.7.6
Hydrogen conditioning of the canister internals

The wagon is now moved to the hydrogen conditioning station, in which the canister is lifted into the conditioning furnace and is locked in position. The wagon is then free for other duties for a period of up to 24 hours during which conditioning takes place. The wagon can then be used for moving another canister from the second furnace to the transfer cell.

When the canister is moved into the furnace, the evacuation pipe passes through a pair of tongs and engages into a coupling for the gas pipe running to the hydrogen and vacuum equipment. The tongs are located immediately above the sealing plate. The design of the coupling will be subjected to special demands. It must be gas-tight and it must be either automatic or remotely controlled. The coupling must have a certain amount of freedom of movement for centring. The procedure is supervised by closed-circuit TV. In the same manner as the equipment hall, the furnace is filled with an inert gas (nitrogen), which prevents oxidation during subsequent heating.

The canister is heated electrically and the heater rating is approx. 50 kW. Hydrogen conditioning will start when the temperature has risen to 350°C.

The canister is evacuated. Vacuum is maintained for a certain period of time, so that the tightness of the sealing cover can be verified. This can be carried out either by monitoring the pressure or by adding helium to the inert gas and then detecting the content of helium in the gas piping during the continued vacuum-raising procedure. If leakage is detected, the canister is returned to the welding station.

Hydrogen which is saturated with steam is admitted through the gas pipe. Steam is added to counteract the tendency of the zircaloy cladding to absorb hydrogen and thus become embrittled. Although this risk is incurred primarily at higher temperatures than those employed in hydrogen conditioning, steam is added here as an additional precaution. The gas pressure is maintained at a value below atmospheric pressure, in order to avoid leakage of hydrogen from the canister. The hydrogen is evacuated after a certain holding time. The procedure is repeated until all oxide in the internals of the canister has been reduced to form water.

The number of cycles and the holding times will be determined by pilot tests. When the hydrogen is admitted into the canister, it is saturated with steam. When the gas is evacuated, it is cooled to a temperature somewhat below that at which it was admitted. As long as steam is formed by the conditioning procedure, the gas will be saturated after cooling. When all oxides have been reduced, the moisture content of the gas will drop and the process can be interrupted.

Raising of vacuum is the last operation in the conditioning procedure, and the evacuation pipe is then sealed. Sealing is carried out by means of the tongs. The tongs first nip and flatten the pipe. Heat is then supplied to fuse the pipe, either by electric heating of the tong arms or by separate heating immediately above the tongs.

The method will be coordinated with the corresponding operation described in Section 2.7.8.

The fundamentals of hydrogen conditioning are discussed in Section 2.2 and Appendix 3.

The hydrogen supplied to the canister is stored in gas storage equipment. The storage equipment should be located in a controlled area, since there is some risk that radioactive substances will be entrained when vacuum is raised and the hydrogen is returned to the storage equipment. On the other hand, the storage equipment need not be located in the equipment hall or some other strictly shielded part of the plant.

The hydrogen is allowed to bubble through a water bath, so that it will be saturated with steam when it is supplied to the canister. It is advisable to use the same water bath before the hydrogen is returned to the storage equipment. This will absorb excess water, and the hydrogen will be cooled and scrubbed, to remove most of the impurities, which will contribute to maintaining the storage equipment and the gas in clean condition. The water in the bath is circulated continuously through the waste system of the station, where cleaning-up takes place.

The risk of oxy-hydrogen forming is eliminated in the furnace and in the equipment hall, since they both have a nitrogen atmosphere. In this section, the hydrogen system is at subatmospheric pressure. Outside the equipment hall, parts of the system are pressurised. These rooms of the plant are provided with effective ventilation.

In view of the fact that some parts of the system are at subatmospheric pressure, nitrogen may leak into the system. The quality of the hydrogen should therefore be periodically monitored. If the nitrogen content should become too high, the hydrogen must be changed to ensure that the effectiveness of conditioning will be maintained.

An approximate calculation of the heat flow through the copper powder has shown that the temperature difference between the fuel and the canister surface will amount to a maximum of approx. 50°C. More accurate calculations may reveal that the difference will be about 10° lower. The fuel will thus not be overheated during the process, in spite of the poor thermal conductivity of the copper powder.

The number of furnaces necessary will be determined only after the hydrogen conditioning procedure has been decided. It is provisionally assumed that four furnaces will be necessary, i.e. two per wagon track. The hydrogen storage equipment should be common, although each furnace will presumably have its own vacuum pump.

2.7.7
Main cover and external sealing cover

From the furnace, the canister is transferred by means of the wagon to the station for fitting the main cover.

The evacuation pipe is cut and removed here. The main cover is then placed on the canister and an external sealing cover is placed on top of it.

The main cover and sealing cover can presumably be handled as a composite unit, if the tolerances can be maintained.

Two devices are provided in the equipment hall for these operations. Both devices serve both of the wagon tracks. One of these devices consists of a robot arm with a grapple and cutting tool. The evacuation pipe is cut off and removed by manual manoeuvring and is then placed in a container.

The second device lifts the main cover by means of a fixture comprising vacuum nozzles. The outer sealing cover is lifted by means of the same fixture or by a grapple that grips the evacuation pipe of the cover.

If the main cover and sealing cover are joined to form one unit, the grapple can lift the entire unit by the evacuation pipe and can then carry out all operations at this station. The outer sealing cover is pressed down so much that its edge is flush with the weld lip of the canister. This is achieved by the fixture or the grapple being equipped with a number of support points that are pressed down onto the weld lip.

All operations are supervised by closed-circuit TV.

The main cover fits into the canister with some clearance. The clearance is designed to allow for hydrogen conditioning and raising of vacuum in the space between the joint surfaces. The position of the cover is determined by the seal weld of the inner sealing cover.

The canister is very warm when the cover is fitted. As a result, due to the temperature difference, the outer sealing cover may be too small for the inside of the weld lip. But careful adjustment of the tolerances on the cover and canister will enable the sealing cover to come into the correct position when resting on the main cover.

The outer sealing cover is seal-welded in the same manner as the inner cover (Section 2.7.5). The equipment will be similar or the same and the procedure will be identical.

2.7.8
Hydrogen conditioning of the cover joint surface

After welding, the canister is moved to a furnace for a second stage of hydrogen conditioning. This is designed to remove oxides from the joint surface between the canister and the cover. The canister is lifted into the furnace and is locked in position. The wagon will then again be free for other duties. The time can be used for emptying the Quintus press and possibly for moving a charged canister to the first furnace as described in 2.7.6 above.

The procedure in the furnace is the same as that described in Section 2.7.6. Tongs for sealing the evacuation pipe and a coupling for the hydrogen and vacuum piping are provided. The top part of the canister is heated electrically to 350°C, using a heater with a rating of approx. 50 kW. Hydrogen is pumped in and out a number of times, and the joint space is finally evacuated and sealed. The procedure is supervised by closed-circuit TV.

In this case, the hydrogen need not be saturated with steam. However, if the same equipment is to be used, steam in the hydrogen will be in no way harmful. The necessary number of cycles and holding times will be determined by pilot tests. Any leakage can be detected when vacuum is first raised, in the same manner as that described in Section 2.7.6, and if leakage is found, the canister can be returned to the welding station for corrective action.

The evacuation pipe must be cut and removed before the hot isostatic pressing process. The canister is therefore returned to the cover station (Section 2.7.7) which is provided with the equipment necessary for this operation.

The canister need not be cooled. Although its external surface will be oxidized when the canister is lifted out of the nitrogen atmosphere in hot condition into the air in the transfer cell, this is of no significance for the continued process. The residual heat is also advantageous in the succeeding HIP operation, where the canister must be heated.

A furnace must be provided for each wagon track. The furnaces have separate vacuum pumps but have common gas storage equipment. The gas storage equipment may be the same as that used for the furnaces described in Section 2.7.6, unless it is required to separate them due to the risk of radioactivity in the gas from the operation described in Section 2.7.6.

The risk of oxy-hydrogen forming has been discussed in Section 2.7.6.

2.7.9
Transfer

The wagon moves the canister from the conditioning furnace to a transfer position under the transfer cell. The opening with this cell is fitted by means of a cover which is open only when the canister is to pass. Other communications of the cell to the next transport wagon and to the store for new canisters are also shut off by covers. There is thus no direct communication between the nitrogen atmosphere and the surrounding rooms, and this prevents the leakage of any radioactivity and restricts the consumption of nitrogen.

The transfer cell is provided with an overhead travelling crane designed to grip the top part of the canister. The canister is provided with a thicker section which is used for all such lifting. The crane lifts the canister up into the cell, the cover is closed, the canister is moved into position above the new wagon, a new cover is opened and the canister is lowered onto the wagon. This wagon is of the same design as the preceding wagon, although it is provided with a bottom plug designed to fit the Quintus press. The canister is now in an air atmosphere.

2.7.10
Hot isostatic pressing (HIP)

The wagon moves the canister into position under the Quintus press. The pressing procedure is briefly as follows:

The bottom plug is locked to the bottom of the cylinder
The Quintus frame is moved to a position around the cylinder
The top and bottom pieces of the frame are applied hydraulically to the top and bottom of the cylinder
The cylinder is evacuated
The pressure medium (argon) is supplied at a pressure up to about 1000 atmospheres.
Heating is switched on. At the same time, the cylinder is cooled. The temperature increases to approx. 550°C and the pressure rises to 1500 atmospheres.
These conditions are maintained for a few hours.
Canister cooling is then started and the pressure medium is returned to the storage equipment.
The frame is moved away and the canister wagon takes over the pressed cylinder.

Pressing is described in more detail in Section 2.2.

One cylinder is used for each wagon track. The frame is common and so is the pressure medium system. Separate electrical and cooling systems are necessary.

A press cycle is expected to occupy about 24 hours and two cylinders therefore provide a margin for service at the mean flow of one canister per 24 hours. An investigation will have to be made at a later date to determine whether radiation protection and other protection equipment are necessary for the maintenance work on a cylinder when pressing is in progress in the other. If such simultaneous activities cannot take place, two frames may possibly be required.

The residual stresses in the copper canister after pressing have been studied. The result is presented in Appendix 6.

2.7.11
Dispatch and inspection

The wagon finally transports the canister to the dispatch section where an overhead travelling crane lifts the canister for inspection and transfer to the deposition process. Inspection comprises primarily weighing and measurement or volume determination, to establish whether the required compression has been achieved. It may be necessary to weigh previously the fuel, the copper powder charged into the canister and the canister itself.

If the inspection has shown the pressing to be unsuccessful, the canister must be returned for renewed evacuation and seal-welding. Machining equipment must be installed for this purpose in the equipment hall to machine new seats for the covers in the top part of the canister.

If pressing has only been partially successful, other problems will arise. This situation is not probable, although it should be taken into account in further studies. The copper powder may then have partially sintered, thus making it impossible to evacuate the canister completely or to transfer the fuel to another canister. Also in this case machining to permit insertion of a new cover may be the best solution resulting in a good outer copper shell but possibly with cavities in the internal volume around the fuel.

2.7.12
Handling times

An assessment of the handling times for the various operations in the process is presented below:

In the drying cell

Lifting, water run-off	0.5 h per lifting unit
Drying	24 h
Charging	0.5 h per canister

The manual operations take 1 h per canister which, at a mean flow of one canister per day, allows this work to be combined with the assembling into units in the buffer pool. The canister wagon will be occupied in this station for 0.5 h.

Filling with powder, conditioning, sealing

Moving the wagon	0.5 h
Filling with powder	1.5 h
Sealing cover with welding	0.6 h
Conditioning	
Lifting	0.1 h
Heating	10 h
Hydrogen conditioning	2 - 10 h
Raising the vacuum, sealing	1 h
Lowering	0.1 h
Total	16 - 24 h

Filling with powder, sealing and preparations for conditioning take approx. 3 h. Conditioning should be program-controlled with central supervision and three shift operation, and is estimated to occupy about 24 hours.

Main cover and second conditioning

Wagon moving operations	0.3 h
Handling of pipes, cover and welding	0.8 h
Conditioning	
Lifting	0.1 h
Heating	2 h
Hydrogen conditioning	2 - 5 h
Raising the vacuum, sealing	0.3 h
Lowering	0.1 h
Total	5.6 - 8.6 h

The operations up to preparations for conditioning occupy slightly more than one hour. Conditioning is program-controlled with central supervision, and is estimated to take a maximum of 8 h.

The manual operations from filling with powder up to preparations for the second conditioning occupy about 4 h. The same person will therefore have time to carry out these operations in one shift, with a comfortable margin for a flow of one canister per day.

2.7.13
Maintenance, repairs, accidents

The layout is such that all operations are separated, so that all handling equipment is in the equipment hall or the HIP hall and so that all transport takes place in the transport ducts and in the drying and transfer cells. By this means, the canister with the radioactive material can easily be moved away if maintenance and repairs should prove necessary, and the HIP hall will be fully accessible when the canister has been removed. The equipment hall is accessible in the same manner, although due to the nitrogen atmosphere, a distinction must be made between short visits, for which protective clothing and breathing apparatus can be used, and work that requires a longer period of time, when a change of atmosphere should be carried out. The second transport duct is fully accessible if the canister is in the press or is lifted out into the dispatch section. The first transport duct is accessible when the canister is not present in it, although the nitrogen imposes the same limitations as in the equipment hall. The part of the duct nearest to the drying cell may possibly require certain protective measures, particularly if the drying cell is fitted with a cover requiring maintenance. Almost no other equipment requiring service is included in the duct.

The drying cell has the highest radioactivity in the plant, since unshielded fuel is exposed to the nitrogen atmosphere. As a result, particular care must be taken in the design, so that service and repairs can be carried out and so that mishaps may receive attention. It must be possible to move the fuel crane on its extended track to the adjacent service room for inspection and maintenance.

The various functions of the overhead travelling crane should be separated and should be connected so that a combination of faults cannot occur. Electrical faults affecting all functions should receive attention outside the cell.

If a travelling function should fail, it must be possible to move the crane by means of cables to the service room. Since the lifting and grapple functions can not fail at the same time, the fuel can be deposited at a suitable place, e.g. in the pool, before the crane is withdrawn.

If the lifting function should fail when the crane is not carrying a load, the crane can be moved to the service room. If the fault should occur when a load is suspended, the load cannot be released due to design and electrical interlocks. One of the following procedures can then be adopted:

- The cable can be cut by means of a built-in electric cutter or an explosive charge. The load will then drop into the pool, which can be temporarily equipped with damping or arresting material, such as steel wire netting.

- If the lifting function should fail in an intermediate position so that lateral displacement is impossible, a remotely controlled robot arm will grip the load and the cable will be cut as described above. The robot arm may be permanently installed in the cell or may be mobile. If it is permanently installed, provision must be made for lifting it out of the cell by means of the crane.

The grapple function can only maloperate in the lowered position, and the cable can then be cut as described above.

The risk of spreading of activity after the fuel has been deposited in the canister as described in Section 2.7.3 may be regarded as very small, since the fuel is firmly supported and is stationary in the canister. Whether or not radioactive dust will be raised when the canister is filled with copper powder will be analysed at a later stage. It does not disturb the encapsulation process, but will complicate the cleaning of the rooms. Impurities that may be entrained in conjunction with the raising of vacuum have been discussed earlier.

After the canister internals have been sealed in the operation described in 2.7.6, the radioactive material is enclosed and no spreading of radioactive dust can occur in the remainder of the process. From the operation described in 2.7.7 and on, radioactivity occurs only as direct radiation from the canister, and when the canister has been removed, the area will be inactive.

Accidents

Three situations will be described in more detail. One of these is if the canister should become jammed on its way up or down in furnaces or the press, the second is failure of the wagon when the canister is supported by it, and the third is if the canister should fall over.

The canister becomes jammed during lifting or lowering

The places at which the lifting travel may be arrested are when the bottom plug supporting the canister is to be entered into or withdrawn from the bottom of the furnace or from the bottom of the press cylinder. In this position, the bottom serves as an effective radiation shield and the equipment is fully acessible from the transport duct. The personnel can always gain access into the transport duct for investigating the fault.

In extreme cases, the plug may become jammed by foreign objects between the plug and the opening. The plug and the canister must then be withdrawn. The plug must therefore be designed so that it can be temporarily secured to the lifting table of the wagon, e.g. by means of bolts. The lifting travel of the wagon is then used for forcing out the plug with the canister. The canister is then lifted into the transfer cell or the dispatch section while the plug is replaced or repaired.

Fault on the canister wagon

Two types of faults may occur, i.e. fault on the lifting travel and a fault on the travelling machinery. In the event of a fault on the lifting machinery, the wagon is moved to the dispatch section or the transfer cell, where the canister is lifted off to allow work to be carried out on the wagon. Faults on the travelling machinery can be attended to by the wagon being withdrawn manually by means of a cable from the service room under the drying cell or the dispatch section. The repair work can be carried out after the canister has been lifted off.

In the event of simpler faults, personnel can briefly walk up to the canister, although the time during which they remain in the vicinity of the canister should be limited to about one minute.

A special fault consists of a fault in the lifting mechanism when the canister is half-lifted. The travelling motion is then blocked physically as well as by interlocks. If the lifting mechanism is pneumatic or hydraulic, a valve on the crane carriage can be opened manually, so that the canister will be lowered by gravity. If the lifting mechanism is mechanical - screws, chains or cables -an extra drive motor must be connected. One suggestion is that an extra carriage be lifted onto the track. The latter is then moved towards the defective carriage and engages itself by means of a pinion on the side of the cariage. The extra carriage must have a motor which will provide the lifting travel of the ordinary carriage through the pinion.

If the canister should fall over

The design of the wagon must obviously be such that the risk of the canister falling over will be negligible. As an example, a pair of wheels must be able to run off the track without the inclination of the canister being such that it will fall over. However, the case of the canister falling over must be analysed. Even though provisional measures employing jacks or hoists may be sufficient and can also be carried out without excessive radiation doses, the possibility of hiring a robot from a special firm should be considered.

If the canister should fall over before it has been filled with copper powder, there is some risk of damage to the fuel and thus of radioactivity spreading in the premises. Extensive decontamination and cleaning will then be necessary. If the canister should fall over later in the process, simpler decontamination and cleaning may be sufficient.

Safety study

A safety study of the encapsulation procedure, primarily concerning hydrogen conditioning and pressing, is presented in Appendix 7.

3
BWR BOXES IN CONCRETE MOULDS

3.1
Type of waste

As outlined in the preceding chapters, the boxes of the BWR bundles will remain in the cassettes after the fuel has been lifted out. Other cassettes comprise the boron glass rod bundles of the PWR fuel, which have been lifted out of the fuel.

The number of boxes is 25560.
The number of boron glass rod bundles from PWRs is 204.

The boxes and rod bundles are embedded in concrete in moulds, in which the boxes are placed in a 7 x 7 square pattern as shown in Figure 3-1. The wall thickness of the concrete mould is 100 mm, which provides sufficient radiation protection to enable the mould to be handled when containing waste which has decayed for 40 years. The boron glass rod bundles, which have a higher radiation, are placed in a similar mould filled with boxes, although with the central nine box positions left empty, thus providing space for four rod bundles. After filling with concrete, these bundles are thus surrounded by an extra layer of concrete corresponding to the thickness of two rows of boxes.

3.2
Concrete moulds for embedding metal parts

The appearance of the mould is shown in Appendix 8.

To allow for efficient handling, all concrete moulds have the same outside dimensions, regardless of the type of contained waste. The mould height of 5300 mm is determinte by the control rods of the BWRs. These are not covered by this study, but will also be embedded and deposited in the same manner as the fuel boxes.

The mould is of square cross-section, with an external side length of 1250 mm. This dimension has been chosen to enable the mould to accommodate 49 boxes (7 x 7).

The wall thickness of 100 mm of the mould can be regarded as a suitable minimum dimension from the manufacturing and strength aspects. At the same time, it provides an adequate shield for the radiation from the contents, to allow for the handling described here.

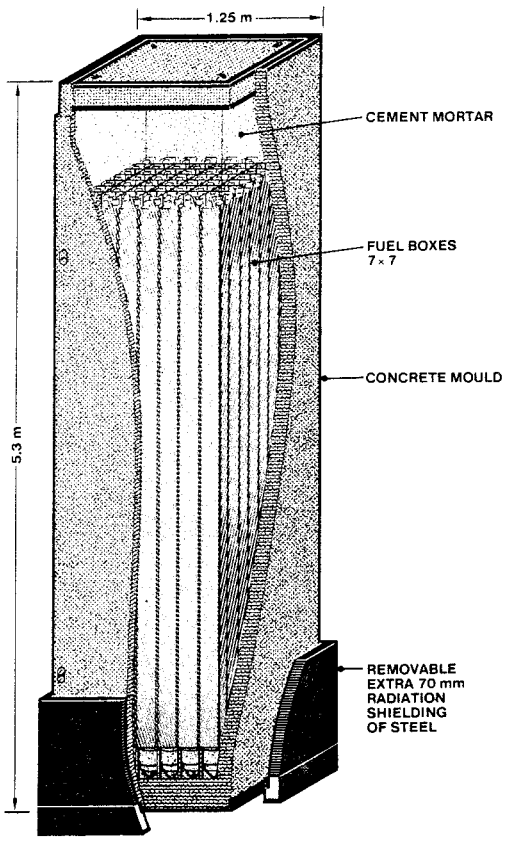


Figure 3-1. Concrete mould for embedding of fuel boxes.

The thickness of the lid end of the mould (lid + grouting) provides sufficient shielding to enable personnel to approach this end of a horizontal mould. This is important from the viewpoint of handling in the final repository (see Section 3.5).

The bottom of the mould is sufficiently thick to enable it to be handled in the station without additional radiation shielding.

The intensity of radiation from the bottom end pieces of the boxes is appreciably higher than that from the remainder of the box, and an additional thickness of approx. 200 mm of concrete would therefore be required on the sides of the mould to provide the necessary radiation shielding. In order to avoid such enlargement of the mould, temporary radiation shielding consisting of 70 mm thick steel is provided at the bottom of the mould. This steel shell is left in position during the transport and handling of the mould and is not removed until shortly before final deposition. The steel shell is then re-used on subsequent moulds.

Recessed lifting hooks that simplify handling by remote control are provided at the top of the mould for handling in the upright position and along one long side for handling the mould in a horizontal attitude. The former method of lifting is used only for handling the mould in the filling and grouting.

In order to stiffen the relatively slender sides of the mould and to provide a good seal during grouting, the lid is seal-welded to the edge of the opening. The lid is provided with a steel edge all round, and this can simply be ground to provide a good fit. This adjustment should preferably be carried out in conjunction with the mould being taken for filling.

The empty mould weighs approx. 7 tonnes, and when it is ready for deposition approx. 20 tonnes. The additional steel radiation shield weighs approx. 2 tonnes. The total weight for lifting is thus approx. 22 tonnes.

A total of approx. 533 moulds are required.

The handling of the moulds is remotely controlled from a radiation-shielded control room.

3.3 Assembly into deposition units and concrete filling

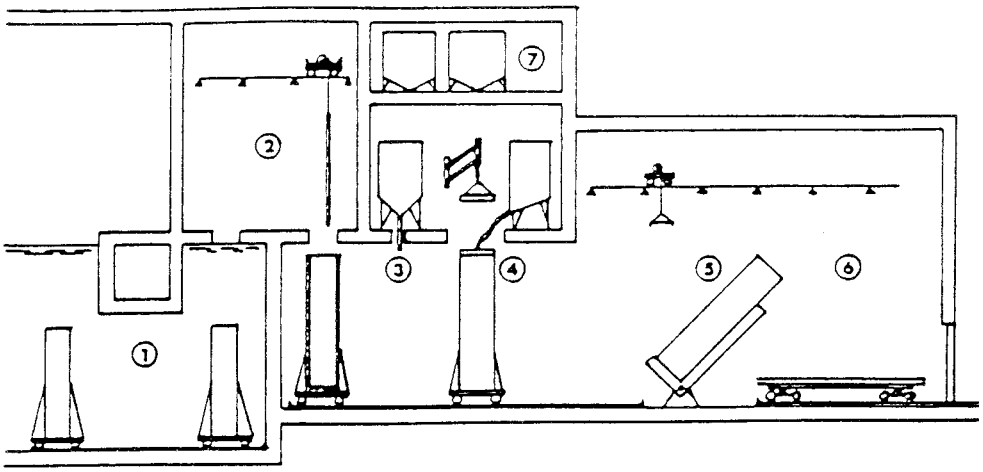
Embedding of the metal parts of the fuel in concrete is carried out in a special casting section in the encapsulation station for spent fuel. Figure 1-1 shows the design of the plant and Figure 3-2 shows the flow diagram for the embedding process. Unless otherwise specified, all handling is remotely controlled.

The vast majority of the metal parts consists of fuel boxes arriving at the encapsulation station together with the fuel in a steel transport cask. For a more detailed description of the receiving procedure, see Section 1.1.

When a cask is discharged, the fuel bundles, including the boxes, are lifted out and are placed in a fuel rack in the buffer pool. The locations in the rack have been adjusted to take into account the risk of criticality. When the fuel bundles are subsequently transferred for encapsulation, the boxes are left in the rack. The rack can accommodate 49 fuel bundles, i.e. the same number as the maximum number of boxes that can be placed in a mould. The buffer pool can accommodate a total of 12 fuel racks.

A smaller lock pool provides communication between the buffer pool and the casting section. A transport wagon that can accommodate one fuel rack runs on the bottom of the lock pool.

When the fuel bundles have been removed from a fuel rack and the rack thus contains only 49 empty boxes, the rack is placed on the transport wagon and is transferred to the mould charging cell. In this cell, the rack is lifted out of the pool and is placed in a pit, in which it is left for the water to run off. The boxes can then be picked out individually for placing in the concrete mould. The empty rack is then returned to the buffer pool.



1. Rack wagon with boxes or rods
2. Transfer to concrete mould
3. Concrete filling
4. Lid application. Concrete injection
5. The mould is laid down
6. Lift to a transport wagon
7. Storage of cement and sand

Figure 3-2. Handling of BWR fuel boxes and PWR boron glass rods.

The drying pit is located deep down below the floor and is lined with stainless steel sheet. The pit can also serve as a buffer store in the event of disturbances. If access to the cell should prove necessary at the same time as the drying pit contains radioactive material, the pit can be temporarily filled with water.

The empty concrete mould with a well-fitting cover is admitted into the casting section in a horizontal position on a transport wagon. The same wagon is then used for transporting the finished mould out of the section. The mould is raised and is placed on a transport wagon running on rails and equipped with a hydraulic hoist. The wagon is run up to the charging station located below an opening in the floor structure towards the mould charging cell. The mould is lifted up to provide a good seal against the floor structure and the cover in the floor structure is opened.

At the bottom of the mould a steel grille has been placed, with a thickness and circular openings that are designed to suit the end pieces of the boxes. The grille terminates at approx. 50 mm above the bottom of the mould, which provides sufficient space for distribution of the concrete.

The boxes are collected and are placed in the mould so that their end pieces enter into the holes in the grille. This prevents the boxes from overturning and thus making charging more difficult.

After the mould has been charged, the cover in the floor structure is closed and the wagon is moved to a casting position, in which the mould is connected to a hole in the floor structure towards the casting cell. After the cover has been opened, a collar is placed in the opening, to prevent splashing of the edges of the hole and the top part of the mould.

Concrete with a fluidizing additive is used for casting. The maximum aggregate size is 4 - 8 mm. Equipment for handling and pumping the concrete is provided in an adjacent room and can be served manually. In the casting cell, the concrete is distributed in the mould by means of a robot arm.

If tests should show that vibration of the concrete is necessary, this can be carried out by means of poker vibrators which can be left in the mould after casting has been completed.

The mould is filled with concrete up to approx. 5 cm below the lid fold. Any excess water collecting on the surface of the cast concrete can be absorbed by spreading a certain amount of dry cement onto the surface. When the concrete has hardened, the collar around the hole is removed and is placed in a container, the cover is closed and the mould is moved to the lid-mounting station.

The lid is lifted onto the mould and a welding robot seal-welds the edge all round. No demands are made on inspecting the tightness of the weld. After welding, the grouting and venting hoses are connected to the adapters on the lid and the empty space in the mould is filled with grouting mortar. Any mortar flowing out of the vent pipe is collected in a container which can be embedded in the subsequent mould.

The mould is then turned onto the horizontal position and is placed on the receiving and dispatch wagon. When a truck or a railway wagon with a transport container is available, the mould is rolled out and is lifted over into the transport container. If obstacles in transport should occur, a minor buffer area in the casting section can be utilised.

3.4 Transport to the final repository

After casting and sealing have been completed, the mould is removed from the casting cell. All subsequent lifting is carried out by means of the lifting hooks provided on one long side of the mould. A lifting beam should preferably be applied to these hooks before the mould is admitted for filling and casting. The lifting beam should be equipped with mechanisms for remotely controlled disengagement, for use when the mould has been placed at the deposition site.

The moulds have to be transported from the encapsulation station to the final repository, which is separate from the final repository for spent fuel. Depending on the distance, this transport may take place by road or rail, possibly in combination with transport by sea.

In the event of external transport, the mould will be transported in a concrete container with a wall thickness of at least 30 cm.

If the distance is short, the moulds will be transported individually. A maximum of two moulds can be accommodated in a concrete container.

3.5 Final repository

The fundamental principles for final storage of spent nuclear fuel are also applied to final storage of the active metal parts. According to the present programme, these are thus deposited at great depth in bedrock which forms the outermost barrier against the spreading of radioactive substances to the biosphere. Similar basic demands are therefore made on the rock as in the deposition of spent fuel, although certain simplifications can be made, since the metal parts have appreciably lower contents of radioactive products. The rock barrier may thus be thinner, metallic encapsulation can be replaced by casting into concrete and the tunnel fill need not have the same water-tightness, plasticity, etc. as that required for other repositories. The tunnels can therefore be filled with concrete instead of sand and bentonite.

Some cracking of the concrete fill must be expected, and the local water flows past the metal scrap will thus be higher than if sand and bentonite were used for filling. However, this is of subordinate importance, since the solubility rate of the metals is very low in the alkaline environment created by the metal being cast into concrete.

The final repository must be located at a depth of at least 300 m below ground surface. The repository consists of two storage tunnels connected to a central area by a communication tunnel (see Figure 3-3 and Appendix 9). The bottom of each tunnel is floated with concrete and is equipped with rails for the deposition vehicle.

Two shafts place the central area in communication with the ground surface. The larger shaft, intended for the transport of moulds and materials, such as concrete, also accommodates ventilation ducts, service pipes, electric power supply, etc. A smaller shaft containing a personnel elevator emerges in the personnel section of the central area. The larger shaft will be a 6.0 m diameter downcast shaft and the smaller a 4.0 m upcast shaft.

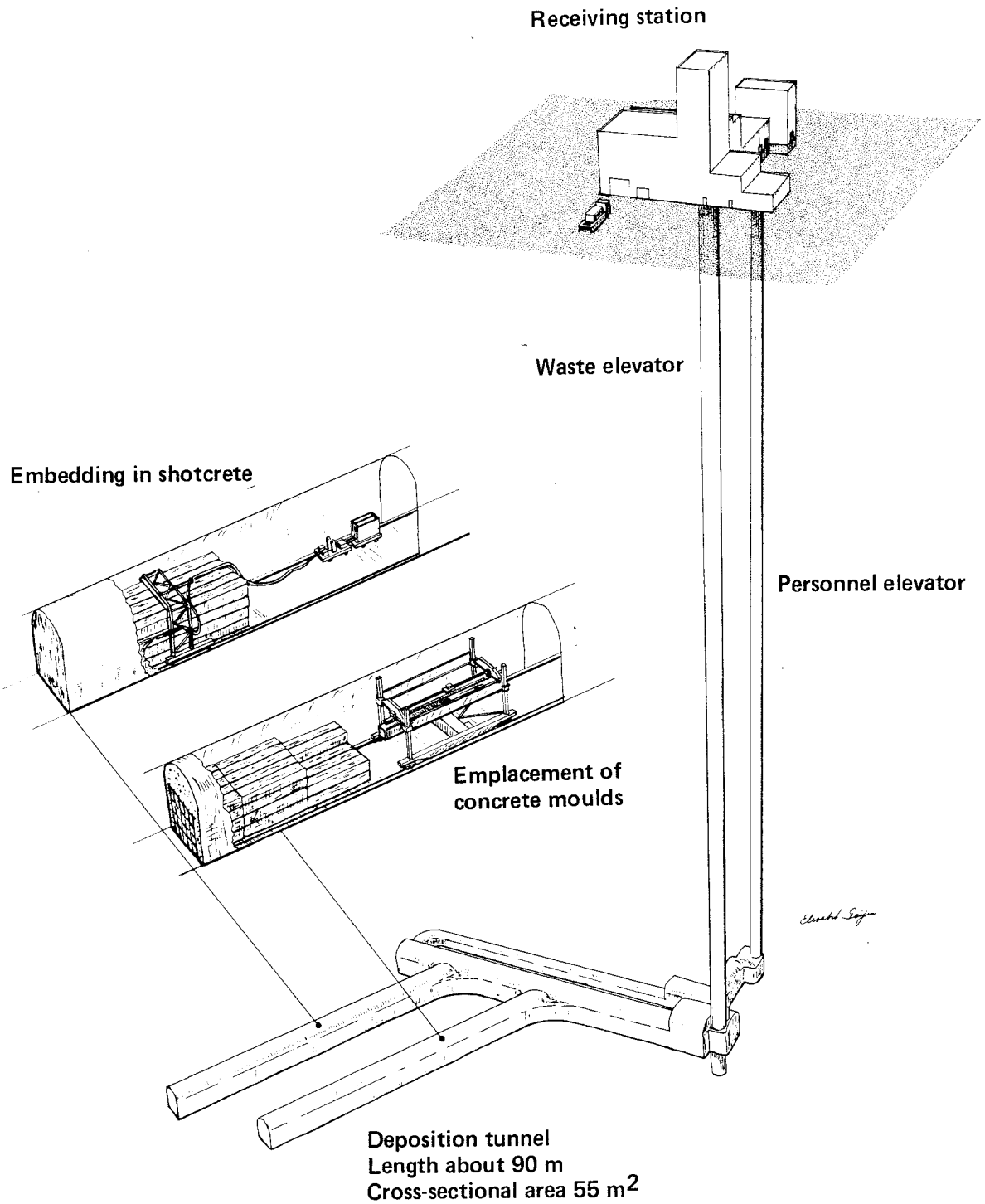


Figure 3-3. Final repository for metal components.

A receiving station (see Appendix 9) is provided at ground surface. In this receiving station, the transport container is unloaded and the moulds are then transferred to the elevator shaft for transport below ground. In addition, the receiving station includes personnel areas, workshop, control room, and rooms for supervision, inspection, service functions for the rock caverns, etc. Most of the activities, including those in progress below ground, are controlled and monitored from the control room.

The elevator which transports the mould consists of two parts. The mould transport section at the top contains a pivoted cradle. This cradle allows for loading and unloading of the elevator with the mould in the horizontal position, though the mould is in the upright position when it is transported down. The driving machinery for the cradle is located on top of the elevator and is accessible regardless of the mould position. The bottom of the elevator is provided with a conventional elevator cage for transporting materials. The mould represents the design load for the elevator.

The deposition rate is expected to be a maximum of two moulds per week. The final deposition procedure is as follows.

The mould arrives in the transport container at the receiving station. The container is run into an unloading air lock and is emptied. Normally, the mould should then immediately be taken below ground, although if obstacles should occur, the receiving station includes a minor buffer area.

Using an overhead travelling crane, the mould is placed in the swung-out cradle of the elevator. The cradle is retracted and locked, and the elevator is then run down to the repository level. The cradle is swung-out and a special deposition vehicle, designed as a straddle carrier mounted on rails, is run over the cradle and raises the mould by engaging in the lifting beam. The deposition vehicle is remotely controlled from the control room at ground surface. The basic design of the vehicle is shown in Figure 3-4.

The deposition vehicle is run into the deposition tunnel. Before the mould is deposited, the temporary radiation protection is removed by means of equipment mounted on the vehicle.

The moulds are deposited with an orientation in the direction of the tunnel - five in width and four in height. The lifting hooks are arranged so that the moulds can be stacked close to one another. The dimensions of the deposition vehicle are such that the vehicle can run over and straddle a full stack of moulds.

When the mould is in position, the lifting beam is disengaged and the vehicle returns. On its way back, it carries the extra radiation shield.

Casting around the moulds is carried out by shotcreting. Shotcreting is carried out from fixed nozzles mounted on a wagon which can straddle the stack of moulds, in the same manner as the deposition vehicle. The shotcreting system also comprises material hoppers and pumps. The material is transported below ground by means of the elevator.

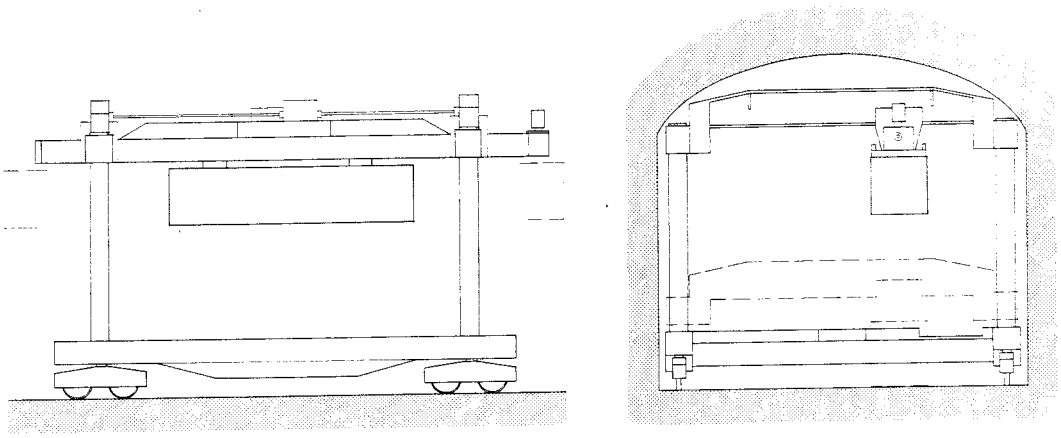


Figure 3-4. Deposition vehicle with concrete moulds in different positions.

Shotcreting of the stacks of moulds should be carried out as the stacks are completed, thus enabling the shotcreting front to be maintained at a relatively short distance from the point at which personnel may be working. This facilitates supervision and enables simpler equipment to be used. In addition, continuous sealing of the tunnel also simplifies ventilation and drainage, etc. However, the shotcreting front should not be closer to the deposition point than about one mould length, in order to minimise the risk of making those surfaces dirty that will be used for supporting the moulds.

No special strength or tightness requirements are made on the concrete. However, the concrete material should have low contents of chlorides, nitrates, sulphides and other corrosion-promoting substances.

The lid ends of the moulds face towards the tunnel, and since these ends have extra-thick concrete, shotcreting may be carried out by direct manual operation. However, the advantage of remote control is that no demands need be made on the ventilation of the deposition tunnel.

When deposition has been terminated after approx. 25 years of operation, connecting tunnels and shafts will be filled with a mixture of sand and bentonite in the same manner as in the spent fuel repository.

3.6 Radiation shielding aspects

As a guideline for the permissible radiation dose in the handling of moulds, the surface dose rate of the mould should not exceed 30 mSv/h (3 rem/h) or the dose rate at a distance of 1 m should not exceed 10 mSv/h (1 rem/h). During transport outside the controlled area, the maximum dose rate is approx. 0.1 mSv/h (10 mrem/h) at a distance of 1 m from the transport vessel.

Moulds with BWR boxes having a wall thickness of at least 100 m satisfies the radiation shielding requirements for internal transport of boxes after 40 years following removal from the reactor. However, the dominating radiation source of the box is the transition piece why, during transport the 70 mm thick steel shell fitted onto the mould end at which the transition pieces are contained improves the radiation shielding. This shell is removed before the mould is placed in the final repository. When the mould is placed in the horizontal position after charging and casting, the bottom surfaces of the mould at which the transition pieces are located will be exposed. To restrict the radiation in this direction, the bottom of the mould is 230 mm thick.

After deposition, a front of lid surfaces will be exposed towards the front of the tunnel. However, boxes as well as boron glass rods have moderate induced activity at this end, and the thickness of the lid together with the grouting therefore provide the necessary shielding. One metre from the front, the dose rate will be only 0.004 mSv/h (0.4 mrem/h).

The moulds containing PWR boron glass rod bundles, which have appreciably higher induced activity than the boxes, have two rows of boxes along the walls. After the mould has been filled with concrete, the radiation shield for the rod bundles will thus consist of the mould wall and a thickness of concrete corresponding to the thickness of two rows of boxes. The rod bundles should be guided by means of spacers in the centre of the pattern of boxes, so that a concrete thickness of at least 440 mm will be achieved. The spacer should be arranged so that the bundles will be no closer to the bottom of the mould, for the same reasons as those presented above for the transition pieces. This can easily be achieved, since the length of the bundles is 3.85 m, which is more than 0.5 m less than the boxes. The thickness of concrete at the bottom will then be 430 mm.

The dose rate at various points around the mould are shown below. It will be noted that these values are comfortably below the specified maximum values. The particulars have been obtained from Reference B.

LIST OF REFERENCES

Reference A — Sandersson A, Szluka T F, Turner J
Feasibility Study of EB Welding of Spent Nuclear Fuel Canisters
Welding Institute Cambridge UK
KBS TR 83-25, April 1983

Reference B — KBS - Final disposal of components with neutron induced activity
- Radiation shielding calculations. (In Swedish)
ASEA-ATOM PM KPC 83-20, Lars Carlquist

Reference C — Encapsulation of spent nuclear fuel - Safety analysis
KBS TR 83-30, ES-konsult AB

LIST OF APPENDICES

Nuclear fuel elements used in Swedish light water reactors

KBS Hans Forsström

1983-04-19
HF/BS

NUCLEAR FUEL ELEMENTS USED IN SWEDISH LIGHT WATER REACTORS - MECHANICAL DESIGN AND ACTIVITY CONTENT IN THE METALLIC PARTS OF THE FUEL

Hans Forsström SKBF/KBS

1 INTRODUCTION

In this report the fuel types that will be used as reference fuel for KBS-3 are described, namely a BWR fuel for Forsmark 3 of ASEA-ATOM design and a PWR fuel for Ringhals 3 of Westinghouse design. Furthermore a short description is given of other fuel elements that have been used and are used in the Swedish light water reactors.

The emphasis in the description is put on the mechanical design of the fuel elements. The enrichment levels and other data relevant for the reactor-physics are thus not treated.

The purpose of the report is to give a basis for a description of the treatment of the metallic parts of the fuel, i e all material in the fuel elements apart from the fuel pins. Data about the latter are, however, also given.

2 BWR

2.1 Different fuel types

In the Swedish BWRs mainly ASEA-ATOM fuel have been used. During the years relatively small changes from a mechanical point of view have been made to this fuel. The F3-fuel can thus be regarded as typical for all ASEA-ATOM fuel so far used in the Swedish reactors. The changes that have been made are described in more detail in section 2.3.1. ASEA-ATOM is at present developing a new fuel element design, the so called SVEA-fuel which differs quite a lot from fuel earlier used (confer section 2.3.3).

In some reactors,Barsebäck and Oskarshamn, fuel made by Exxon has been used and in Forsmark fuel from KWU will be used (section 2.3.2).

The fuel channels have all been delivered by ASEA-ATOM and are almost identical to the fuel channels used in F3; the only exception being the fuel channels from Oskarshamn 1 which are 125 mm shorter. The wall thickness of the fuel channels has also varied somewhat.

2.2 Reference fuel, Forsmark 3

A F3-standard fuel element is shown in fig. 1. The main data have been collected in tables 1 and 2. The fuel element consists of a fuel bundle and a fuel channel.

The fuel bundle contains 63 fuel rods and a spacer capture rod. Of the fuel rods 47 are normal rods, 4 are tie rods and 12 are corner rods. The spacer capture rod is made of a Zircaloy tube. The fuel rods are kept together by the top and bottom tie plates and 6 spacers. The ends of the tie rods penetrate the top and bottom tie plates and are locked by nuts. In the same way the spacer capture rod is locked by a nut under the bottom tie plate. The remaining rods are loosely fitted against the top tie plate with springs.

The fuel rods are filled with fuel pellets which are secured with a plenum spring at the top.

The fuel channel consists of a quadratic tube (with rounded corners) of Zircaloy and a transition piece at the bottom made of stainless steel.

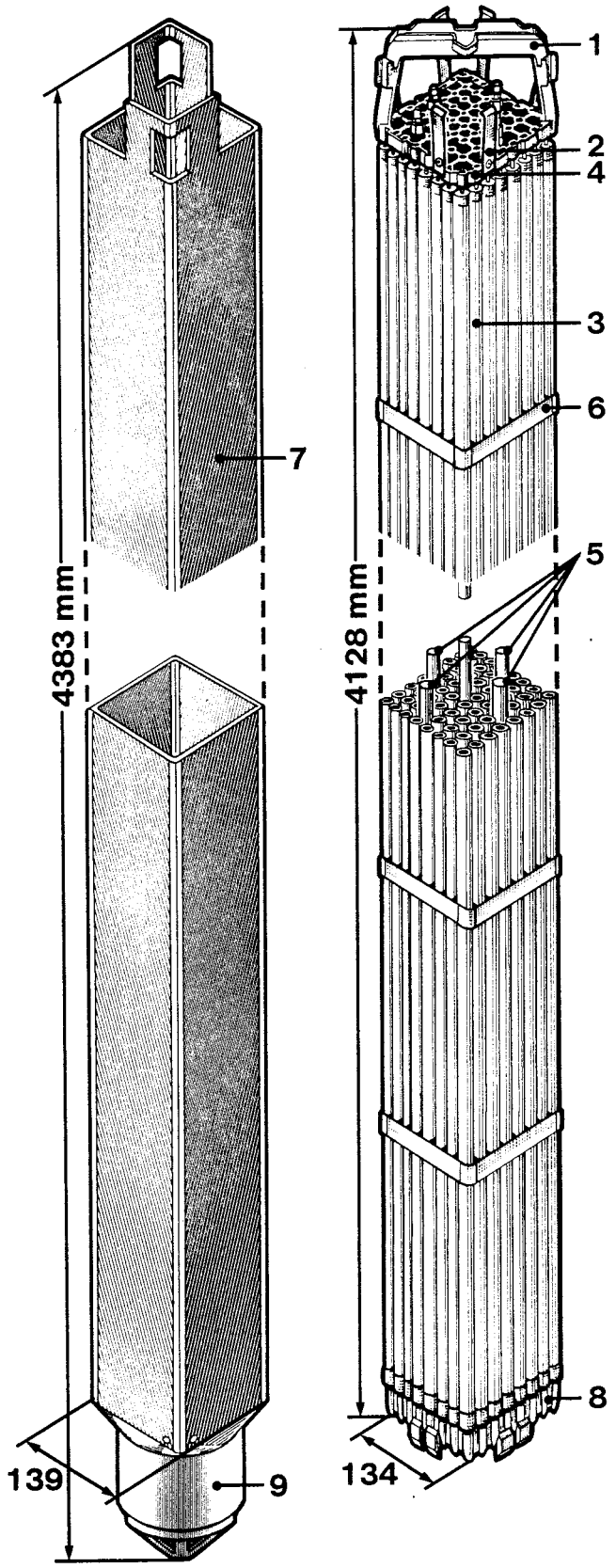
2.3 Variants of BWR-fuel

2.3.1 ASEA-ATOM fuel elements

Apart from the Oskarshamn 1-fuel all ASEA-ATOM fuel elements have the same dimensions as the Forsmark 3-fuel element. The O1-fuel element is 125 mm shorter and correspondingly lighter.

The most important differences between different ASEA-ATOM-fuel elements are the type and number of spacer capture rods. Up to mid 1976 the fuel element contained 64 fuel rods and thus no spacer capture rod. At that time a massive spacer capture rod of Zircaloy was inserted. Also some old fuel was rebuilt. In some fuel elements also a Zircaloy tube was inserted in addition to the massive rod. This was done in 1980. These fuel elements thus contain two spacer capture rods. In fuel delivered after 1980 only one spacer capture rod made of a Zircaloy tube is included like in the F3-fuel.

From reactor-physics reasons some fuel elements (172) in the first core of F3 and O III contain, in addition to the spacer capture rod also 3 "water rods" (tubes of Zircaloy), that have replaced fuel rods. This type of fuel elements will not be used in the replacement cores. Some rebuilt fuel elements in Ringhals and Oskarshamn have more water rods, up to four.



1 HANDLE
2 SPRINGS
3 FUEL ROD BUNDLE
4 TOP TIE PLATE
5 TIE ROD
6 SPACER
7 FUEL CHANNEL
8 BOTTOM TIE PLATE
9 TRANSITION PIECE

Fig. 1: BWR-fuel element
(ASEA-ATOM)

In five fuel elements in each of the first cores of F1, F2, F3 and O III one fuel rod has been replaced by a rod containing a start-up neutron source. In this rod the fuel pellets have been replaced by distance rods of zircaloy-2 and neutron source units with Cf-252 sources.

Older fuel elements delivered before 1981 have a slightly heavier spacer.

The plenum spring in fuel delivered up to 1976 was smaller.

The top tie plate has a different design for internal and external pump reactors. In the internal pump reactors two leaf springs have been replaced by fixed distance blocks.

2.3.2 Exxon and KWU-fuel elements

These fuel types have a mechanical design that is similar to the ASEA-ATOM fuel. However, the choice of material and the dimensions differ somewhat as is shown in table 3. Both the Exxon and the KWU-fuel have only one fuel rod diameter. In the table data for the Exxon-fuel that have been used in Barsebäck is shown.

In all cases ASEA-ATOM fuel channels have been used.

2.3.3 SVEA-fuel elements

ASEA-ATOM is now developing a new fuel element, the so called SVEA-fuel. At present about ten SVEA fuel elements are being tested in Swedish reactors. The SVEA-fuel differs from the standard fuel mainly in that the fuel bundle has been divided in four subassemblies and that the fuel channel has an internal cross (confer fig. 2). The amounts of material in the metallic parts of the fuel will thus be changed, but only modestly.

3 PWR

3.1 Different fuel types

In the three PWRs so far three types of fuel have been used. In Ringhals 2 that has fuel elements with 15 x 15 fuel rods at first Westinghouse-fuel was used and then KWU-fuel. In Ringhals 3 and 4 that both have 17 x 17 fuel elements, mechanically identical Westinghouse-fuel elements have been used.

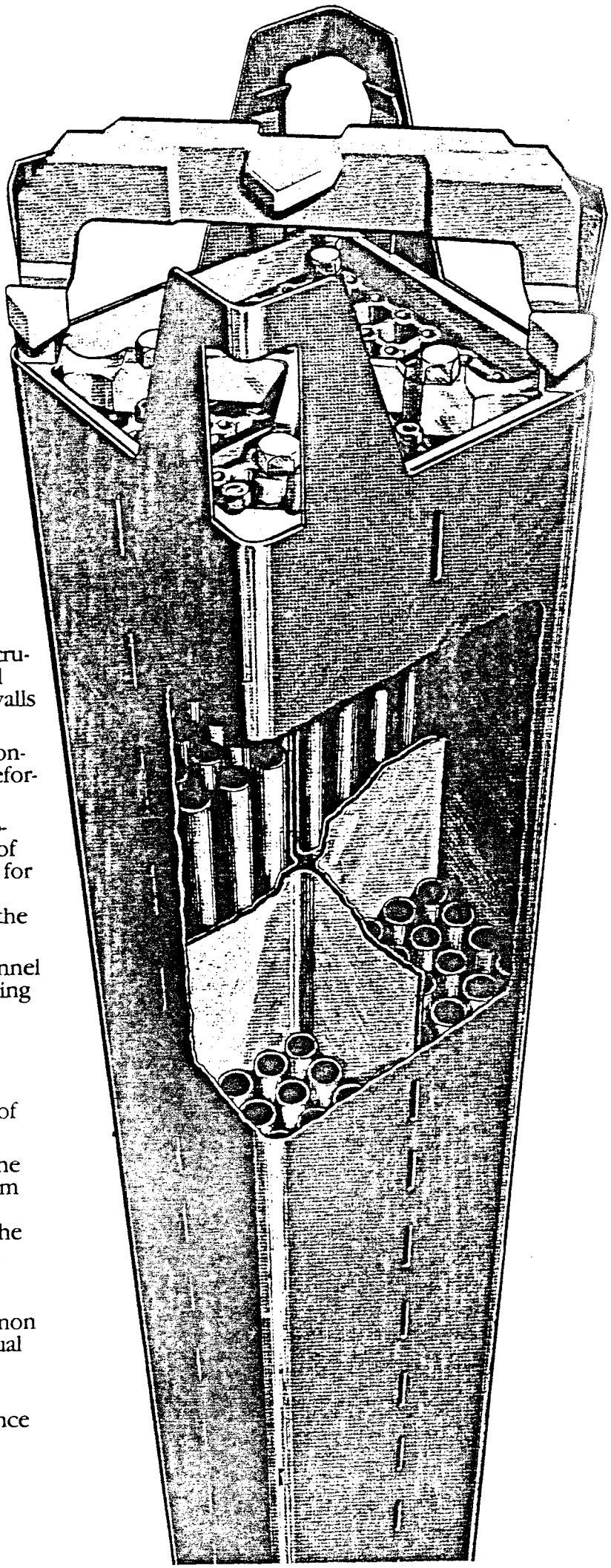


Fig. 2 SVEA-fuel element

Mechanical design

The non-boiling water inside the SVEA fuel assembly is introduced through an internal cruciform structure attached to the fuel channel walls. The internal structure and the outer walls are an integral mechanical component.

The integral channel design also ensures a considerable reduction in channel wall creep deformation.

The much improved creep deformation properties are utilized to minimize the amount of Zircaloy in the channel walls and also allow for narrowing the outer water gaps, without reducing the control rod blade clearance at the end of channel life.

The transition piece to which the SVEA channel is attached can be designed to suit all operating BWRs and full mechanical compatibility is ensured between the SVEA fuel and fuel of earlier design.

The SVEA fuel bundle consists of four sub-bundles separated by the internal structure of the channel.

The design principle of the sub-bundles is the same as before, with separate top and bottom tie plates and spacers of ASEA-ATOM low pressure drop design. The top tie plates of the four sub-bundles are attached to a common handling piece. Although the total SVEA assembly, with sub-bundles and channel, is handled as one unit as in the past, the common handling piece can be removed for individual handling of the sub-assemblies.

The fuel rod is of the standard ASEA-ATOM design which has an outstanding performance record.

All materials used in the SVEA assembly are identical to those in the earlier design.

3.2 Reference fuel, Ringhals 3

A R3-standard fuel element is shown in fig. 3. The main data have been collected in table 4. The fuel element contains 17 x 17 rods, 264 of which are fuel rods, 24 are controlrod guide tubes and one is guide tube for neutron flux measurements. The rods are kept together by the top and bottom tie plates (top nozzle, bottom nozzle) and eight spacers with the controlrod guide tubes and the instrumentation guide tube.

The fuel pellets in the fuel rods are kept in place by a plenum spring at the top.

3.3 Variants of PWR-fuel elements

In table 4 also data for Ringhals 2-fuel elements from Westinghouse and KWU are given. In some KWU-fuel elements a solid zircaloy rod has replaced a fuel rod and in some elements spacers of zircaloy have been tested.

3.4 Burnable absorbers

In the first core burnable absorbers in the form of absorber rod bundles are used in the PWRs. They are positioned in the controlrod guide tubes. In table 5 data for these absorber rod bundles are given. In Ringhals 3 one absorber rod bundle contains up to 24 absorber rods kept together by a top tie plate.

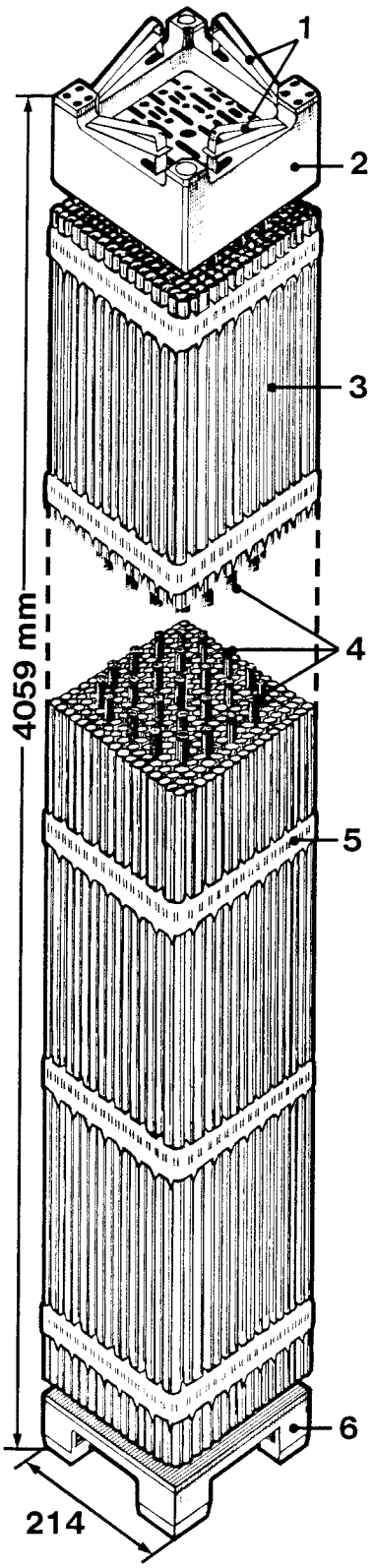
4 DATA FOR THE METALLIC PARTS OF THE FUEL ELEMENTS TO BE USED IN KBS 3

4.1 General

In KBS-3 the assumption is made that a total of 6000 tons of spent fuel (uranium weight) will be disposed of, 4550 tons of BWR-fuel and 1450 tons of PWR-fuel. In the following all BWR-fuel is assumed to be of the reference type for Forsmark 3 and all PWR-fuel is assumed to be of the reference type for Ringhals 3. The number of fuel elements will then be:

25,560 BWR-fuel elements and
3,125 PWR-fuel elements.

Each BWR-fuel element is assumed to contain one fuel channel. In reality some fuel channels have been used for two fuel bundles. This assumption is thus conservative.



1 SPRINGS
2 TOP NOZZLE
3 FUEL ROD
4 CONTROLROD GUIDE TUBE
5 SPACER
6 BOTTOM NOZZLE

Fig. 3: PWR-fuel element (Westinghouse)

4.2 Amount of material

4.2.1 BWR

Fuel cladding	1220 ton	Zircaloy-2
Spacer capture rod	20 "	"
Top and bottom tie plates Screws	68 "	Stainless steel SIS 142333
Spacers Springs	27 ton	Inconel X-750
Fuel channels	900 ton 160 "	Zircaloy -4 Stainless steel SIS 142352

4.2.2 PWR

Fuel cladding	330 ton	Zircaloy-4
Guide tubes	30 "	"
Top and bottom tie plates Screws, Springs	56 "	Stainless steel AISI 304
Spacers	20 "	Inconel-718
Absorber rod bundles	2 " 0.9"	Stainless steel AISI 304 Boron glass

4.2.3 Material composition

The composition of the materials used is given in ref 1. For stainless steel and Zircaloy no data are given on the content of niobium. According to information from Sandviken the niobium content in SIS 142333 is typically 100 ppm and in Zircaloy-2 less than 50 ppm. If these values are used the total amount of niobium in the metallic parts of the fuel will be 1.3 tons, mainly in the pieces made of Inconel.

The total amount of nickel can in the same way be calculated to 58 tons.

4.3 Activity content

The activity content in neutron-irradiated fuel element parts from similar fuel elements as the reference fuel has been calculated in ref 2 and in appendix A. These calculations have here been adjusted to account for the differences in amount of material. The results have been collected in table 6-9.

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Neutroninducerad aktivitet i bränsleelementdetaljer ("Neutron induced activity in the metallic parts of the fuel")
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3 KJELLBERT, N.

Calculation of Nb-94 content in the metallic parts of the fuel.
Personlig information.

Table 1

Data for Forsmark 3-fuel (the weights are given per fuel element, where nothing else is indicated).

Fuel element			
Length	4383 mm		
Width (max)	151 mm		
Weight	298 kg		
Fuel bundle			
Length	4128 mm		
Width (max)	151 mm		
Weight	256 kg		
Weight of Uranium	178 kg		
Top tie plate incl. handle	1,5 kg	SIS 142333	
and springs and screws	0,14 kg	Inconel X-750	
Bottom tie plate	1,1 kg	SIS 142333	
Spacers (6 pcs)	0,87 kg	Inconel X-750	

Fuel rods	Normal	Corner	Tie rods	
Number	47	12	4	
Length	3998	3998	4053 mm	
Outer diameter	12,25	11,75	12,25 mm	
Cladding (kg/rod)	0,76	0,73	0,79	Zircaloy-2
Uranium dioxide (kg/rod)	3.265	2.959	3.265	
Plenum spring (kg/piece)	0.035		SIS 142331	

Spacer capture rod		
Length	4036 mm	
Outer diameter	12.25 mm	(incl. warts 15,5 mm)
Weight	0,77 kg	Zircaloy-2
Springs (59 pcs)	0,04 kg	Inconel X-750
Nuts (9 pcs)	0,06 kg	SIS 142343
Fuel channel		
Length	4383 mm	
Width	139 mm	
Wall thickness	2,5 mm	
Weight	41,7 kg	
Channel tube	35,4 kg	Zircaloy-4
Transition piece	6,2 kg	SIS 142352
Screws (4 pcs)	0,08 kg	Incoloy 800

Table 2

Forsmark 3-fuel element. Total amount of material (kg/fuel element)

	Fuel bundle	Fuel channel
Uranium dioxide (incl. about 0.5 kg gadolinium oxide)	202	-
Zircaloy-2	48,4	-
Zircaloy-4	-	35,4
Inconel X-750	1,1	-
Stainless steel	4,9	6,3

Table 3

Comparison between the main data for AA, Exxon and KWU-fuel elements. (The weights are given per element where nothing else is indicated).

	ASEA-ATOM (F3)	EXXON (B1)	KWU (F1)
Fuel bundle			
Length (mm)	4128	4127	4126
Width (mm)	151	147	151
Weight (kg)	256	262	258
Weight of uranium	178	174	176
Top plate incl. handle and springs (kg)	1,5 SS 0,14 Inconel	1,5 SS 0,18 Inconel	1,6 SS
Bottom tie plate (kg)	1,1 SS	1,0 SS	1,2 SS
Spacers (kg)	0,87 Inconel	1,5 Zr-2 0,3 Inconel	1,7 Zr-4 0,3 Inconel
Fuel rods number	63	63	62
Length (mm)	3998	4011	4016
Outer diameter (mm)	12,25/11,75	12,29	12,3
Cladding (kg/rod)	0,76 Zr-2	0,86 Zr-2	0,79 Zr-2
Uranium dioxide (kg/rod)	3.265/2.959	3.136	3.214
Plenum spring (kg/pc)	0,035 SS	0,043 Inconel	0,04 SS
Spacer capture rod number	1	1	2
Weight (kg/rod)	0,77 Zr-2	2,87 Zr-2	0,94 Zr-2
Springs	0,04 Inconel	0,15 Inconel	
Nuts	0,06 SS	0,07 SS	0,1 SS
Total amount of material in the fuel bundle			
Uranium oxide (kg)	202	197	199
Zircaloy (kg)	48,4	58,4	52,5
Inconel (kg)	1,1	3,3	0,5
Stainless steel (kg)	4,9	2,5	5,4
Al_2O_3 (kg)	-	0,2	0,2

Table 4

Data for different PWR-fuel elements (the weights are given per fuel element where nothing else is indicated).

	Ringhals 3	Ringhals 2	
	Westinghouse	Westinghouse	KWU
Type	17x17	15x15	15x15
Length (mm)	4059	4059	4057
Width (mm)	214	214	214
Weight (kg)	665	655	645
Weight of uranium (kg)	464	460	435
Top nozzle (kg) incl. springs	7,0 Stainless Steel 0,5 Inconel	8 SS	6,7 SS
Bottom nozzle (kg)	5,7 Stainless Steel	6 SS	5,7 SS
Spacers (number)	8	7	7
Weight	6,3 Inconel 718	6 Inconel	5,6 Inconel
Fuel rods (number)	264	204	204
Length	3852	3856	3864
Outer diameter (mm)	9,50	10,72	10,77
Cladding (kg/rod)	0,4 Zircaloy-4	0,5 Zr-4	0,59 Zr-4
Uranium dioxide (kg/rod)	1,99	2,55	2,42
Plenum spring (kg/pc)	0,02 Stainless Steel	0,02 SS	0,02 SS
Guide thimbles (number)	25	21	21
Length (mm)	3900	3900	3918
Outer diameter (mm)	12,3	13,9	13,9
Weight (kg)	9,6 Zircaloy-4	9 Zr-4	13,2 Zr-4
Screws	0,2 Inconel 718	0,2 Inconel	0,07 SS

Total amount of material in the fuel bundle

Uranium dioxide	526	521	494
Zircaloy-4	115	112	133
Stainless steel	18	16	13
Inconel	7	7	5

Table 5

Data for burnable absorbers in PWR

	R3	R2
Length (mm)	3850	3850
Width (mm)	168	143
Number of rods/bundle	16/20/24	12/16/20
Number of bundles	68	68
Total number of rods	1072	832
Weight/bundle (kg)	15,9/19,2/22,5	14,5/18,5/22,5
Top tie plate	2,8 SS AISI 304	2,5 SS
Weight/rod (kg)	0,82	1,0
Steel (kg)	0,51	0,61
Boron glass (kg)	0,31	0,39
B_2O_3 (W/O)	12	12

Table 6

Induced activity in the metallic parts of the fuel

	Activity (GBq/ton U) after						
	10 years	100 years	1.000 years	10.000 years	100.000 years	1 M years	10 M years
PWR							
Fuel cladding + springs	30000	1000	40	25	12	4,4	0,07
Top nozzle	6700	270	4,2	3,4	1,5	-	-
Bottom nozzle	25000	1000	16	13	5,7	-	-
Controlrod guide tubes	600	2,7	1,3	0,89	0,64	0,42	-
Spacers	30000	8400	140	120	47	0,04	-
Total in the fuel bundle	92000	11000	200	160	67	4,8	0,08
Boron glass rods (Gbq tot)	$5,9.10^6$	$1,7.10^5$	2700	2100	920	0,4	-
BWR							
Fuel cladding + springs	12000	1200	42	28	14	4,8	0,07
Top tie plates and handle	4200	400	6,3	5,0	2,2	-	-
Bottom tie plates	4000	380	5,9	4,7	2,1	-	-
Spacers	10000	4000	58	49	22	0,009	-
Spacer capture rod	24	2,7	0,27	0,19	0,13	0,076	-
Total fuel bundle	30000	6000	110	87	40	4,9	0,07
Fuel channel tube	2200	43	20	13	8,5	5,5	0,09
Transition piece	5200	490	7,8	6,2	2,7	-	-
Total fuel channel	7400	540	28	19	11	5,5	0,09

Table 7

Induced activity in the metallic part of the fuel bundle (GBq/tU)

Nuclide	Half life (years)	Activity (GBq/ton U) after 10 years	100 years	1.000 years	10.000 years	100.000 years	1 M years	10 M years
PWR								
C-14	5735	12	12	11	3,6	-	-	-
Co-60	5,25	48000	0,3	-	-	-	-	-
Ni-59	80000	140	140	140	130	60	0,02	-
Ni-63	92	21000	11000	12	-	-	-	-
Zr-93	$1,5.10^6$	3,7	3,7	3,7	3,7	3,5	2,3	0,04
Nb-93 m[x)]		1,5	3,7	3,7	3,7	3,5	2,3	0,04
Nb-94	20000	12	12	11	8,2	0,36	-	-
BWR								
C-14	5735	22	22	20	6,7	-	-	-
Co-60	5,25	5600	0,04	-	-	-	-	-
Ni-59	80000	79	79	78	72	33	0,01	-
Ni-63	92	12000	5900	6,7	-	-	-	-
Zr-93	$1,5.10^6$	3,8	3,8	3,8	3,8	3,6	2,4	0,04
Nb-93 m[x)]		1,7	3,8	3,8	3,8	3,6	2,4	0,04
Nb-94	20000	1,2	1.2	1,1	0,84	0,04	-	-

x) Daughter to Zr-93

Table 8

Total activity in the metallic parts of the fuel bundles (corresponding to 6000 tons of spent fuel)

Nuclide	Half life (years)	Activity (TBq) after 10 years	100 years	1.000 years	10.000 years	100.000 years	1 M years	10 M years
C-14	5735	120	120	100	35	-	-	-
Co-60	5,25	95000	0,7	-	-	-	-	-
Ni-59	80000	560	560	560	520	240	0,1	-
Ni-63	92	85000	43000	49	-	-	-	-
Zr-93	$1,5.10^6$	23	23	23	23	22	14	0,2
Nb-93 m		10	23	23	23	22	14	0,2
Nb-94	20000	23	23	22	16	0,7	-	-
Total		280000	44000	790	630	280	29	0,4

Table 9

Total activity in fuel channels and absorber rod bundles (corresponding to 6000 tons of spent fuel)

Nuclide	Half life (years)	10 year	100 years	Activity (TBq) after 1.000 years	10.000 years	100.000 years	1 M years	10 M years
C-14	5735	59	59	53	18	0,3	-	-
Co-60	5,25	11000	0,07	-	-	-	-	-
Ni-59	80000	33	33	32	30	14	0,006	-
Ni-63	92	4800	2400	2,8	-	-	-	-
Zr-93	$1.5.10^6$	20	20	20	20	19	12	0,02
Nb-93 m		8,9	20	20	20	19	12	0,02
Nb-94	20000	1,9	1,9	1,8	1,3	0,06	-	-
Total		40000	2600	130	90	52	30	0,04

Calculation of content of Nb-94 in the metallic parts of the fuel

Kjellbert /3/ has calculated Nb-94-content in spacers in BWR and PWR respectively. At unloading the following values are found

	BWR	PWR
kg Nb/tU	0,05	0,65
CiNb/tU	0,0185	0,256

Also the other parts contain small amounts of Nb.
According to information from Sandviken the following values are typical.

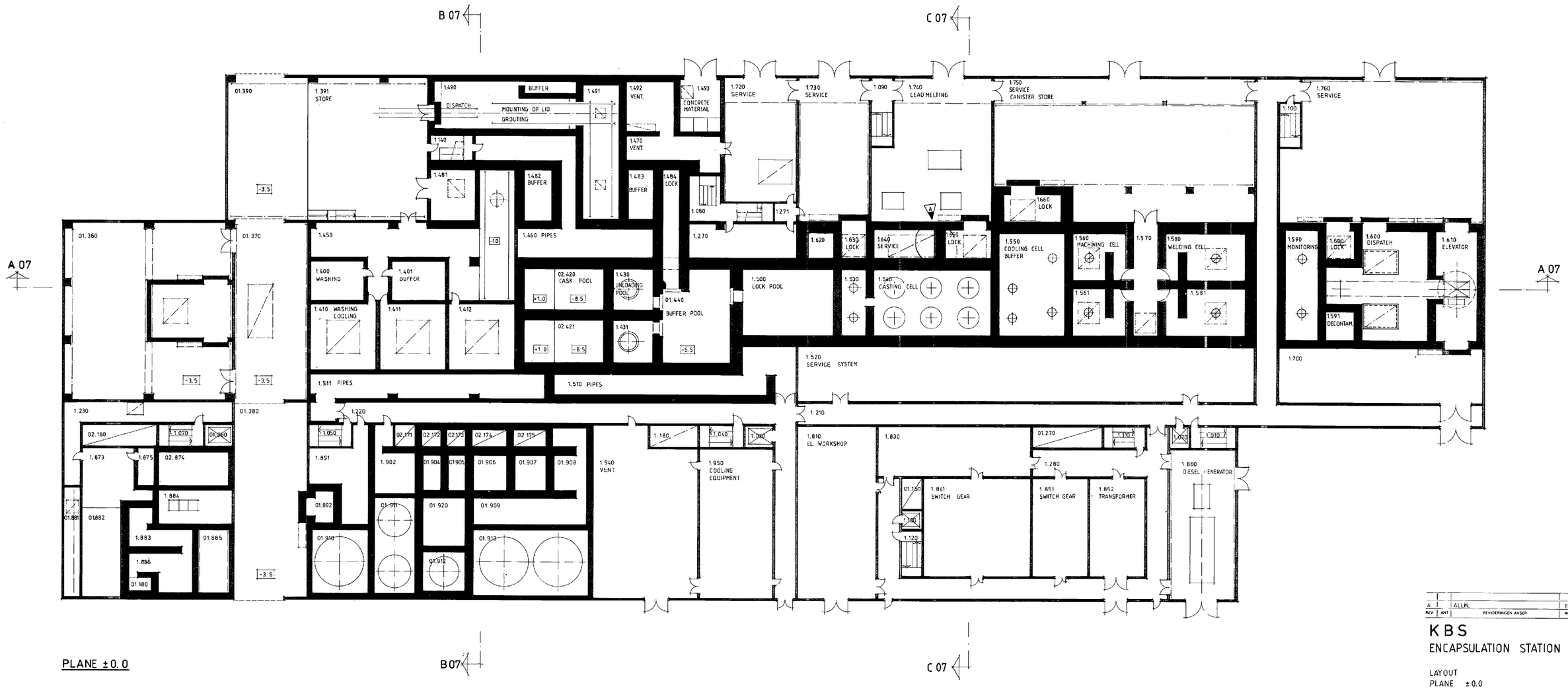
SIS 2333, 2352 AISI 304	0,03 w/o
Zr-2, Zr-4	0,01 w/o
Inconel X-750	0,9 w/o
Inconel X-718	5,0 w/o

From these values the activity content of Nb-94 (at unloading) in the different components can be calculated.

	Nb-94	
	Ci/tU	Gbq/tU
BWR		
Fuel cladding + spacer capture rod	0,010	0,37
Spacers	0,019	0,70
Top- and bottom tie plates	0,003	0,11
Fuel channel	0,011	0,41
PWR		
Fuel cladding	0,010	0,37
Spacers	0,30	11
Top and bottom tie plates	0,005	0,19

KBS - Encapsulation station - Layout

VBB, Lars Ageskog



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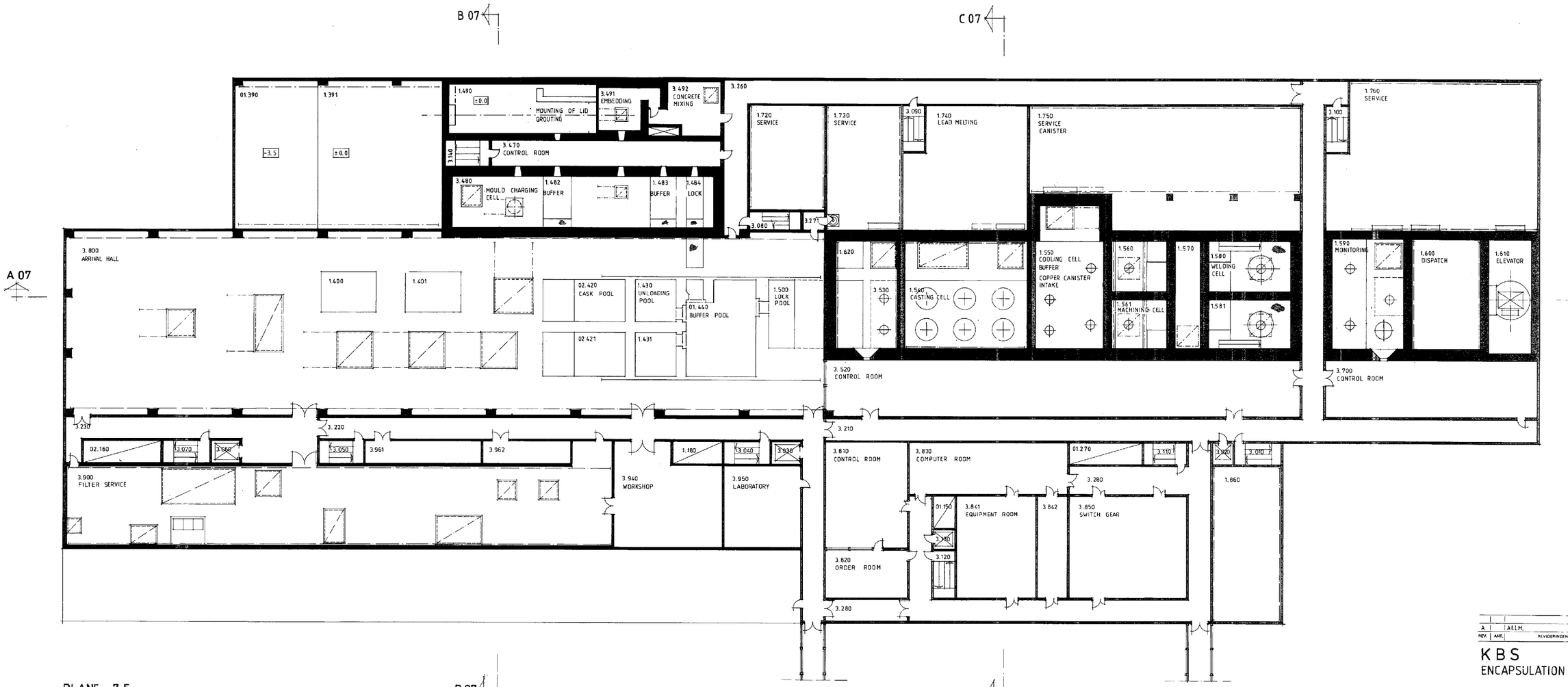
KBS
ENCAPSULATION STATION

LAYOUT
PLANE ±0.0

KONSTRUERAD	RITAD	GRANSKAD	REG.NUMMER
LEA	HOS		B 87 95
SKALA	RITNINGSNUMMER		REV.
1:	BSAB 04		A

STOCKHOLM DEN 81 12 12

VBB
BOX 5038
102 41 STOCKHOLM 5
TEL 08-7827000



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KBS
ENCAPSULATION STATION

LAYOUT
PLANE +7.5

KONSTRUERAD	RITAD	GRANSKAD	REG-NUMMER
LEA	HOS		B 87 95

SKALA	RITNINGSNUMMER	REV.
1 :	BSAB 03	A

STOCKHOLM DEN 81 12 12

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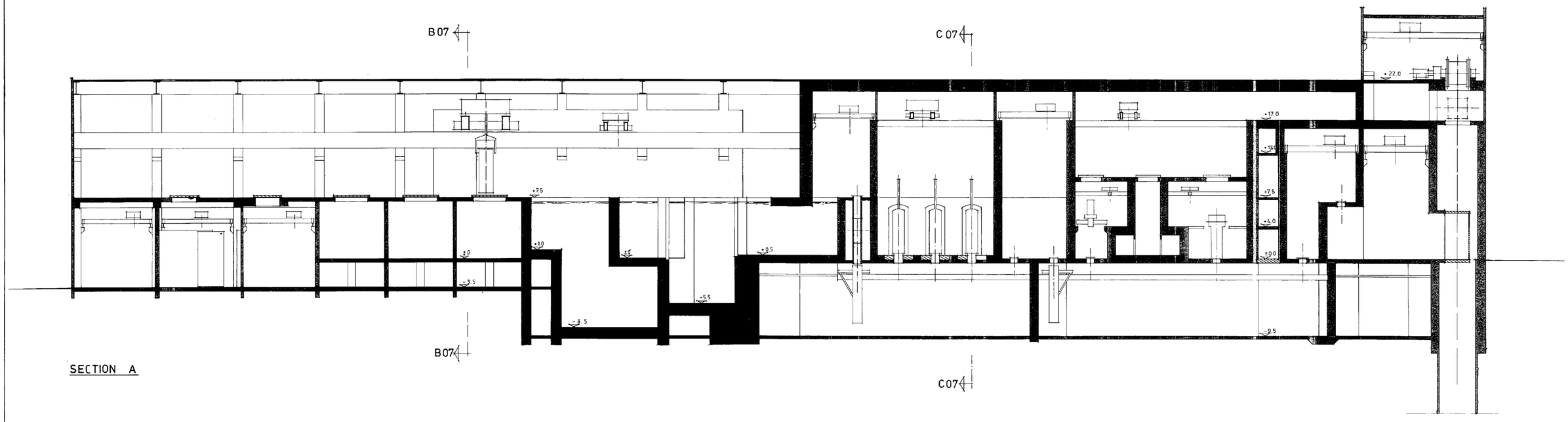
TEL. 08-22 85 80



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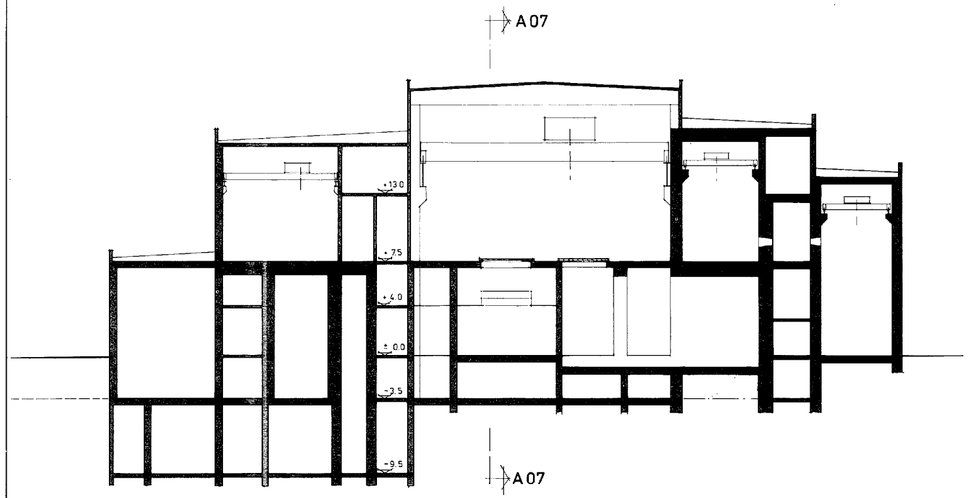

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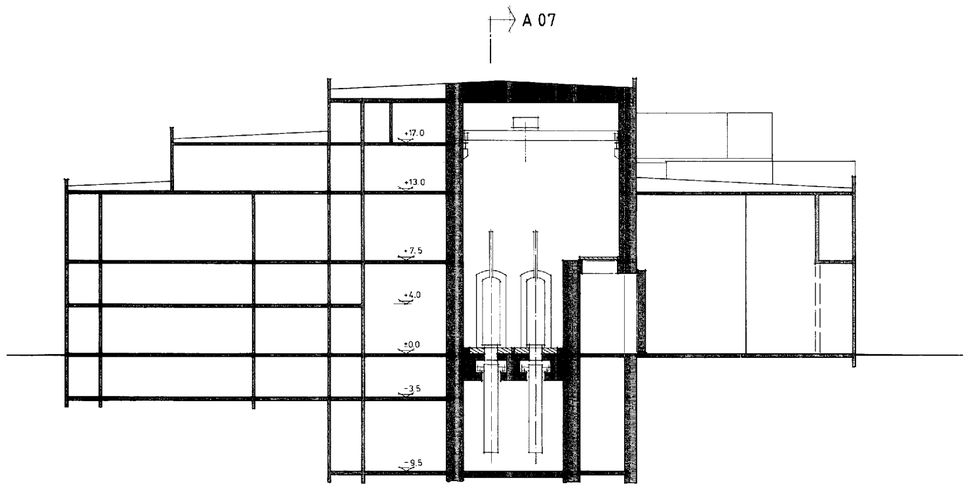

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A		ALLM.		SKJ	LEA	830316

KBS
ENCAPSULATION STATION

LAYOUT
SECTIONS

KONSTRUERAD	RITAD	GRANSKAD	REG NUMMER
LEA	HOS		B 87 95

SKALA	RITNINGSNUMMER	REV.
	BSAB 07	A

STOCKHOLM DEN 87 12 12

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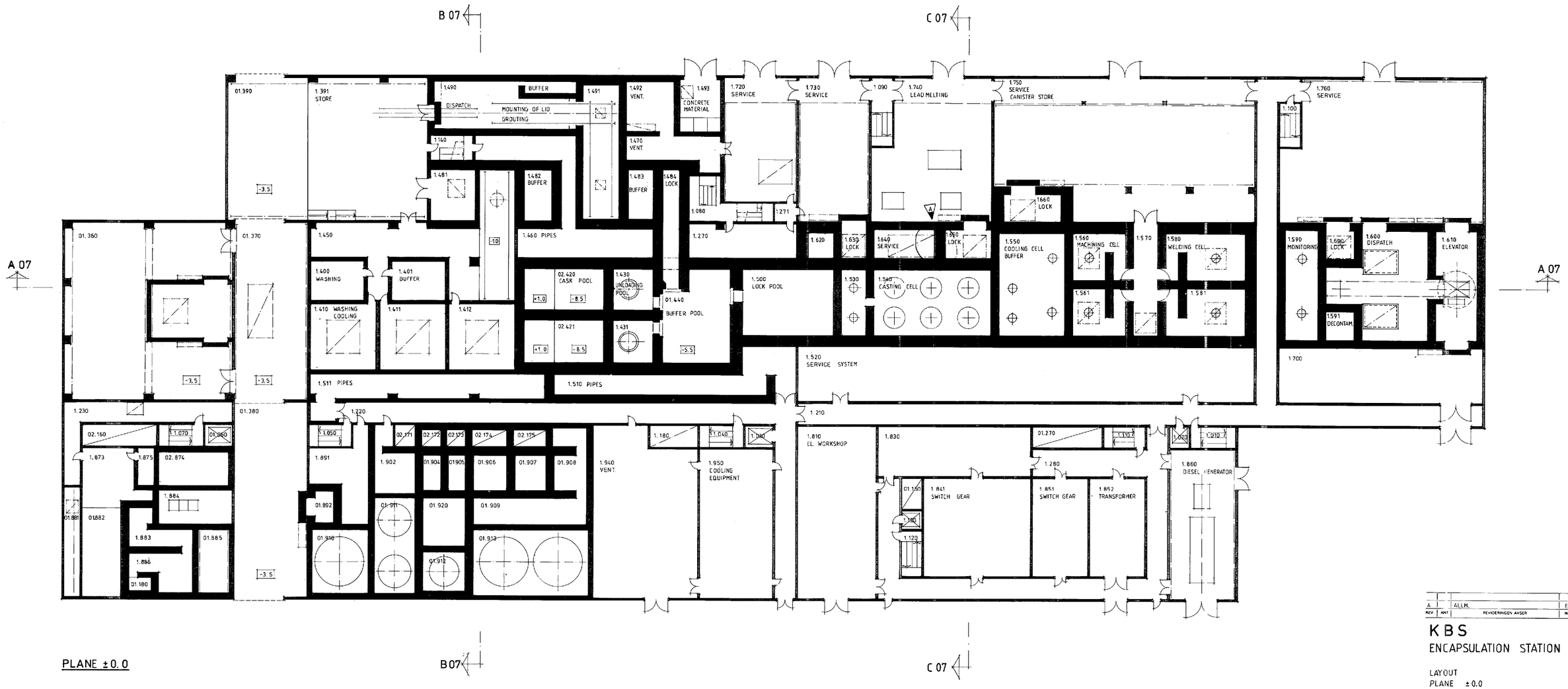
TEL. 08-7 62 70 00



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REV.	ANT.	REVIDERINGEN AVSER		RITAD	GRANSK. DATUM

KBS
ENCAPSULATION STATION

LAYOUT
PLANE ±0.0

KONSTRUERAD	RITAD	GRANSKAD	REG.NUMMER
LEA	HOS		B 87 95
SKALA	RITNINGSNUMMER		REV.
1:	BSAB 04		A

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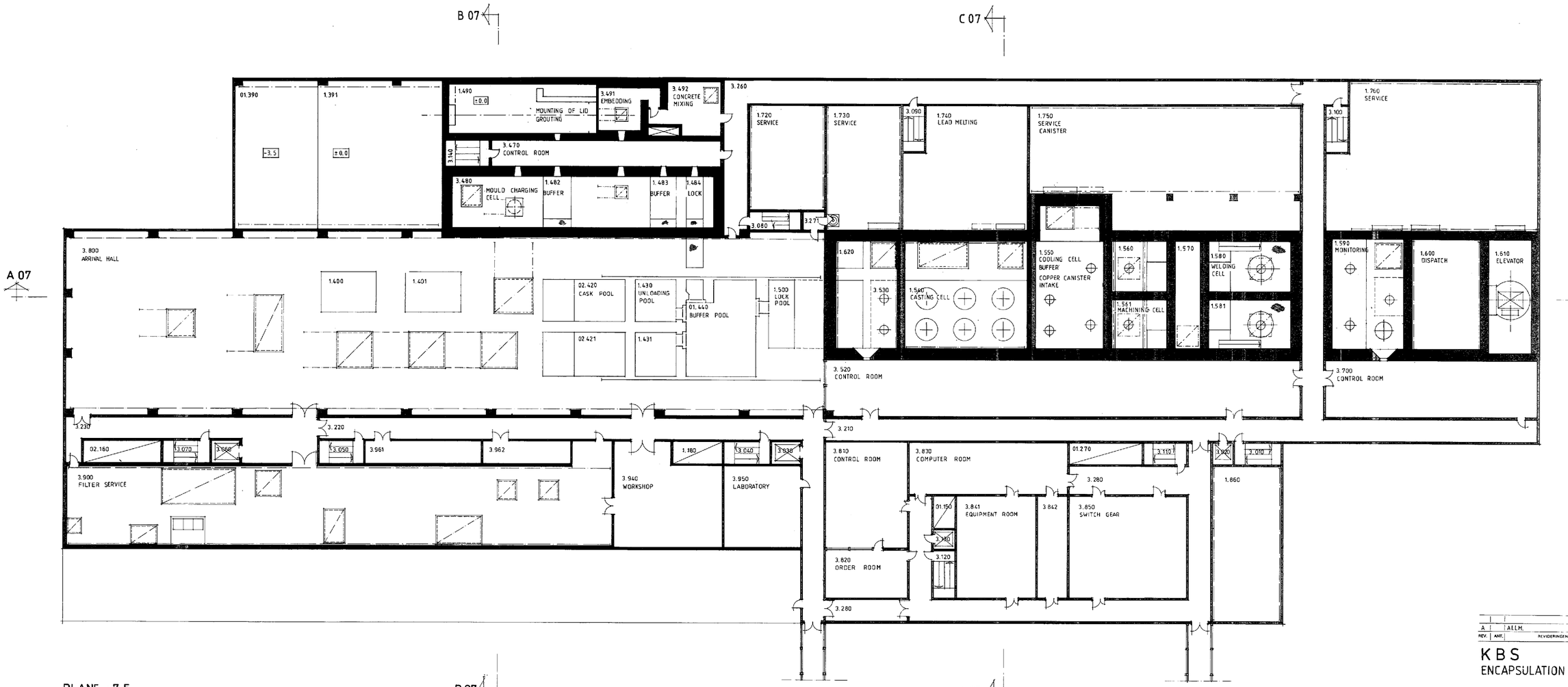

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ENCAPSULATION STATION

LAYOUT
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KONSTRUERAD	RITAD	GRANSKAD	REG-NUMMER
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SKALA	RITNINGSNUMMER	REV.
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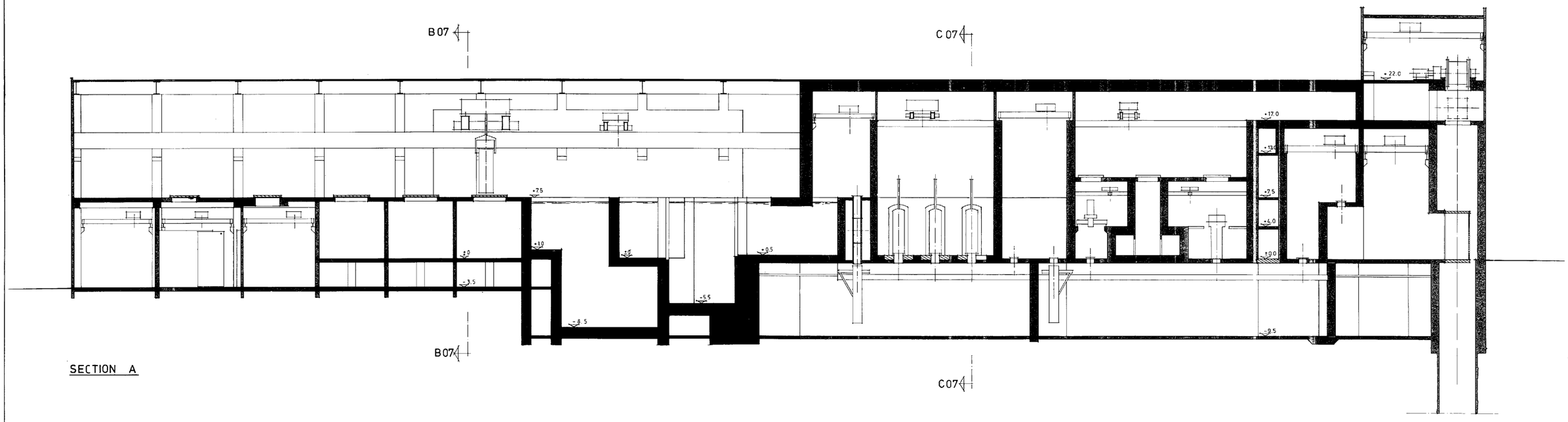

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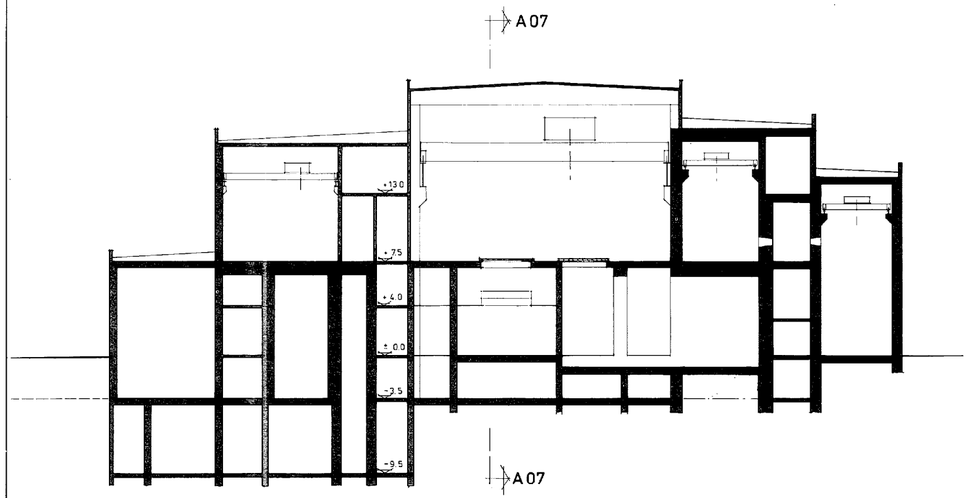

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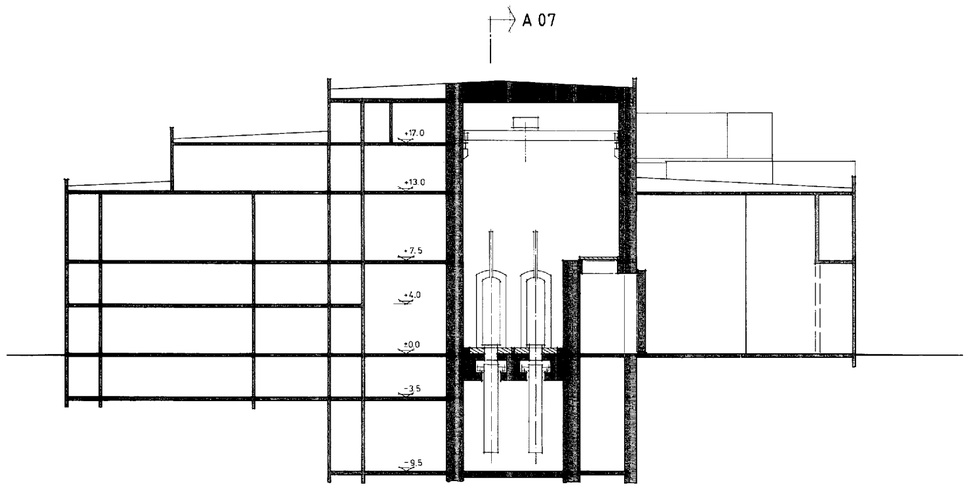

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LAYOUT
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	BSAB 07	A

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KBS 3 - Fuel aspects

AA BK 82-219, Gunnar Vesterlund

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KBS

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Sammanfattning/Abstract

ABSTRACT

In KBS 3 the feasibility of encapsulating spent fuel in copper powder by means of hot isostatic pressing (HIP) is studied. Copper powder and fuel is placed in a outer canister of copper, which is seal-welded and finally pressed in HIP.

Before the HIP-process the powder is conditioned in the canister in wet hydrogen gas, whereby the powder is activated by reduction of surface oxide.

In this report a review of the process steps dry handling, conditioning and HIP pressing is made in order to identify possible critical points for the fuel.

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(LP)

1 INTRODUCTION

In this project the possibility of achieving an encapsulation for spent fuel in copper, where solid copper encloses each fuel rod, is studied. This has been proved possible by using hot isostatic pressing (HIP). In the process 8 BWR or 2 PWR and 2 BWR fuel bundles are enclosed in one copper canister. No dismantling of the bundles is made. After receiving and unloading of fuel casks from CLAB, the fuel is dryed and loaded into a copper canister. The canister is filled with copper powder and sealed with a welded inner lid. The interior is conditioned with wet hydrogen gas and evacuated. A main lid is applied, an outer seal-welding is made and evacuation and HIP is performed.

Below are given special views on the process and on phenomena, which may appear when spent fuel bundles are handled.

2 THE DRYING PROCESS

The purpose of this process is to remove moisture as far as possible. Remaining moisture as well as surface oxide will deteriorate the result of the HIP process. The oxide on the copper powder gives a bad binding at HIP.

A special problem may appear when fuel, which has been damaged in the reactor use, is handled. Water will fill up the space between UO_2-fuel and zircaloy cladding. This space represents 5-15% of the net UO_2 volume where the span is due to facts like type of reactor etc. The frequency of the damages is low, however, and can be expected to be 0.02% of all fuel rods or 0.5-1% of all fuel bundles. In certain cases a reconstruction of bundles may have been performed so that damaged rods are collected in special bundles where several (a dozen) damaged rods are comprised. All damaged bundles can be assumed to be identified in the sipping in CLAB and may therefore be subject to a specially thorough drying, if necessary. The drying should, particularly for damaged fuel, be made in dry, streaming gas in such convection conditions that moisture is extracted by boiling. As a matter of coincidence a vast experience of the efficiency of such a boiling process is available.

In Studsvik and in some other test reactors a regular neutron radiographing of recently damaged fuel is made. The rods are then tested in the reactor, often until cladding fracture is achieved, after which neutron radiographing is made. This radiographing is particularly sensitive for the presence of hydrogen or water. In Studsvik about 100 rods are radiographed annually, a great deal of which is damaged. In ca 1% of the cases water appears in the free spaces of the rod.

The radiographing is normally made 10 h to 2 weeks after the removal from the reactor. Damaged rods are first fitted with dry casings in order to avoid leakage of activity (I-131) in the process. During the neutron radiographing it has been stated that the cladding surface temperature is 50°C. The efficiency of the moisture extraction is observed from the fact that moisture often is seen condensed on the inside of the casing.

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Damages occuring on fuel rods in power reactors are normally somewhat different from those presented above. Power reactor rods have often experienced a course of secondary damage, which results in an opening of the cladding fracture. The course is that the type of damage, which is the most frequent at least in BWR, normally leads to very small and thin cracks in the cladding, which even have been shown to be able to tighten during the reactor operation, when the rod power rating is lowered after the occurrence of the damage, as in the R2 reactor.

Through penetration of moisture after a longer period of operation with this type of damage, as in a power reactor, the damage will open. This means in a process discussed here, that fuel should be even more easily dried than indicated for the example with the R2 reactor test rods. Test rods are normally shorter, however, (0.5-2 m) than power reactor rods (4 m), which makes the drying more difficult.

The water extraction from damaged fuel rods leads to a deposition on the outer cladding surface of a deal of the inventory of cesium compounds (CsI etc) in the gap between UO_2 fuel and cladding. The deposition forms a porous layer. Cesium compounds are normally easily dissolvable in water. The amount of easily accessible cesium is usually small, however, as the rod is assumed to have been damaged during reactor power operation, after which a great deal of the gap inventory has been emitted to the reactor water. The fission yield for cesium is about 20%, i.e. at full burn-up there is about 10 g cesium in the rod, 1 g of which is in leachable form in the gap. The amount of activity in this easily leachable part is approx. 50 Ci (mainly Cs-137 with a half-life of 30.2 years), which can give a certain contamination when handling the fuel.

Another source of contamination in the drying step is crud on the cladding surface, i.e. mainly metallic impurities deposited from the reactor water and activated during the presence in the reactor. The amount of crud on the cladding varies a lot due to among other things the purity of the reactor water in various power plants. Measurements which have been made show that the crud amount usually is less than 10 g/m^2. Used as a mean value over the fuel surfaces this figure can be regarded as conservative for spent fuel of both BWR and PWR type. The composition and the density of the crud is among other things depending on the materials, which have been used in the primary systems of the reactors. The main ingredient for BWR as well as PWR is iron (40-95%). On rods from BWR the crud is usually relatively loose. About 75% can normally be brushed off, but the remainder can only be removed by grinding. The content of activity in this crud is low after the intermediate storage.

Directly after the removal from the reactor the crud layer activity is maximum about 0.5 Ci/m^2, of which Co-60 is 0.1 Ci/m^2. After an intermediate storage period of 40 years in CLAB the crud layer activity is dominated by Co-60 (with a half-life of 5.3 years), which has the been reduced to approx. 0.5 mCi/m^2.

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In certain cases more heavily damaged fuel may arrive to the encapsulation station. An example of this is PWR fuel, which has experienced so-called baffle jetting, implying that the cladding in certain areas of a bundle has been badly damage on some rods. Extensive growth of so-called secondary damage, leading to a strong embrittlement of some fuel rod, may be observed on damaged BWR fuel.

As a conclusion it can be stated that drying in hot gas has great opportunities to be successful. A certain contamination with Cs-137, Co-60 and fragments of UO_2 must be considered in dry handling. However, the decontamination problems should not be exaggerated. Great experience has been gained from decontamination of considerably more contaminated hot cells.

3 CONDITIONING OF THE COPPER POWDER

In order to achieve an acceptably good binding between the copper powder grains in the HIP the powder should be conditioned after filling. An earlier conditioning can be difficult as the powder becomes too active and gets a character of bad flowing. A good flowing is needed to fill up all cavities, e.g. the spacer capture rod in BWR bundles, the guide tubes in PWR bundles and spaces around spacers. The conditioning reduces the copper oxide on the powder surfaces by repeated vacuum pumping and filling with wet hydrogen. The copper oxide is very easily reduced and the equilibrium content of hydrogen is very low. The amount of copper oxide to be reduced may be considerable, which implies that the hydrogen content in any case must be big (50%) in order to avoid to many pumpings. The process may require up to 7 days.

The temperature should not exceed 400°C. As the inner gas pressure in a burnt-up PWR fuel rod can amount about 60 bar at room temperature, a circumferential stress of approx. 100 MPa is reached at 400°C, which is about 50% of the stress which gives stress corrosion in iodine atmosphere (iodine as a fission product is present as CsI inside the cladding). In pure hydrogen the zircaloy cladding is rapidly hydrogenated. At 350°C about 32 ml/cm^2 is absorbed in 10 minutes according to figure 1. This corresponds to a hydrogen content of more than 5000 ppm in the BWR cladding. Such a hydrogen absorption cannot be accepted in the process as the cladding thereby would be seriously embrittled, as can be seen from figure 2. The absorption of hydrogen should not be allowed to exceed about 100 ppm, otherwise embrittlement can appear in the cooling process after the conditioning. The ductility is strongly reduced by the hydride phase, liberated in the cladding, and small cracks or fracture indications in the cladding tube may lead to fracture since even cold rods have a substantial inner gas pressure (helium and the fission gases krypton and xenon in comparable amounts). The gases which could be released (ca 1 litre NTP/rod) are relatively harmless from the health point of view (noble gases), but they are not desirable in the process.

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The hydrogen reaction with pure zirconium surfaces is fairly well known since a long time. Several experiments have shown that the oxide films on the zircaloy surface forms a strong obstacle for the reaction. When an oxidized zircaloy surface is exposed to pure hydrogen gas no reaction occurs at first, but after a certain period of incubation a very rapid reaction takes place. The equilibrium pressure, at which the reaction turns to the opposite direction, is very low. The interpretation, which has been given for the reaction kinetics with hydrogen gas on an oxidized zircaloy surface is that a destruction of the oxide film occurs during the period of incubation so that absorption of hydrogen soon is enabled. The velocity of the destruction increases with temperature and the electric conductivity of the oxide film decreases during the incubation period, which is consistent with a model of explanation, in which the permeability of the oxide film increases, when a certain substoichiometry is achieved.

In experiments with hydrogen-zircaloy reaction the reaction often starts on edges and other roughnesses on the test samples. In many reported experiments, e.g. reference 1, it has proved hard to obtain reproducible results due to the difficulty of achieving a dry enough atmosphere. According to reference 2 an oxygen content of only $O_2/H_2 > 10^{-4}$ is required to maintain the passivity of the surface oxide and prevent the commencement of hydrogenating. In other studies (reference 3) an amount of oxidizing agent, corresponding to the one which is consumed by the zircaloy surfaces when oxidized with normal velocity has shown to be sufficient. Normal velocity oxidation means then that velocity which is determined not by the supply of oxygen but by anion or electron diffusion through the oxide film. At 350-400°C the oxidation velocity in steam under such conditions, given as weight increase per day, is ca 1 mg/dm^2 according to figure 3. Calculated for the total zircaloy surface of 8 BWR bundles this corresponds to a moisture consumption of ca 0.3 g H_2O/h.

Such an amount of water can be added for instance by wetting the hydrogen in water at 25°C with a flow of about 10 l H_2/h, if flowing through should be practicle in the process. Since water is also formed from the reduction of copper oxide a passivating situation as above is obtained at lower flow.

In the row of experiments in this field are also reported certain studies where hydrogenating has occurred when a sufficient amount of oxidizing agent has been available in the atmosphere. A report is given as reference 4 where a hydrogen overpressure of 172 bar with 343°C water has given hydrogenating corresponding to about 200% of the formed corrosion hydrogen. But this should only give 2 ppm increase of hydrogen content per day in the cladding, which can be accepted in a time of up to the 7 days discussed for the process.

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In another experiment (reference 5) made at 500°C, 1 atmosphere and 50 vol % hydrogen, similar values are reported, i.e. more than 200% hydrogen absorption compared with the amount of hydrogen formed by corrosion. Due to the high temperature with a corrosion velocity of ca 50 mg/dm^2 per day the hydrogenating is considerable in this case. In both these last mentioned experiments the hydrogenating starts when a so-called transition in the corrosion kinetics has appeared. The zircaloy oxidation in water or steam is subject to such a transition from approximately cubic to linear kinetics at an oxide thickness of 2-7/um. After-transition oxidation can thus be assumed to appear on spent power reactor fuel.

In a conclusion it can be stated that a light wetting of the hydrogen should be sufficient to prevent deteriorating hydrogenating of the zircaloy cladding under the conditioning at 350°C. A good safety margin from the experimental value $H_2/H_2O = 10^4$ should be maintained, however, say $H_2/H_2O < 10^2$ (volume), which is possible by wetting the hydrogen.

4 THE HIP PROCESS

In the hot isostatic pressing process the fuel is exposed through the copper powder to a compression of 1500 bar at about 550°C during some 4 h. At first a pressurization of the outer canister takes place up to about half the pressure and then the canister is heated up to 550°C, whereby the gas expansion increases the pressure to 1500 bar. The fuel is thus first subject to an increasing temperature after which the pressure is increased gradually. The high pressure and temperature result in a collapse of the cladding against the fuel pellets and the spring in the top of the rod. In spent fuel there may also appear shorter gaps in the pellet column, arising from an aftersintering of the pellet during operation. At 550°C the zircaloy cladding is relatively ductile and the collaps should not lead to rod fractures. The radiation hardening from the neutron radiation during operation is already recovered in the temperature range 450-500°C. But even if the temperature has not reached this range before cladding has been exposed to a considerable pressure, the rods will normally not be damaged, as the neutron radiation does not influence the ductility of the material. Since the deformations which can be expected on the fuel during the HIP process are not known, it is difficult to estimate the probability for cladding damages more than in a principle way. In BWR as well as PWR bundles there are spacers of Inconel X-750 or Inconel 718, both of a complicated design, why the copper flow around them during the fusion is hard to foresee. These materials are also very hard even at 550°C, why high local pressures may appear on the cladding tubes, where the spacer springs contact the tubes.*)

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*) Later HIP tests have shown that no significant impression can be found after the process.

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During the HIP at 550°C hydrogen is emitted from the cladding, but only to a negligible amount. The equilibrium pressure of hydrogen in the atmosphere is only about 0.1 torr when the cladding content is 1000 ppm. Typical values of cladding hydrogen content is considerably lower i.e. approx. 100 ppm after reactor operation, where the equilibrium pressure is 10^{-3} torr. Damaged rods may contain higher quantities.

If fuel rods are damaged during HIP, at most ca 1 litre NTP gas is emitted per rod (Xe, Kr, He). This can make the fusion of the copper powder difficult and may result in porosity. Among other fission products CsI is the most volatile (emitted iodine can be expected to appear as CsI). The equilibrium pressure of CsI at 550°C is totally negligible, however. Possibly may the freesetting of noble gases, if a rod is damaged, result in freesetting of particular CsI.

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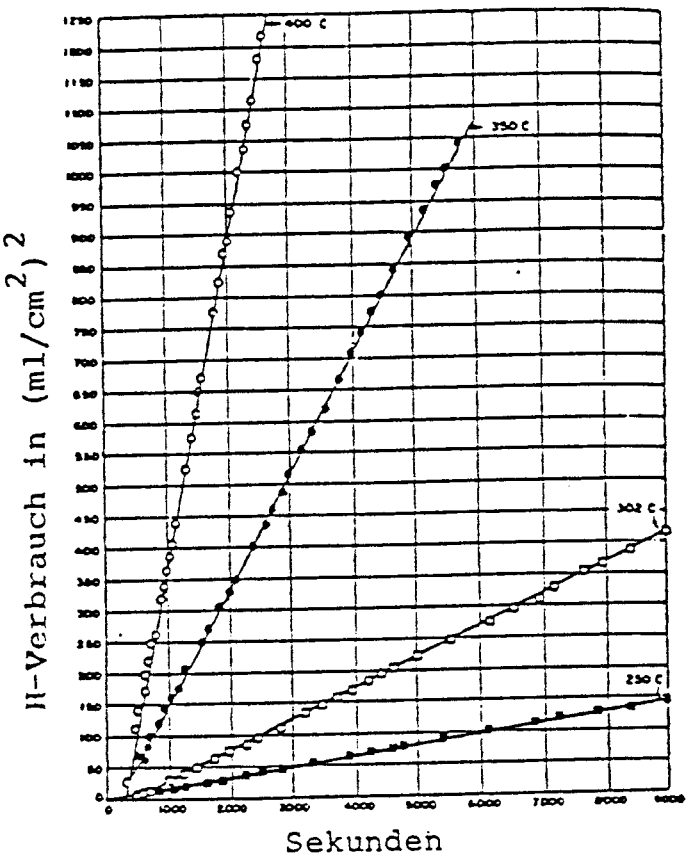

Figure 1. Absorption of hydrogen in zirconium at various tempeatures.

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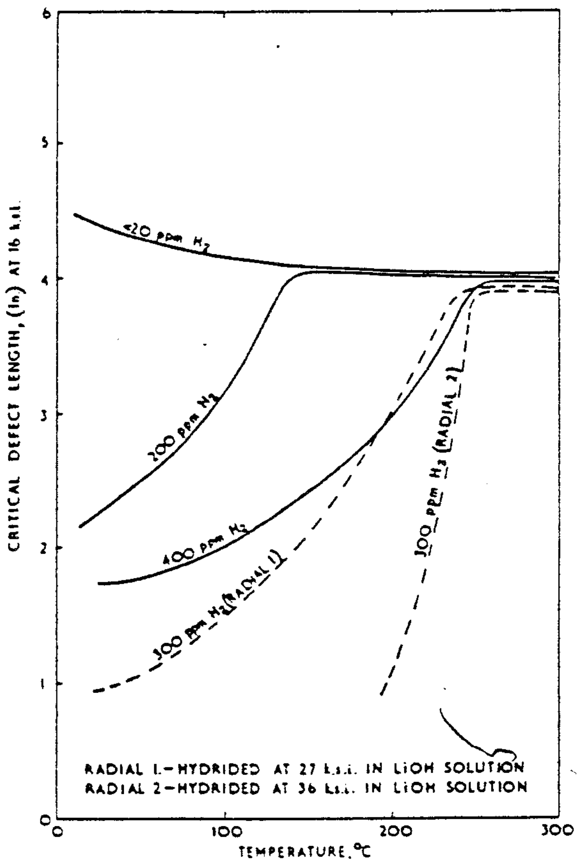

Figure 2. Variation in critical defect length with temperature for Zircaloy-2 with varying hydrogen content.

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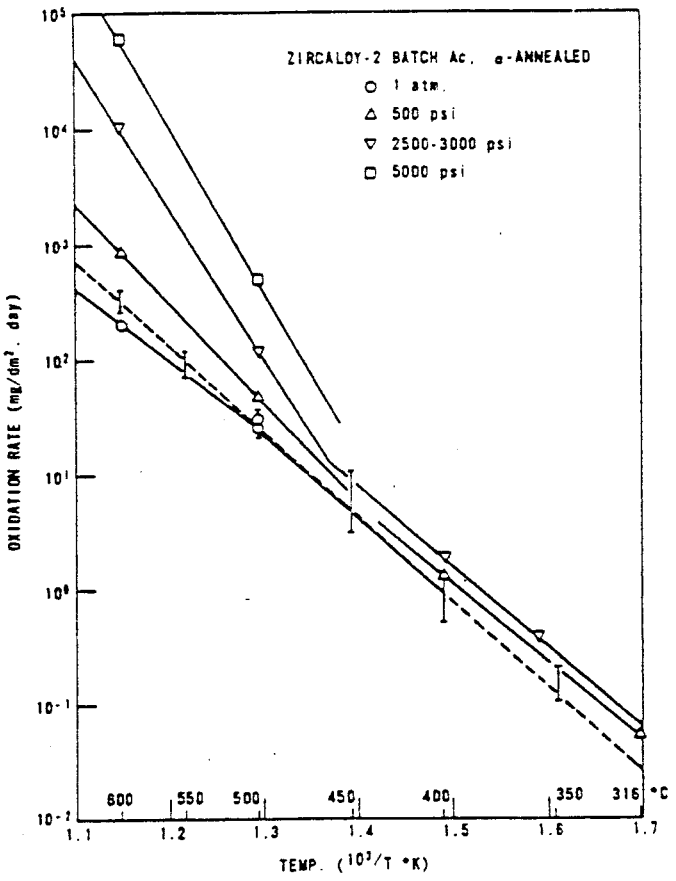

Figure 3. Zircaloy-2 corrosion in steam.
Influence of pressure.

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KBS 3 - Copper canister for direct disposal - Radiation levels

AA PM KPC 83-19, Klas Lundgren

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Kopia till
TAB

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KBS 3 - Copper canister for direct disposal - Radiation levels

Sammanfattning/Abstract

According to present plans, copper canisters will be used for final storage of spent nuclear fuel from Swedish LWRs, after the fuel has decayed for 40 years. Two different concepts are discussed, i.e. welded or pressed canisters. The radiation levels outside the canisters have been reported earlier, although certain modifications to the design of the canister have led to new calculations being carried out, and these are presented in this Memorandum.

The checked reference cases are assumed to contain 8 BWR fuel bundles with a burn-up of 33 MWd/kg U. The resulting gamma dose rate on the surface of the canisters will be 1.9 mSv/h in the case of the welded canisters and 9.0 mSv/h for the pressed canisters, whereas the neutron dose rate will be 1 mSv/h on both types. A disturbance analysis (different types of fuel, different burn-up, non-centred fuel racks, etc.) shows that the maximum gamma dose rate may be 6 - 14 times higher and the neutron dose rate may be 5 times higher.

This Memorandum also gives particulars of the radiation level in the handling of unshielded fuel and presents proposals for the design of a handling radiation shield for the canisters. If a maximum of 0.1 mSv/h at a distance of 1 m from the surface of the canister is assumed, the additional shielding may consist of 9 -11 cm of steel + a neutron shield (e.g. 10 - 15 cm of borated polyethylene). As an alternative, the shielding may consist of 35 - 40 cm of concrete.

(LP)

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CONTENTS

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1 INTRODUCTION

According to present plans, copper canisters will be used for encapsulating the spent nuclear fuel from Swedish LWRs for terminal storage. It was expected that encapsulation would take place after a decay period of 40 years following removal of the fuel from the reactor. The radiation levels and the radiation energy emitted to the water have been reported earlier in a number of reports (Ref 1 and Ref 2).

Two different concepts are being discussed at the present time, i.e. welded canisters and pressed canisters. In the former case, the fuel is encapsulated into the canister by means of molten lead, whereas in the latter case, hot isostatic pressing is used for encapsulating the fuel in a copper matrix. In both cases, it is assumed that the fuel is in the form of a number of intact fuel rod bundles (BWR or PWR). The planned design of a welded canister containing 8 BWR fuel rod bundles is shown on drawings No AA 201 168 and AA 201 282 (Appendix 1). The pressed version is expected to be of similar design, possibly with the addition of a fuel rod bundle in the centre, instead of the leadfilling pipe.

Ref 2 presents calculations for the two different types of canisters. The handling dose rates and the radiation energy emitted to the water outside the canisters in the final repository are both calculated. The effects of the fuel type (BWR or PWR), burn-up and the thickness of copper are studied by varying the parameters. However, the canisters proposed at the present time differ somewhat from those discussed in Ref 2, and a check calculation has therefore been considered necessary.

The check calculation has been carried out for two cases, i.e. welded canister and pressed canister containing 8 BWR fuel rod bundles. In both cases, it is assumed that the design of the canister will be as shown in Appendix 1, i.e. the only difference is that, in the latter case, the lead is replaced by copper.

The results of the check calculation are presented in this Memorandum. In addition, the radiation level outside an unshielded BWR fuel rod bundle is reported, to provide particulars of the radiation levels that may be expected in the handling of fuel in the handling cell. On the basis of Ref 2, the discussion in the last section analyses the effect of variations in the fuel particulars and the geometry on the results and comments on the need for additional radiation shielding in the handling of the canisters.

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2
RADIATION SOURCE TERMS

Radiation source terms corresponding to those in Ref 2 have been used in these calculation, i.e. the ORIGEN results (Ref 3) for the fission product and actinide activity and the AKT-GAMMA results (Ref 4) for the neutron-induced activity in the structural materials. However, an important correction has been made, i.e. the ORIGEN results for the gamma energy group with a mean energy of 0.575 MeV has been corrected to a mean energy of 0.66 MeV (i.e. same as the photon energy of Cs-137). The need for this change has been demonstrated in comparative calculations with source terms from the BEGAFIP computer code (Ref 2).

The gamma radiation source terms for a BWR fuel rod bundle with a mean burn-up of 33 MWd/kg U and a decay time of 40 years are shown in Table 1.

3
CALCULATIONS

The CYLGAM and GAMEN computer codes (Ref 5) have been used to carry out the gamma transport calculations. No new calculations have been carried out for the contribution of the neutrons to the dose rate, although an estimate has been made on the basis of the results in Ref 2. This is considered to provide satisfactory results, since the variation due to the different copper or lead shield thicknesses is small in the case of neutrons. In addition, the neutron dose rates outside the two different types of canisters have been considered to be equivalent.

The calculation geometry is shown in Figure 1. The assumed cylinder geometry has demanded certain simplifications as compared to the design in accordance with Appendix 1. The regional homogenisation used is shown in Table 2. Figure 1 also shows the points at which the dose rates have been calculated. The calculation results are shown in Table 3.

To provide information on the radiation levels around unshielded fuel, the dose rates at different distances from a BWR fuel bundle have also been calculated. The results are shown in Table 4.

4
DISCUSSION

The calculations reported in Table 3 show that the radiation level has a maximum in the radial direction. The radiation level is low axially upwards, and extra radiation shielding is therefore certainly unnecessary in this direction for the handling of the canisters.

The calculation outlined in the preceding section deals only with one case, which is also somewhat idealized. To obtain a more comprehensive picture of the radiation levels from various types of canisters, an analysis should also be carried out of various disturbances, such as different types of fuel, different burn-up, non-centred fuel rack, etc. An analysis of this type, largely based on the results from Ref 2, has been made and is presented in Table 5. The analysis concerns radiation levels in a radial direction.

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A comparison of the figures in Table 3 with those in Table 5 will reveal that the surface dose rate from the welded canister will be a maximum of 32 mSv/h (27 and 5 mSv/h for gamma and neutrons, respectively) and that from the pressed canister, 59 mSv/h (54 and 5 mSv/h, respectively). The corresponding radiation levels at a distance of 1 m from the canister will be 8.9 mSv/h (7.4 and 1.5 mSv/h, respectively) and 17 mSv/h (15 and 1.5 mSv/h, respectively).

Some type of extra radiation shielding will be necessary for the handling and transport of the canisters. The design prerequisites for such a shield have not been established, although a radiation level between 0.01 and 0.1 mSv/h at a distance of 1 m from the surface of the canister should be acceptable. As a calculation example, we presuppose a maximum of 0.1 mSv/h at 1 m from the canister, with equal contributions from gamma and neutrons. The gamma radiation must thus be attenuated by a factor of approx. 150 for the welded canister and approx. 300 for the pressed canister. The necessary attenuation factor for neutrons is approx. 30.

If the shield is to be made of steel, it must be supplemented with a special neutron shield. To obtain the required attenuation factors for gamma radiation, the thickness must be 9 cm for the welded canister and 11 cm for the pressed canister. If a neutron shield of borated polyethylene type (with a hydrogen content of approx. $6 \cdot 10^{22}$ atoms/cm^3) is used, a thickness of 10 - 15 cm will be necessary.

As an alternative, the shield can be made of concrete. A sufficient attenuation of gamma radiations as well as neutrons will be provided by a concrete thickness of 35 cm for the welded canister and 40 cm for the pressed canister.

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Table 1

Gamma source terms for a BWR fuel bundle (average burn-up 33 MWd/kg U, decay period 40 y)

Part	Energy bounds (MeV)	Average energy (MeV)	Source term (MeV/g,s)
Fission products + actinides in the fuel (per g of U)	0 - 0,45	0,3	1,47E8
	0,45 - 0,70	0,66	9,80E8
	0,70 - 1,0	0,85	1,52E7
	1,0 - 1,5	1,25	1,50E7
	1,5 - 2,0	1,75	9,06E5
	2,0 - 2,5	2,25	1,11E2
	2,5 - 3	2,75	5,10E2
	3 - 4	3,5	3,78E1
	4 - 6	5	2,31E1
	6 - 8	7	3,74E0
Springs (SS)	0,5 - 1,0	0,79	3,01E3
	1,0 - 1,5	1,25	8,00E6
Top tie plate incl. handle (SS)	0,5 - 1,0	0,79	1,29E3
	1,0 - 1,5	1,25	3,75E6
Bottom tie plate (SS)	0,5 - 1,0	0,79	2,26E3
	1,0 - 1,5	1,25	5,81E6

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Table 2

Regional homogenisation for a copper canister (welded or pressed) containing 8 BWR fuel rod bundles. (See also figure 1)

No	Content	Welded (g/cm^3)		Pressed (g/cm^3)	
1	Fuel	UO_2	2,41	UO_2	2,41
		Zr	0,55	Zr	0,55
		Pb	7,7	Cu	6,1
		(U	2,12)	(U	2,12)
2	Spring	SS	0,32	SS	0,32
		Zr	0,55	Zr	0,55
		Pb	7,7	Cu	6,1
3	Top tie plates incl. handles	SS	0,54	SS	0,54
		Pb	10,5	Cu	8,3
4	Bottom tie plates	SS	1,04	SS	1,04
		Pb	9,8	Cu	7,7
5	Filling	Pb	11,34	Cu	8,93
6	Canister	Cu	8,93	Cu	8,93

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Table 3

Radiation levels (mSv/h) at different positions outside a copper canister (welded or pressed) containing 8 BWR fuel rod bundles (Positions described in figure 1)

Position		Welded gamma	Welded neutrons	Pressed gamma	Pressed neutrons
upwards					
1		<0,001	0,001	<0,001	0,001
2		0,002	0,002	0,007	0,002
3	d = 0,5 m	<0,001	<0,001	0,001	<0,001
4	d = 1,0 m	<0,001	<0,001	<0,001	<0,001
5	d = 2,0 m	<0,001	<0,001	<0,001	<0,001
6	d = 5,0 m	<0,001	<0,001	<0,001	<0,001
radial					
7	d = -5 mm	2,6	1	12	1
8	d = 0	1,9	1	9,0	1
9	d = 0,5 m	0,83	0,4	3,9	0,4
10	d = 1,0 m	0,53	0,3	2,5	0,3
11	d = 2,0 m	0,30	0,2	1,4	0,2
12	d = 5,0 m	0,10	0,05	0,46	0,05
downwards					
13		0,12	0,2	0,48	0,2
14	d = 0,5 m	0,051	0,09	0,22	0,09
15	d = 1,0 m	0,022	0,04	0,10	0,04
16	d = 2,0 m	0,007	0,01	0,033	0,01
17	d = 3,0 m	0,001	0,002	0,006	0,002

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Table 4

Radiation level outside an unshielded BWR fuel rod bundle (burn-up 33 MWd/kg U, decay period 40 y)

Distance (m)	Dose rate (Sv/h)
0	72
0,5	6,5
1,0	3,1
2,0	1,2
5,0	0,26

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Table 5

Radiation levels outside copper canisters (welded or pressed) - Disturbance analysis (Reference case see table 3)

Disturbance	Factors Welded gamma	Welded neutrons	Pressed gamma	Pressed neutrons
PWR (38 MWd/kg U) instead of BWR (33 MWd/kg U)	1,2	1,1	1,2	1,1
Higher burn-up (20%)	1,2	2,5	1,2	2,5
Non-centred fuel rack (d = 13 mm)	5,5	1,2	2,2	1,2
Thinner wall thickness (d = 5 mm)	1,3	1,0	1,3	1,0
Shorter decay period (30 y)	1,4	1,6	1,4	1,6
Total	14	5	6	5

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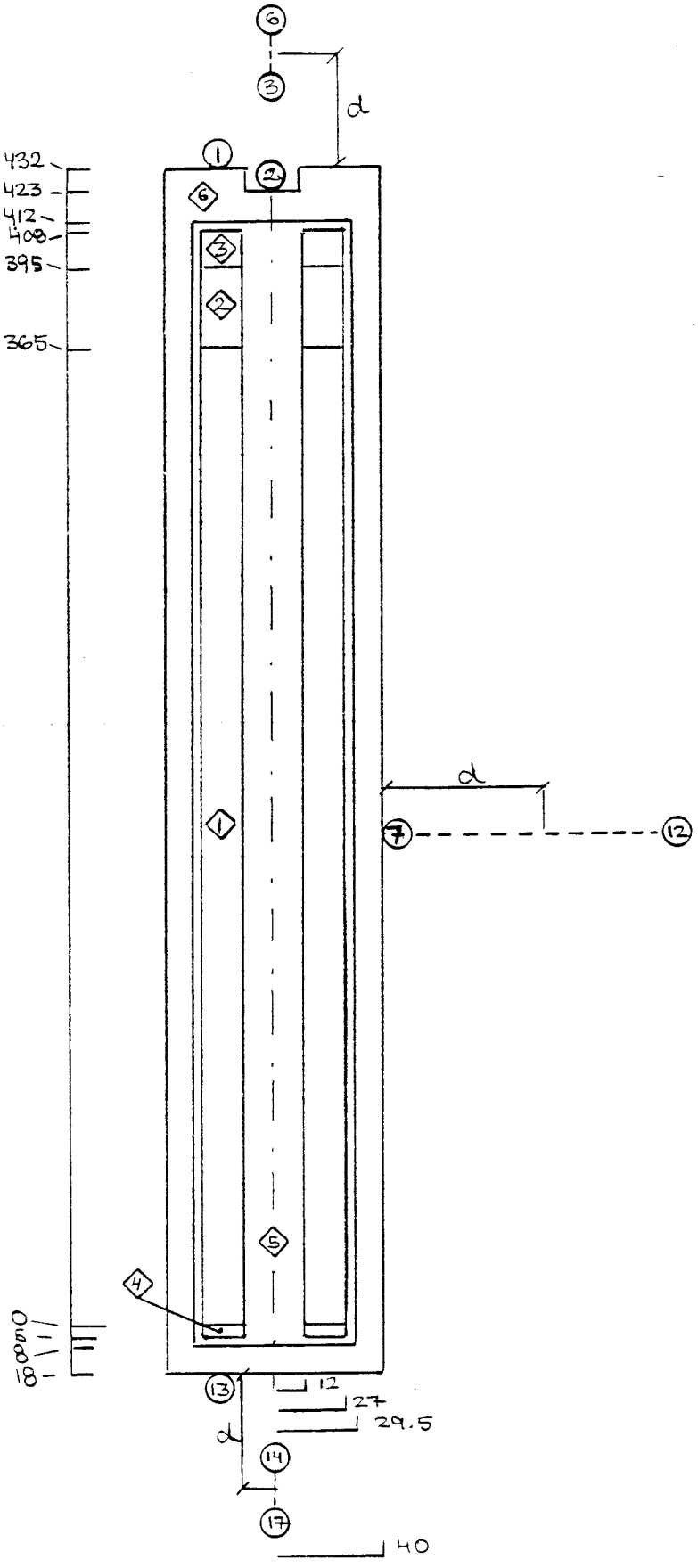
Figure 1. KBS 3 - Copper canister containing 8 BWR fuel rod bundles - Calculation geometry and dose rate positions

Scale 1:25

X Region No X
Homogenisation, see table 2

(X) Position No X
Dose rates, see table 3

cm



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KBS 3
Ställ med bränsle-knippen för direkt-deponering.

AA 201 168

Blad/Sheet 1
Skala/Scale 1:5

Konstr./Designer Lidström
Kontr./Checked R

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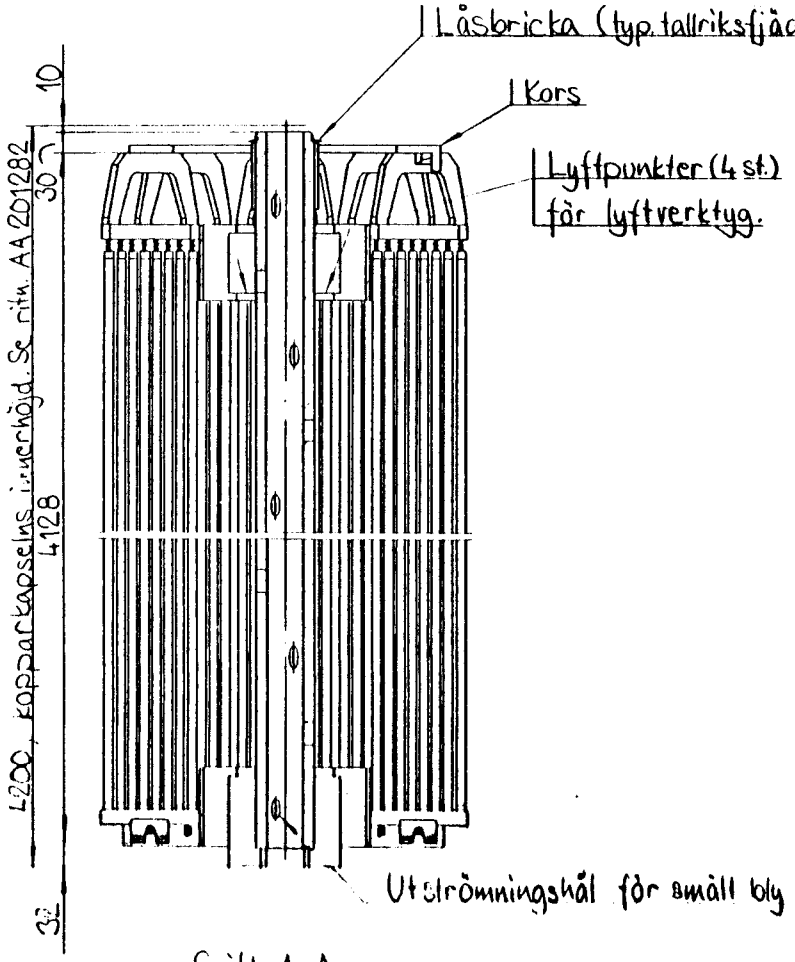
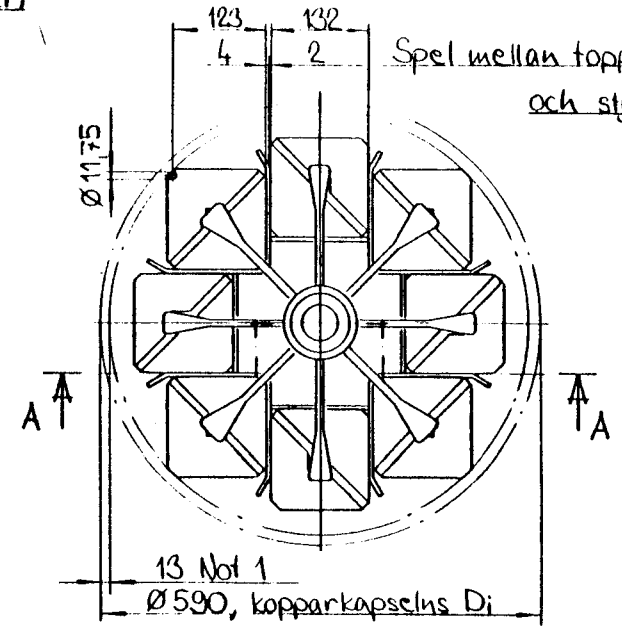


Snitt A-A



PM KPC 83-19 E Appendix 1a

Skala 1:1 | Skala 1:2 | Skala 1:2,5 | Skala 1:5

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KBS 3

Kopparkapsel för direktdeponering

AA 201282

Blad Sheet: 1 · Forts Cont: –

Skala Scale: 1:5 (1:1)

Mätnoggrannhetsklass enl. SMS 715 / Tolerance class acc. to SMS 715: ☒ Medel Medium ☐ Fin Fine

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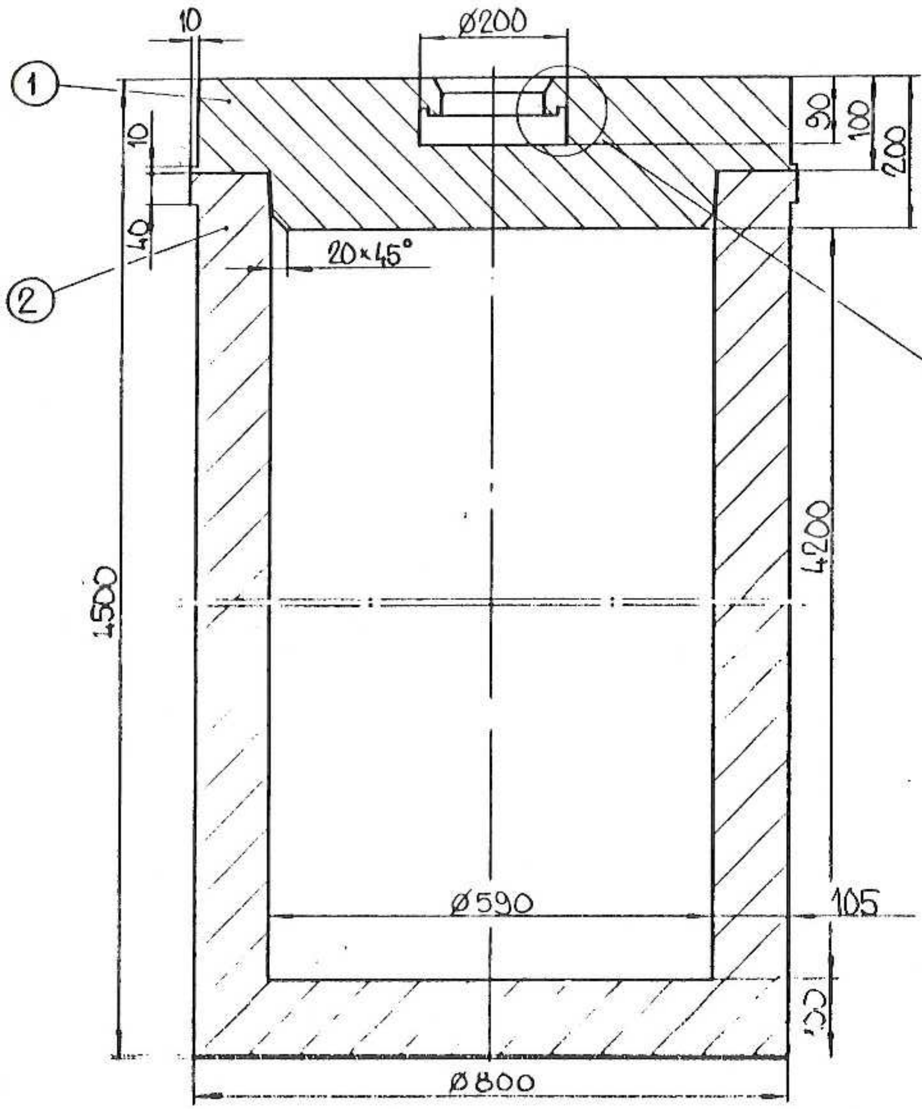
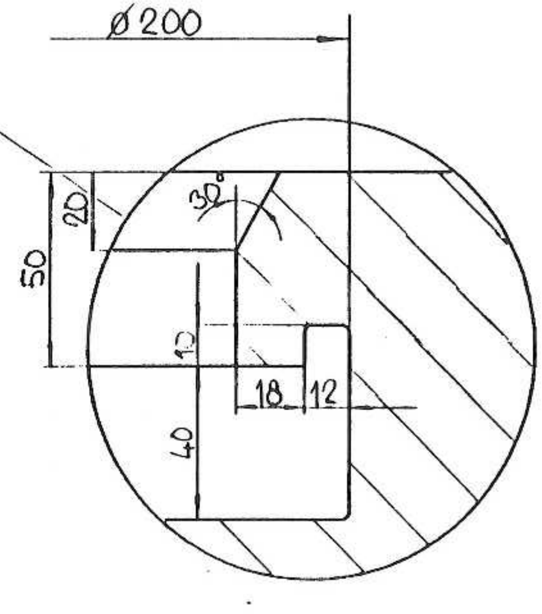
	1	2		Behållare		SS5015-02	D=800 L=4400





Skala 1:1

PM KPC 83-19E Appendix 1b

Skala 1:1 · Skala 1:2 · Skala 1:2,5 · Skala 1:5

Orientering Location · Ändring Revision · År vecka Year Wk · Tj st Dept · Godk Appd

KBS 3 - Mechanical Study of the Capsule

AA KUA 83-223, Anders Landström

ASEA-ATOM

Kopia till
TAB , KUA2, KUB1

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Memorandum
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KUA 83-223

Distribution	Från/From	Datum/Date	Reg.	Sida/Page
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Författare/Author
A Landström, 7408

Utfärdare/Issued

Granskad/Examined

Godkänd/Approved

Titel/Title

C 440.5126 KBS 3 - Mechanical Study of the Capsule (Canister)

Sammanfattning/Abstract

The Cu-capsule is filled up with lead which prevents unlimited deformations of the walls. Due to creep and external pressure it is assumed that the capsule will be deformed so that the decrease of volume equals the volume of residual enclosed cavities. Stresses due to pressure have been calculated on an elastic basis. High bending stresses are obtained in the centers of the heads and in the transitions between heads and cylinder. The elastic stresses fall below the tensile strength but nonlinear analyses in order to establish the strain history in the capsule have not been performed. If however the assumption is made that the expected creep induced volume decrease is obtained through deformation of the cylindrical wall only, a simplified analysis gives acceptable margins to the ultimate elongation of the material.
The study also shows that stresses which occur during lifting of the capsule are acceptable.

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1
INTRODUCTION

The capsule consists of a cylinder with a flat head. To the open end a cover is welded. In the cylinder the used fuel rods are placed after which it is filled with lead. The external pressure depends on the expansion of the bentonite in the storage and on the water pressure. Due to the lead the deformations of the capsule wall will be limited which prevents unacceptable long term creep deformations.

2
DRAWING

AA 201 282 (Appendix 1)

3
MATERIAL

Copper SS 5015-2

Properties according to TKN 73:

Temp. ^{o}C	20	100	125	150
σ_{ber} N/mm^2	54	54	52	49

Thermal expansion:

25 - 100^{o}C: $\alpha = 16.8 \cdot 10^{-6}/K$

20 - 300^{o}C: $\alpha = 17.7 \cdot 10^{-6}/K$

$E = 118\ 000\ N/mm^2$

$\nu = 0.3$

4
DESIGN DATA

External pressure: 160 bar

Temperature: 100^{o}C

Cavities may exist inside the capsule corresponding to 2 % of the internal volume.

5
LIFTING

Volume of Cu = 1.114 m^3

$\rho_{cu} = 8930\ kg/m^3$

Internal volume = 1.148 m^3

Disregarding the fuel rods the capsule is filled with lead.

$\rho P_b = 11340\ kg/m^3$

Total weight = M = 8930·1.114 + 11340·1.148 = 23 tons.

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The highest stress occurs in the cover at the cut where the tool is applied:

Diameter = 200 mm

Thickness = 40 mm

Area = $\pi \cdot 200 \cdot 40 = 25133$ mm^2

$\tau = 23000 \cdot 9.81/25133 = 9$ N/mm^2

$2\tau = 18$ N/mm^2 < σ_{ber}

6 ELASTIC CALCULATIONS

The elastic stresses in the capsule have been calculated with ASEA thin shell code R01030 under the assumption of 160 bar external pressure without support from the enclosed lead. The calculation model and stresses are found in appendices 2-5. As expected high elastic bending stresses are obtained at the centers of the heads and at the transitions between heads and cylinder. The total stress at any point falls well below the ultimate strength which should be at least 210 N/mm^2. In the welded joint at the upper cover the axial stress was calculated to -26.5 N/mm^2 compressive and the bending stress 78.8 N/mm^2 which gives a tensile stress 52.3 N/mm^2 at the outside and a compressive elastic stress -105.3 N/mm^2 at the inside of the joint.

7 CREEP DEFORMATION

Creep effects give a long term compression of the capsule with the lead filling up enclosed cavities. Regarding the design data the deformation of the capsule is supposed to correspond to a 2 % decrease of internal volume. It is reasonable to assume that the 2 % decrease is obtained through compression of the cylindrical wall only.

Cylinder length = L = 4200 mm

Outer radius = R = 400 mm

Thickness = t = 105 mm

Disregarding the influence of the heads, the cylinder is uniformly deformed along the following reduced, undisturbed length:

$L - 2 \cdot 2{,}4 \cdot \sqrt{R \cdot t} \approx 3200$ mm

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2 % of internal volume = $0.02 \cdot 1.148 \cdot 10^9$ =

= $2.3 \cdot 10^7$ mm^3.

This gives the required radial deformation:

$\delta = 2.3 \cdot 10^7/3200 \cdot \pi \cdot 590 = 3,87$ mm

The largest strain is obtained at the joint between cylinder and cover. The corresponding maximum elastic strain is:

$\varepsilon_{max,\ bend} = 1.82 \cdot \delta/R_i$

where R_i = inside radius = 295 mm

$\varepsilon_{max,\ bend} = 1.82 \cdot 3,87/295 = 2,4$ %

These calculations are based on the assumptions that the creep is determined from deformation of the cylinder, neglecting the influence from the heads, and that the deformations at the ends are proportional to the elastic deformation at a certain compression of the cylinder. The maximum strain has thus been somewhat underestimated but with regard to the ultimate elongation for Cu,

$\varepsilon_u \approx 45$ %

there is a considerable safety margin.

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KBS 3

Kopparkapsel för direktdeponering

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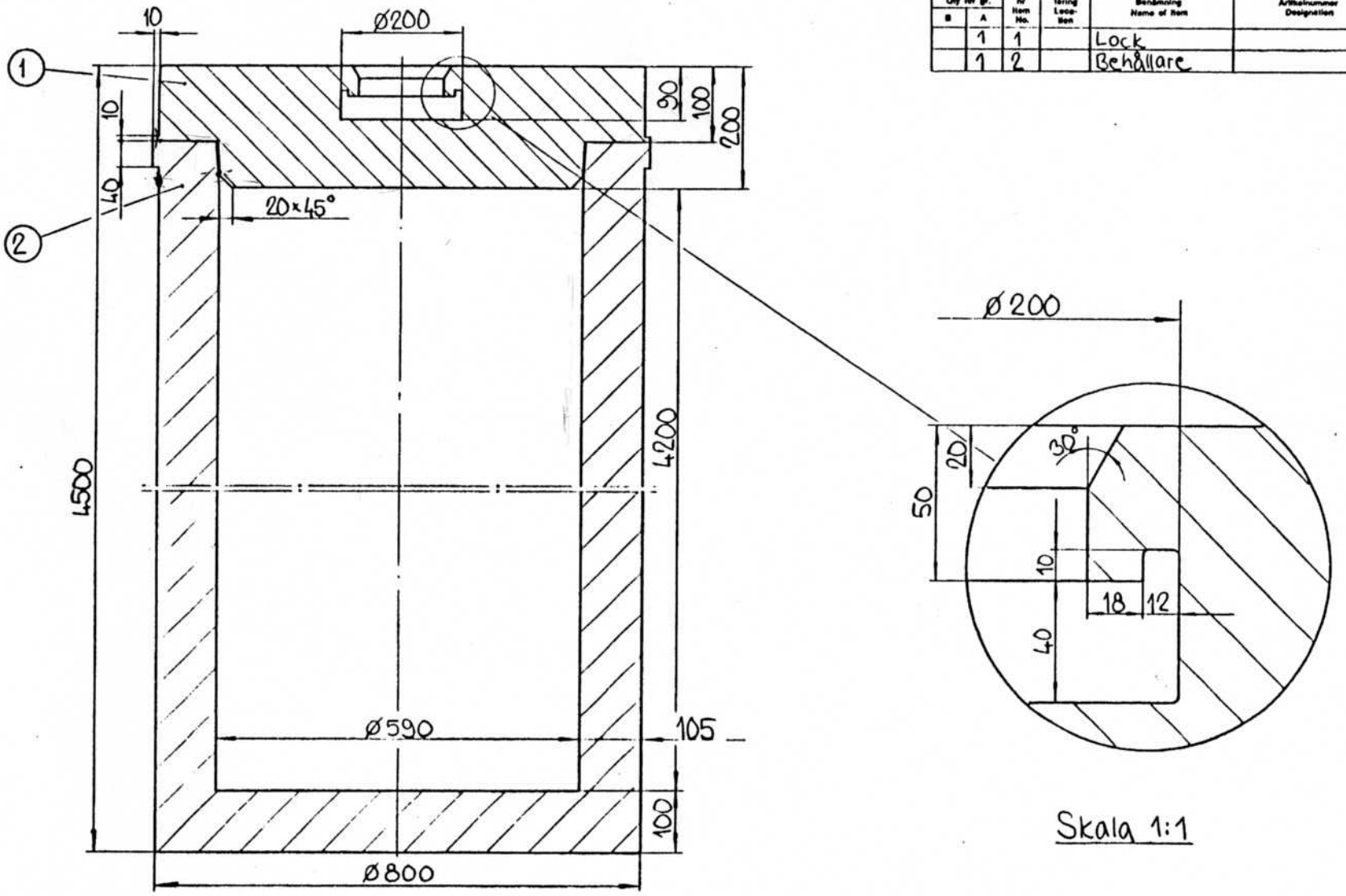

Skala 1:1

KUA 83-223

Appendix 1

SHELL STRUCTURE.

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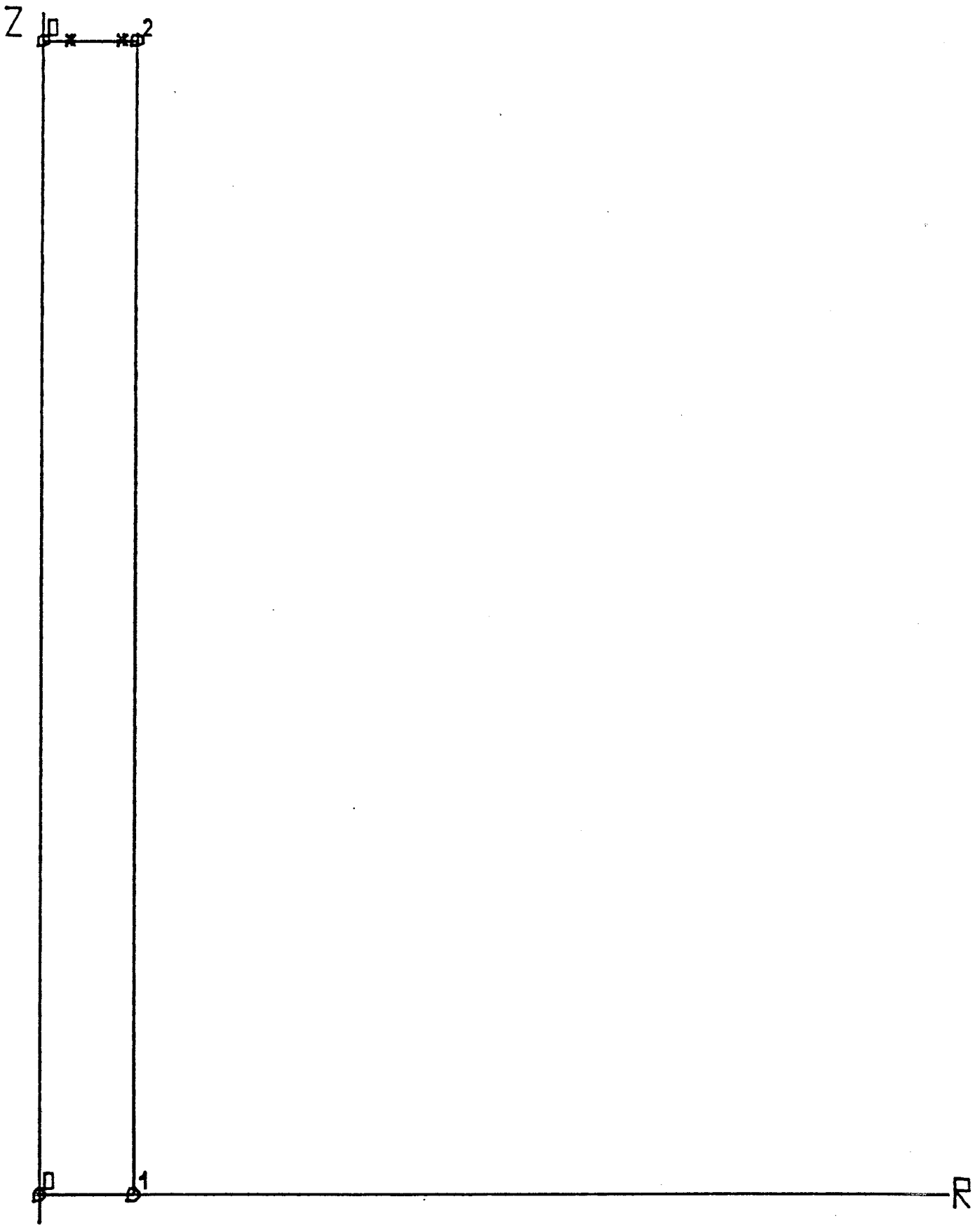
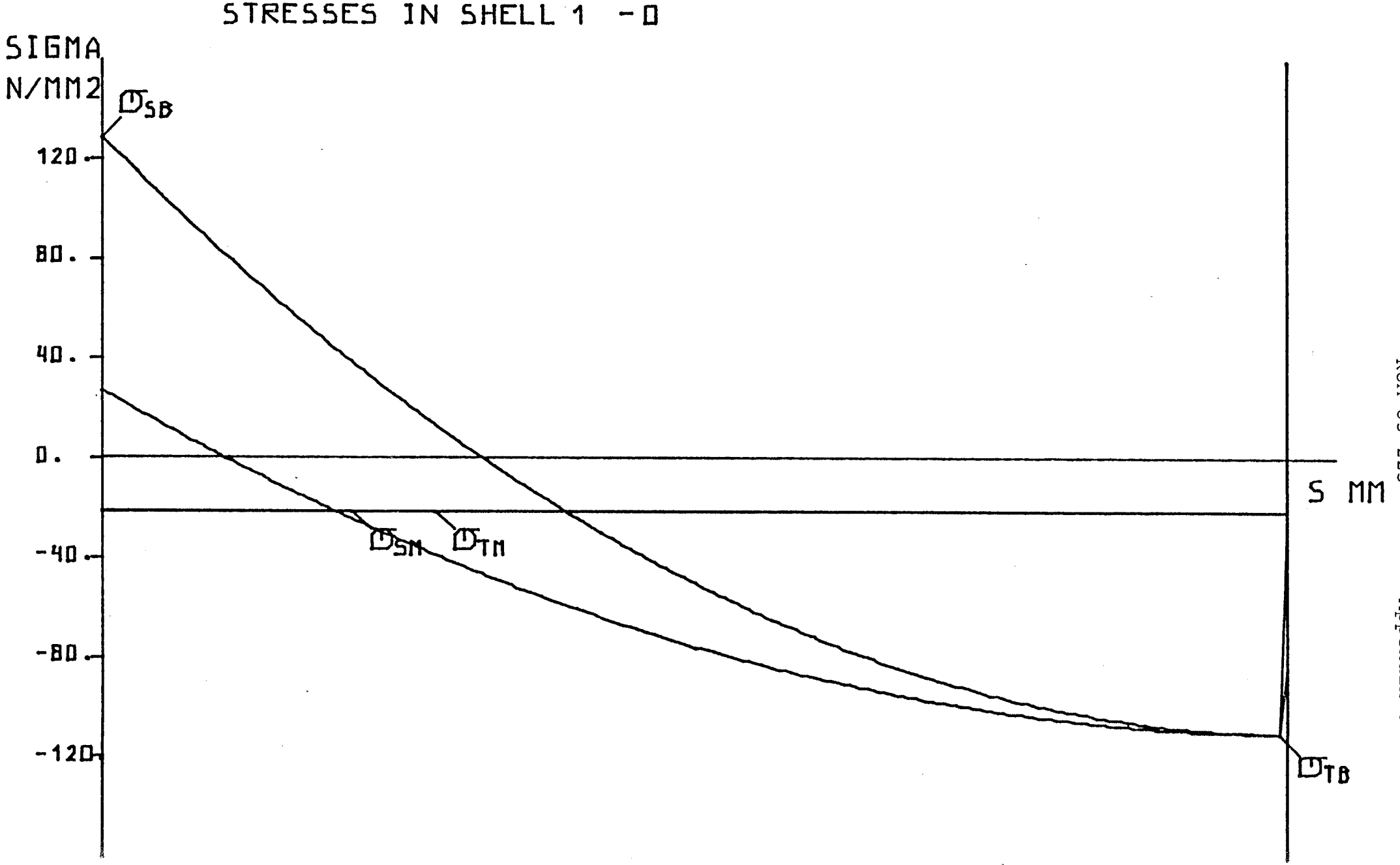
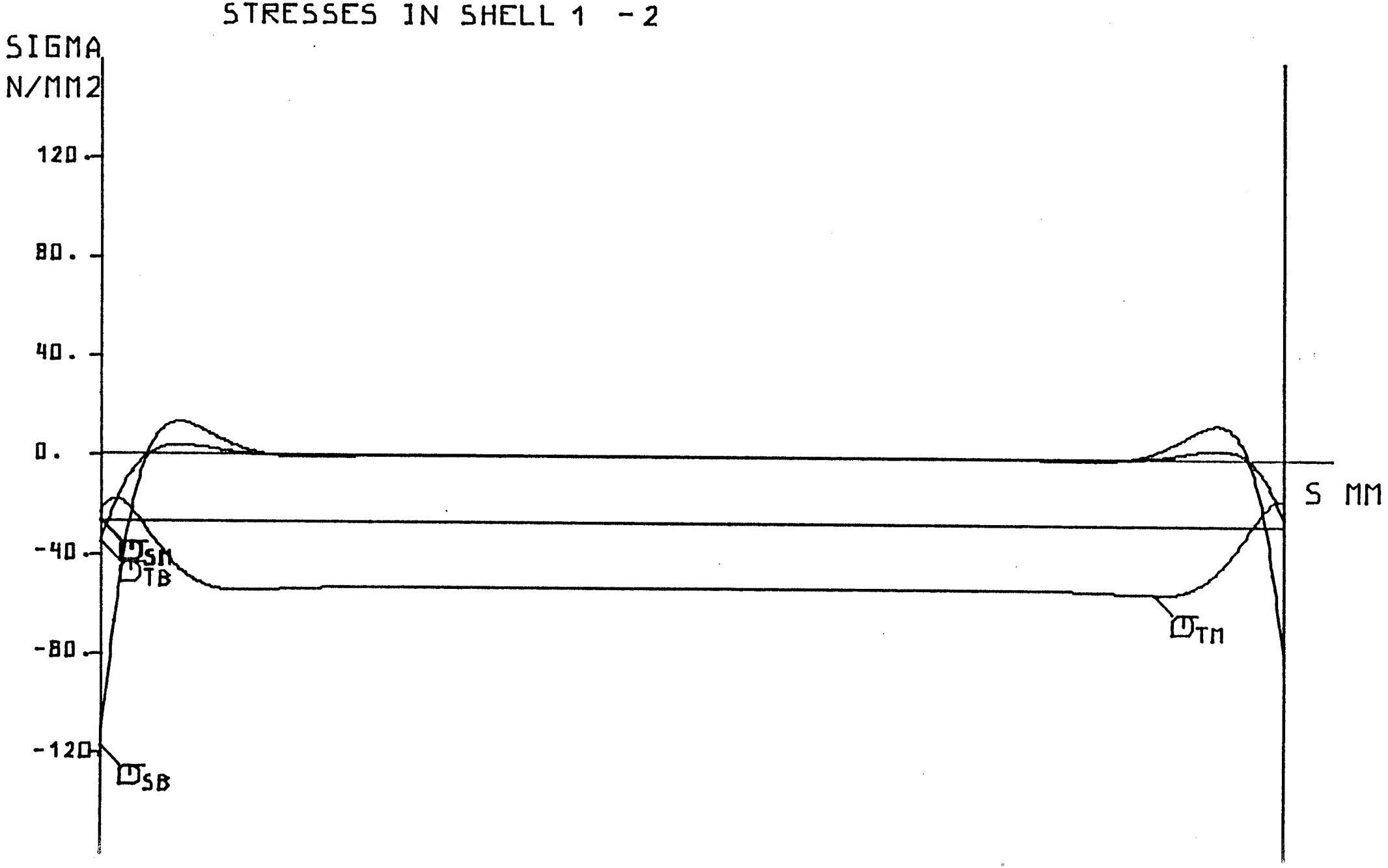
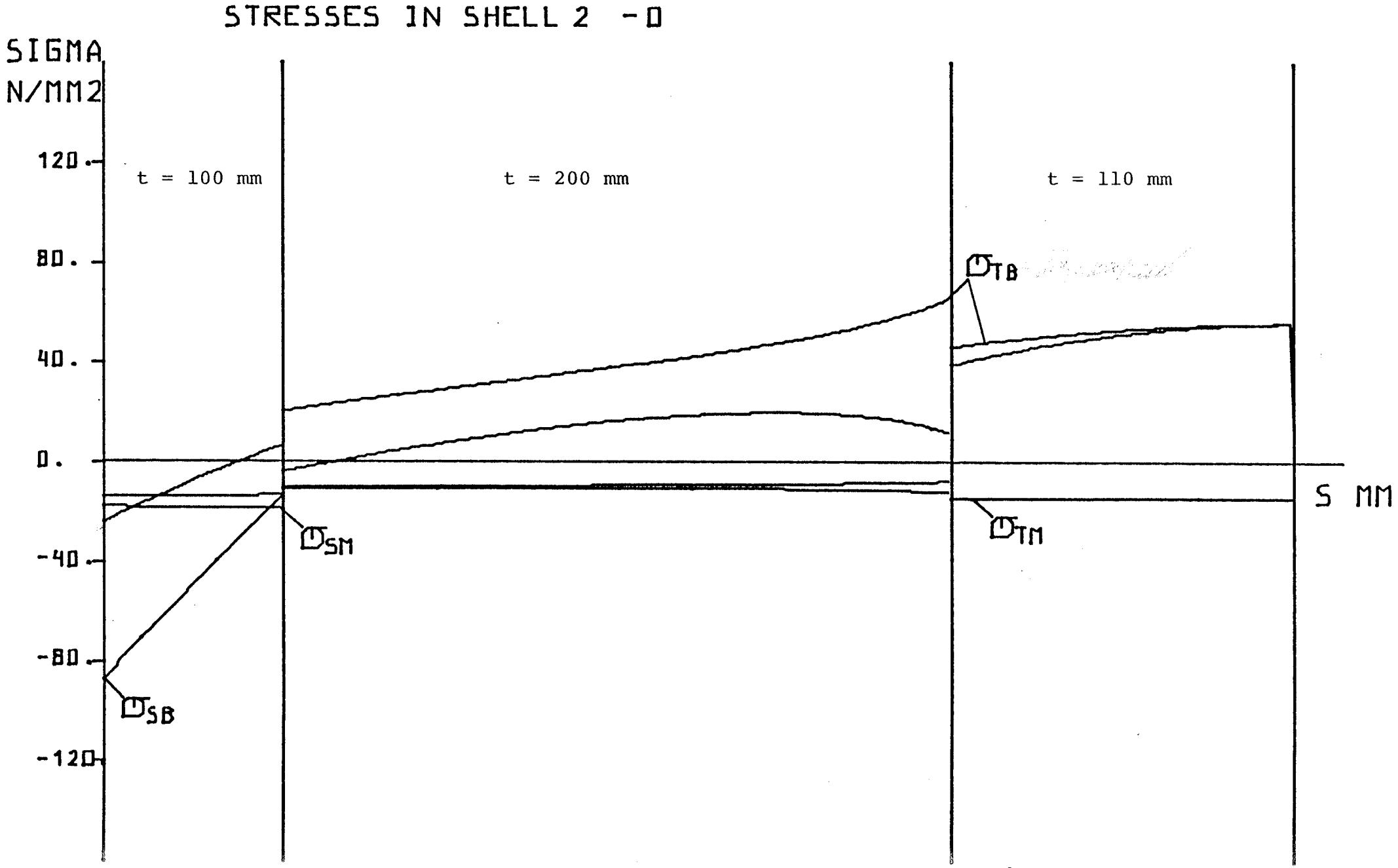



STRESSES IN SHELL 1 -0
SIGMA
N/MM2
σSB
120
80.
40.
0.
-40
-80
-120
S MM
σSM
σTM
σTB


STRESSES IN SHELL 1 -2
SIGMA
N/MM2
120
80.
40.
0.
-40
-80
-120
S MM
σSM
σTB
σTM
σSB


STRESSES IN SHELL 2 -D
SIGMA
N/MM2
120.
80.
40.
0.
-40.
-80.
-120.
t = 100 mm
t = 200 mm
t = 110 mm
S MM
σSB
σSM
σTB
σTM

Residual stresses in HIP canister for disposal of spent nuclear fuel

ASEA TR KYBA 83-087E, Håkan Lind

ASEA

Teknisk rapport
Technical Report

TR KYBA 82-087 E

Författare - Author
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Godkännare - Approved by
B Nilsson

Uppdragsgivare - Requested by
M Burström KX 3

Titel - Title
Residual stresses in HIP-canister for disposal of spent nuclear fuel

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Datum - Date 82-11-19

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[ ] Provning, experim. undersökning - Test, experimental investigation

[ ] Delrapport

[X] Slutrapport

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Antal textsidor - No. of pages of text
4

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15

Sammanfattning - Summary

This report gives an account of the results from a thermo-elasto-plastic analysis of a copper canister manufactured by Hot Isostatic Pressure (HIP) at a temperature of 500°C.

When cooling the copper canister residual stresses will occur near its surface because the core of the cylindrical canister consists of nuclear fuel element with lower thermal expansion than the copper mantle.

A temperature calculation has been performed, which shows that fast cooling corresponding to a cooling effect of 100 kW in the pressing oven gives a maximum temperature difference between the canister center and the surface less than 5°C. This temperature difference will have very small influence on the residual stresses after cooling. The temperature difference is therefore neglected in the following thermo-elasto-plastic calculation. The temperature has instead been decreased homogeneously from 500°C to 25°C, starting with a state of no stresses at 500°C.

The results of the calculation show that the copper canister becomes plastic and the residual stresses in the copper canister surface will be:

Circum stresses σ_φ = 50 - 92 N/mm^2

Axial stresses σ_z = 115 - 122 N/mm^2

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	HIP-copper Nuclear fuel Residual stress	

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I kolumnen för keywords införs då så önskas engelska motsvarigheter till ämnesorden samt engelska uttryck utan svensk motsvarighet.
Med övriga nyckelord avses t ex materialbeteckning, produktbeteckning, leverantör, kund, etc.

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CONTENTS

1 INTRODUCTION

According to a proposal for a method for final disposal of spent nuclear fuel there will be seven pieces of fuel elements, each consisting of 64 rods, to be placed in a copper canister and then filled up with copper powder.

This canister will be sealed by Hot Isostatic Pressure (HIP) at a temperature of 500°C. During this process the copper powder and copper cylinder will become a homogeneous material. During the cooling of the copper canister stresses will appear in the surface of the copper cylinder due to the fact that the fuel rods have lower coefficient of thermal expansion than copper. A thermo-elasto-plastic calculation has been done to determinate the residual stresses that will appear.

2 GEOMETRY

The proposed design of the copper canister is shown in appendix 1 The dimensions are before the HIP-process. In order to take the shrinking that will occur during HIP-process into consideration, the dimensions can be scaled with measured shrinking on a smaller copper canister. The dimensions on the fuel elements after the HIP-process are shown in appendix 2.

In the calculation a 2-dimensional model has been used. This means that the results are valid for conditions so far away from the canister ends, that the influence from the ends can be neglected. Symmetries of the cannister have been taken into account, so only a quarter of the cross section needs to be modelled.

3 TEMPERATURE CALCULATION

After the HIP-process at 500°C the canister will be cooled to 25°C. The canister will be cooled in the press and the cooling effect Q is estimated to $\approx$ 100 kW in the temperature range 500°C - 25°C. Geometry and material data for temperature calculation are given in appendix 3.

The calculation of the temperature shows that the maximum difference in temperature between the surface and center of the canister is maximum 5°C during the cooling process.

4 THERMO-ELASTO-PLASTIC CALCULATION

Earlier calculations of the residual stresses after cooling show that the copper canister surface will be plastic, see reference 3.

A thermo-elasto-plastic calculation has then been performed. The calculation model is shown in appendix 4.1.

Material 1 consists of HIP copper powder and seven fuel elements. Material data for uranium-dioxide UO_2 are shown in appendix 4.2.

The UO_2 rods will together with HIP-copper make an anisotropic material. A micromechanical model that takes this into consideration has been used when determining material data, see appendix 5. This means that material 1 is linear-elastic but has temperature dependent anisotropic properties.

Material 2 consists of the forged copper cylinder and the pressed copper powder between fuel element and the forged copper cylinder. The measured tensile stress-strain relation for the forged copper according to reference (1) has also been used for the pressed copper powder.

In the calculation the assumption of generalized plane deformation (GPD) is used. This means that the strain perpendicular to the plane (ε_z) is constant all over the area.

The results from the temperature calculation were that the temperature difference between center and surface of the canister was less than 5°C at a cooling effect of 100 kW. This effect is the highest that can be obtained at forced cooling of the canister in the press oven. In practice a forced cooling will likely not be used. Instead a normal cooling will be used. At a normal cooling the cooling effect is $\approx$ 10 kW and the temperature difference between the canister center and the surface will then be $\approx$ 0.5°C. This small difference in temperature between surface and center will not influence on the residual stresses after cooling. In the thermo-elasto-plastic calculation the temperature then has decreased uniformly all over the model, from an assumed no-stress state at 500°C to room temperature.

5 RESULTS

The calculation gives the following residual stresses on the surface of the copper canister at 30°C; the circum. stress σ_φ = 50-92 N/mm^2 and the axial stress σ_z = 115-122 N/mm^2. The stresses versus the φ-coordinate are shown in appendix 6.

Plotts of plastic strain, σ_x, σ_y, σ_z and principal stress are shown in appendices 7.2 - 7.5.

6 REFERENCES

1. LR KYDP 82-175

   Dragprov av snitt och pulverpressad koppar.

2. KYBA TR 0301-4038

   Konstitutiva samband utvidgade med termiska effekter för kompositmaterial.

3. IFM Akustikbyrån. TM 5.242.02

   Uppkomst av restspänningar i HIP-kapslar.

4. ASEA-ATOM PM RB 78-42

5. ASEA TR KYBA 82-087

   Restspänningar i HIP-kapsel för förvaring av utbränt kärnbränsle.

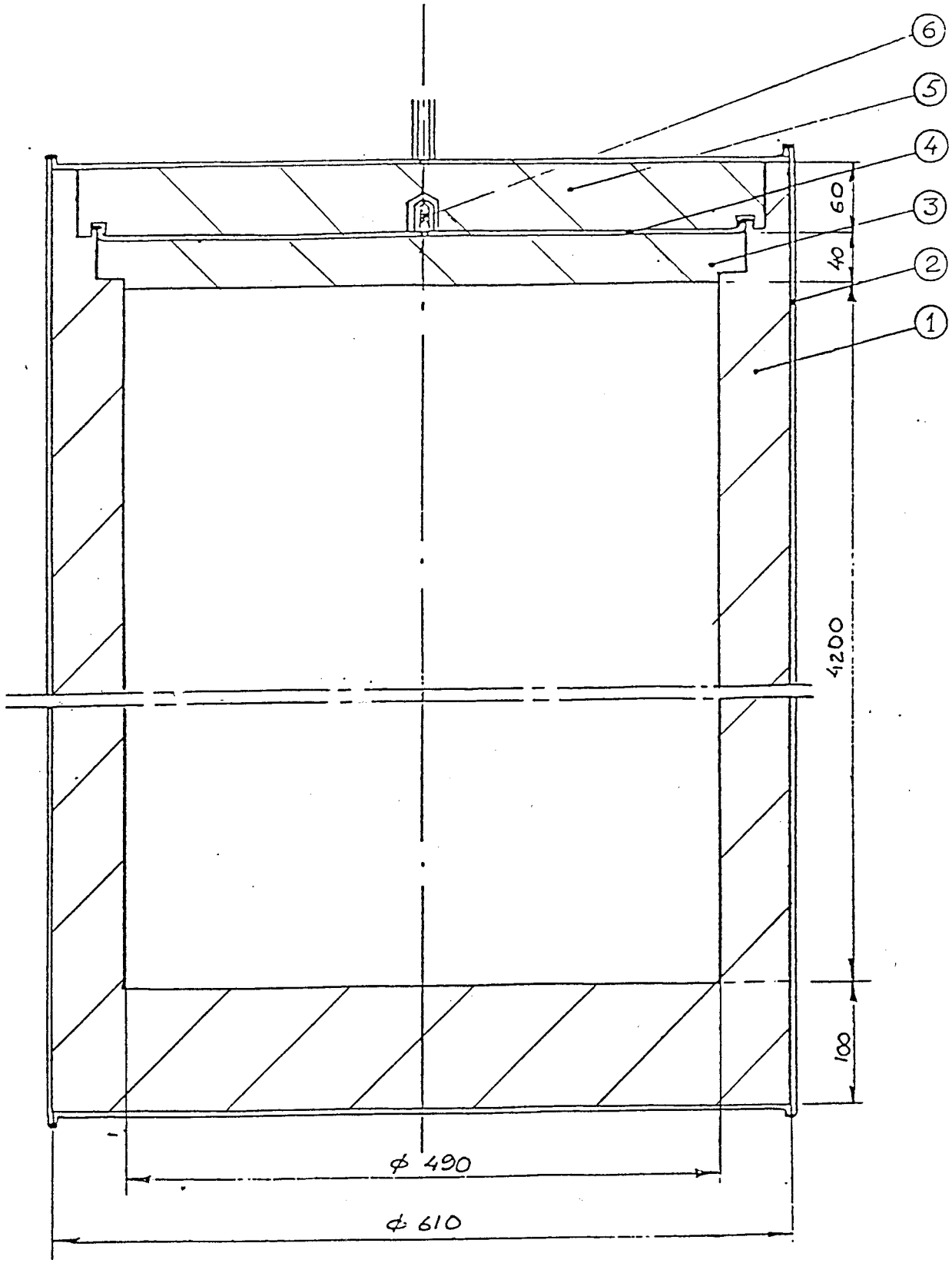
PROPOSED DESIGN OF COPPER CANISTER

The canister illustrated in figure 1 is made of copper in cast and forged quality. The thick-walled cylinder (1) is gas-tight and functions as an inner canister together with the thin closing (4) .

The inner canister prevents spreading of dust and gas from the fuel to the joint. In order to increase the safety in the system against leaking during HIP the canister has an outside thin cap that surrounds the whole unit. This cover is the primary sealing against HIP gases and seals of all joints during HIP-process. In a case where the outside cap (2) should leak during HIP, the closing (4) together with support closing (3) is another independent barrier against leaking gas.

The function of the support closing is to prevent axial deformation of the thin closing (4). But with two independent welded closing according to the figure the evacuation and reducing of hydrogen gas must be done in two steps.

This means that the evacuation pipe (6) from the first closing must be located in a counter-sinking in the outer closing. The design of the canister assumes that the gas-tight material for cylinder with bottom can be manufactured. Today it is not possible to purchase such a material in one piece and that is why the full-scale canister that is planned in the next step of this project will have a forged cylinder and a separate end. This means that there is only an outside HIP-gas-barrier in the system with higher demands on gastighting on the outside cap as a result.

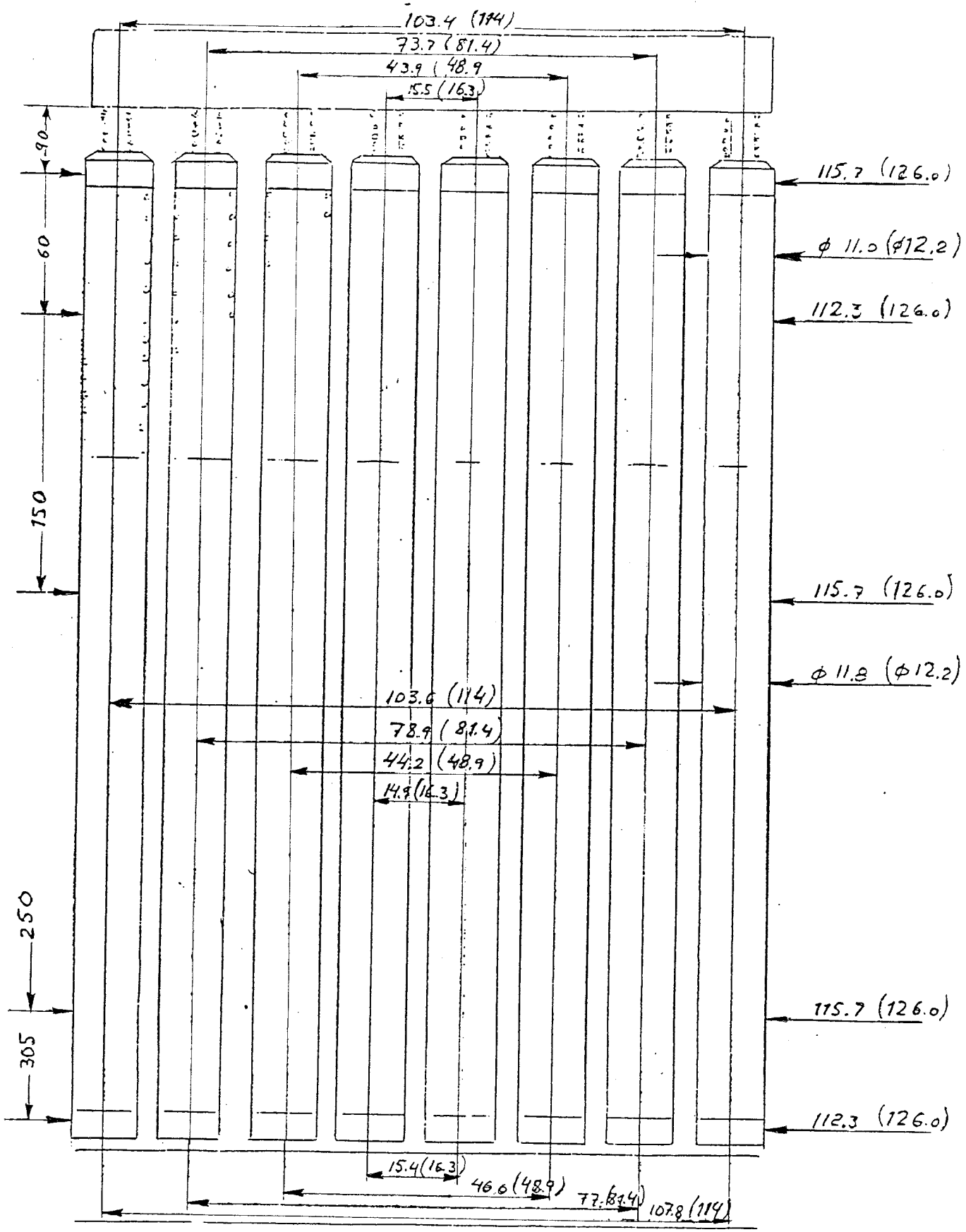

6
5
4
3
2
1
60
40
4200
100
ϕ 490
ϕ 610

Measured of outside dimension on a small-scale canister

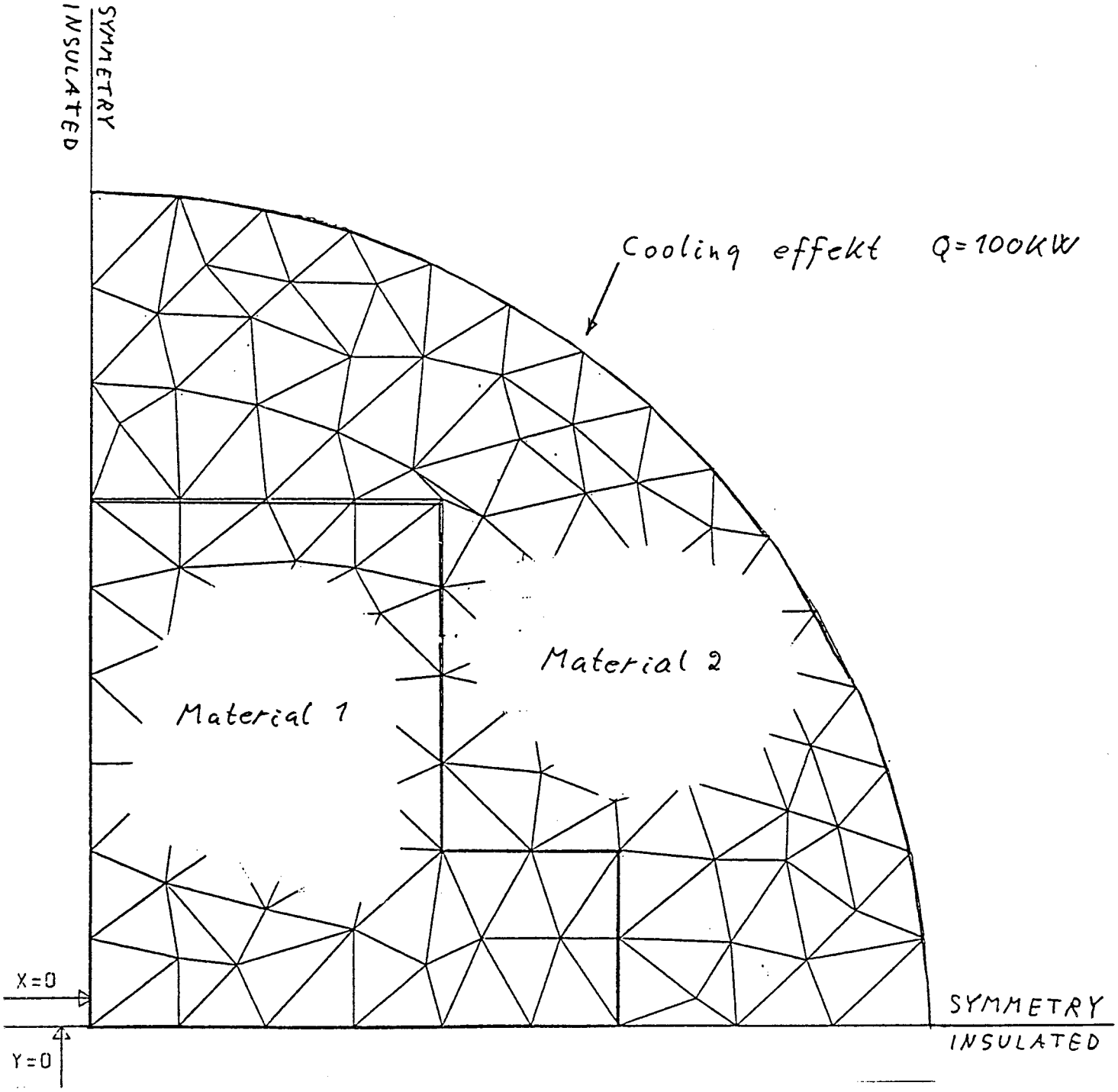
	Before HIP	After HIP	Shrinking %
D_y topp	289	288	0.5
D_y center	289	278	4
D_y bottom	289	288	0.5
L periphery	575	570	1
L center	575	563	2

Dimension of scaled canister after HIP

Dimension before HIP is in brackets



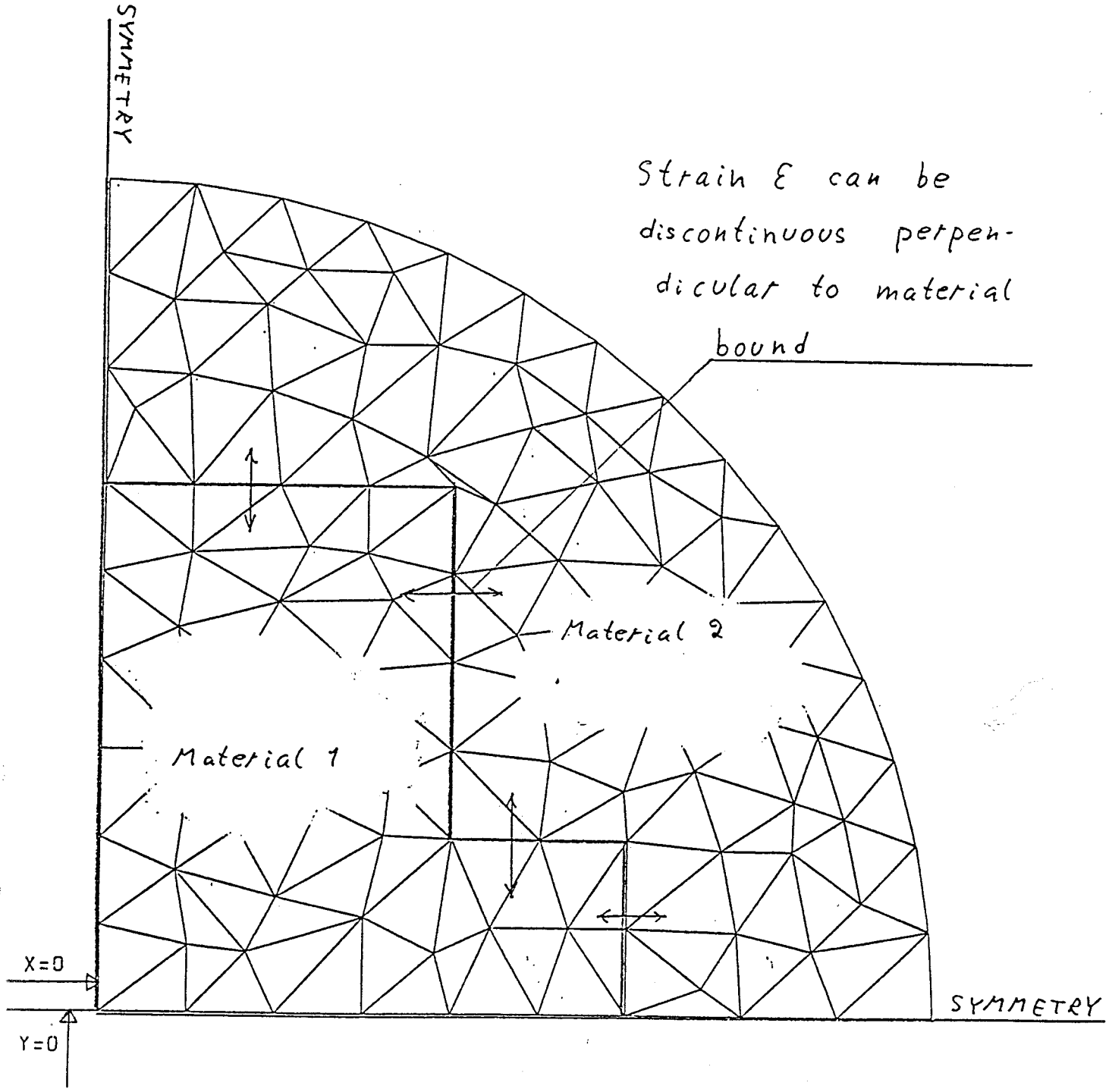
Temperature model



Material data for temperature calculation

	UO_2 see ref. (4)	Material 2 Copper	Material 1 UO_2 + copper
λ Conductivity W/m·k	$\lambda = P \left\{ \frac{4040}{464+T} + 0.01216 \cdot \exp(0.001867 \cdot T) \right\}$ där T = temperature ^oC P = porosity correction factor =1.0	385 at 100°C 373 at 400°C	$\lambda_1 = V_{UO_2} \cdot {}_{UO_2} + (1-V_{UO_2}) \cdot {}_{CU}$ V_{UO_2}=volume part UO_2=0.49
Cp Thermal capacity J/kg·K	$4186(7.26 \cdot 10^{-2} + 3.33 \cdot 10^{-6}(1.8 \cdot T+32) - 4.74 \cdot 10^{-3}/(1.8 \cdot T+492)^2)$ T = temperature ^oC	398 at 100°C 414 at 400°C	$Cp_1 = ({}_{UO_2} \cdot V_{UO_2} \cdot Cp_{UO_2} + {}_{CU} \cdot (1-V_{UO_2}) \cdot Cp_{CU})/9574$
Density ρ kg/m^3	10500	8800	V_{UO_2}=volume part UO_2=0.49

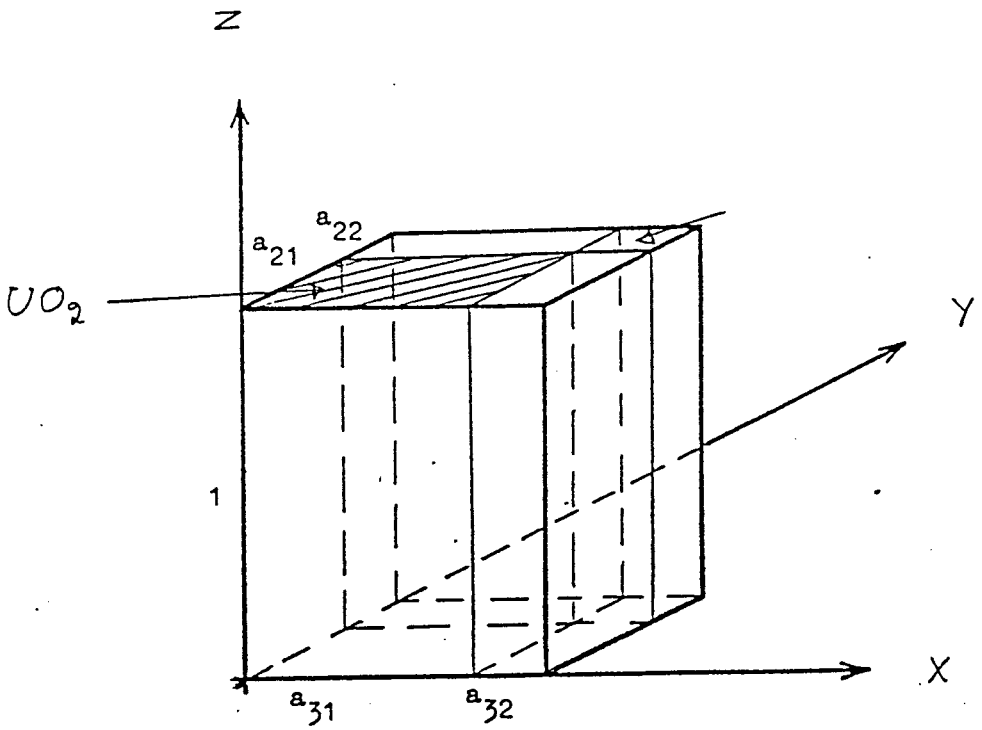
Elasto-plastic model



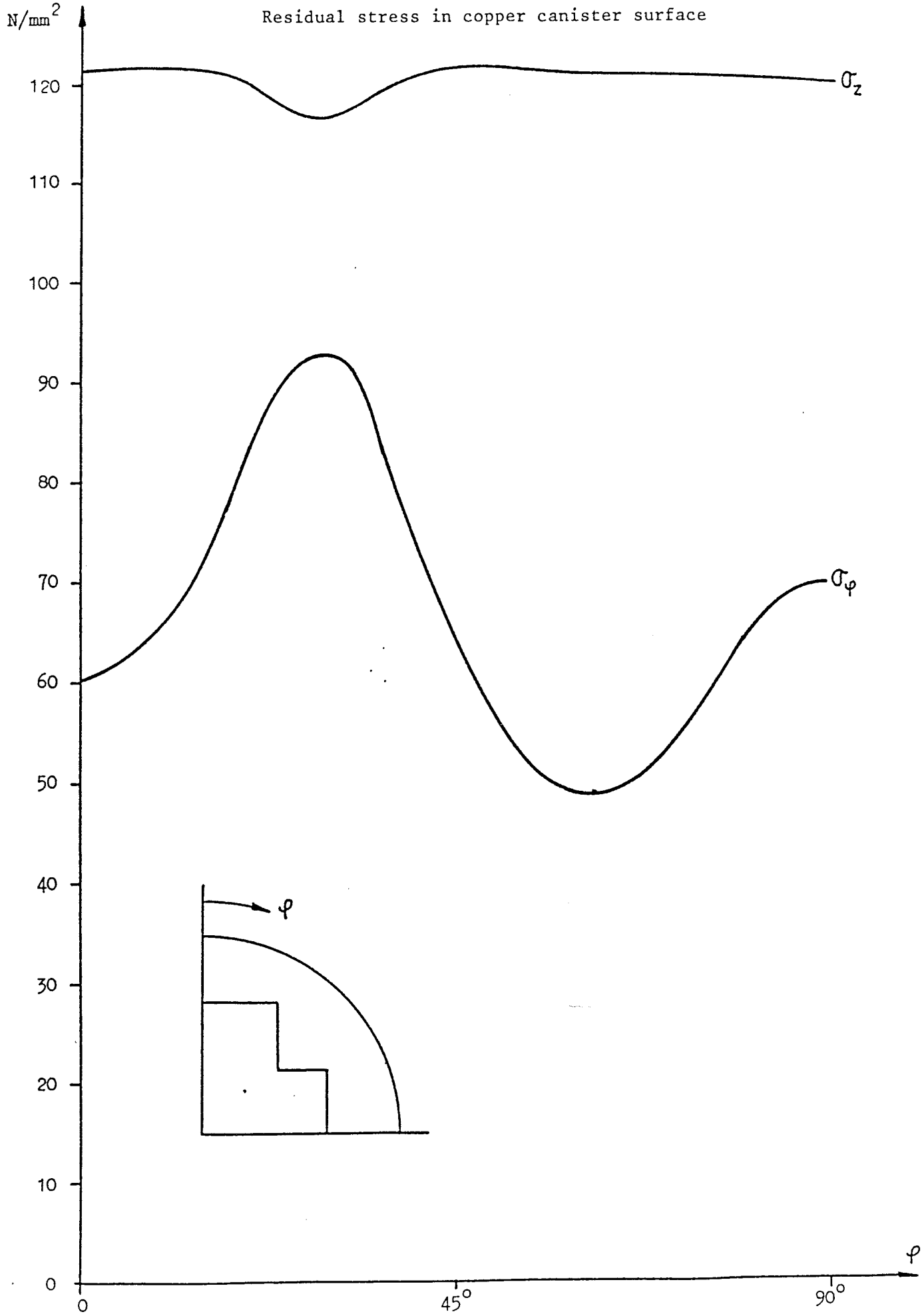
Material data for thermo-elasto-plastic calculation

	UO_2 see ref. (4)	Material 2 Copper	Material 1 UO_2 + copper according to micromechanical model
Young's modulus E	$(1-1.92(1-\rho_o))\times$ $(2.16710^5-30.03\cdot T-7.999\cdot 10^{-3}\cdot T^2)$ where $\rho_o=0.95$, T = temperature	$122\cdot 10^3$ at 50°C $56\cdot 10^3$ at 450°C	$E_x=E_y=219\cdot 10^3$, $E_z=225\cdot 10^3$ } at 50°C $E_x=E_y=133\cdot 10^3$, $E_z=158\cdot 10^3$ } at 450°C
Coefficient of heat expansion $\alpha\ K^{-1}$	$7.016\cdot 10^{-6}+2.887\cdot 10^{-9}\ T$ $+3.343\cdot 10^{-19}\ T^2$, T = temperature	$16.9\cdot 10^{-6}$ at 50°C $19.8\cdot 10^{-6}$ at 450°C	$\alpha_x=\alpha_y=12.3\cdot 10^{-6}$, $\alpha_z=11\cdot 10^{-6}$ } at 50°C $\alpha_x=\alpha_y=14.6\cdot 10^{-6}$, $\alpha_z=11.1\cdot 10^{-6}$ } at 450°C
Poissons ratio ν	0.304	0.33	

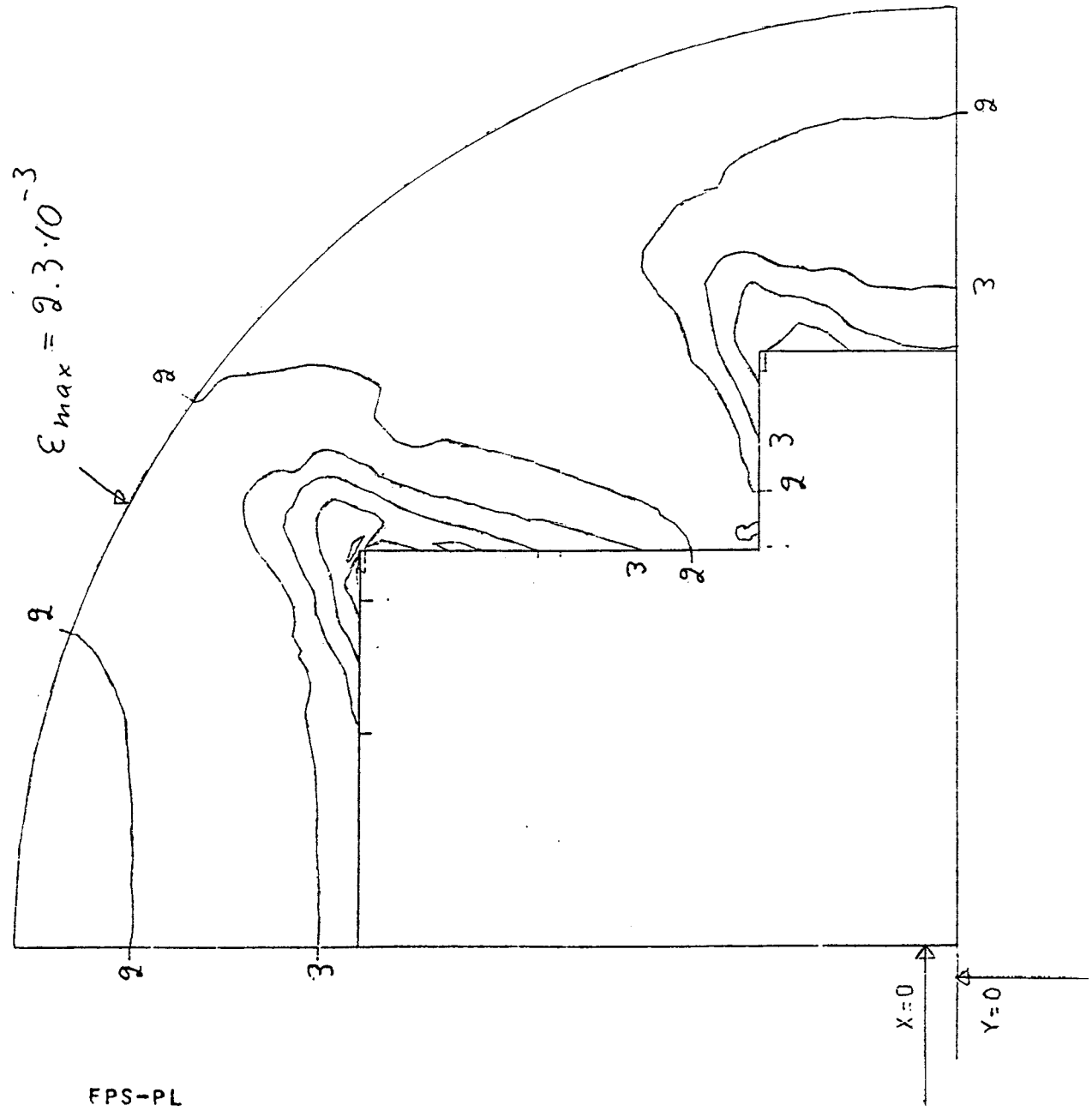
Micromechanical model for determination of anisotropic material properties



Residual stress in copper canister surface



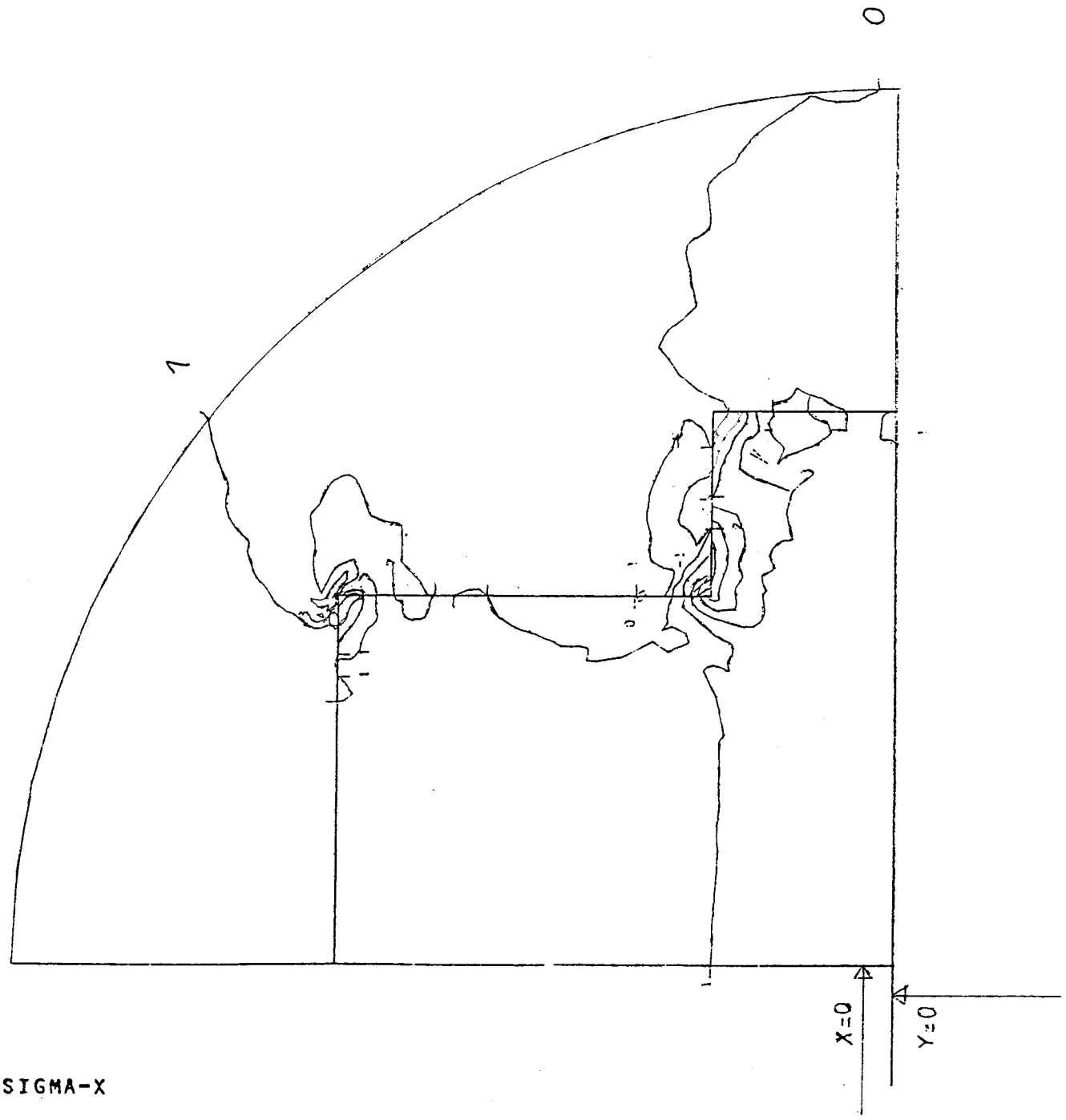
ε-plastic



FPS-PL

1	1.0E-3	2	2.0E-3	3	3.0E-3
4	4.0E-3	5	5.0E-3	6	6.0E-3
7	7.0E-3	8	8.0E-3		

$-\sigma_x$

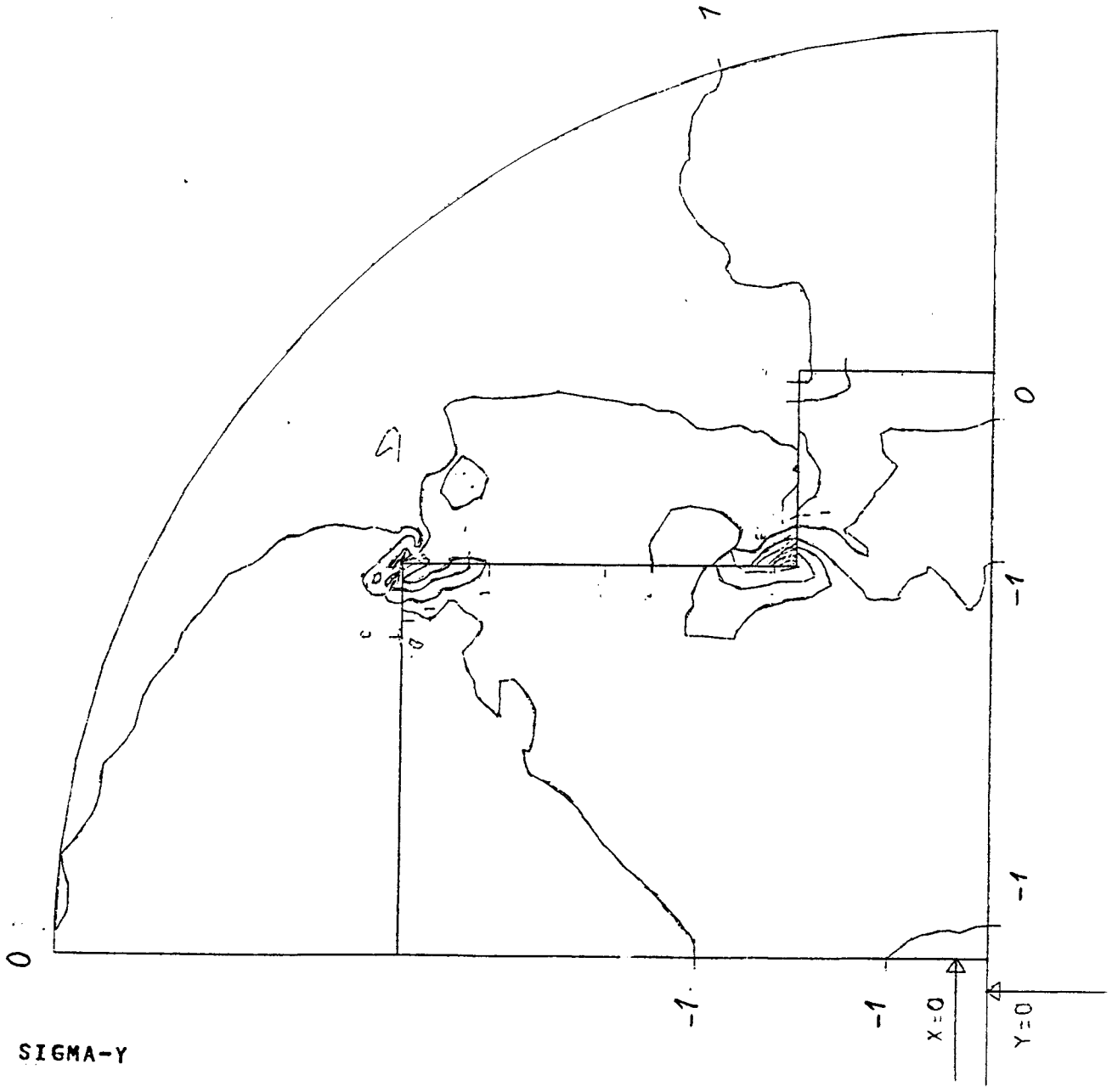


SIGMA-X

-5	-250.0	1	50.00	7	350
-4	-200.0	2	100.0	8	400
-3	-150.0	3	150.0	9	450
-2	-100.0	4	200.0	10	500
-1	-50.00	5	250.0		
0	0.	6	300.0		

N/MM^2

$-\sigma_y$

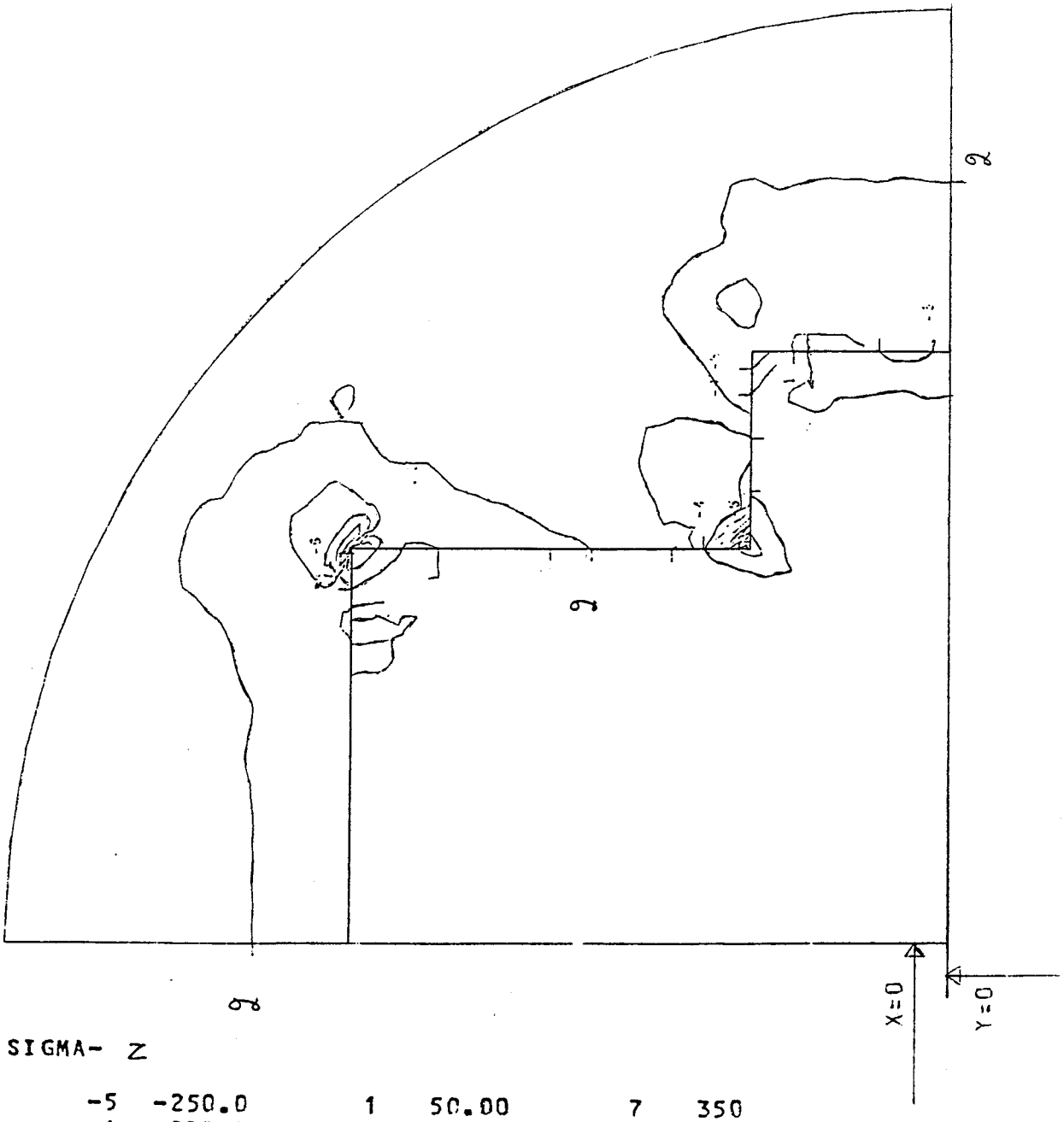


SIGMA-Y

-5	-250.0	1	50.00	7	350
-4	-200.0	2	100.0	8	400
-3	-150.0	3	150.0	9	450
-2	-100.0	4	200.0	10	500
-1	-50.00	5	250.0	11	550
0	0.	6	300.0	12	600

N/MM^2

σ_z

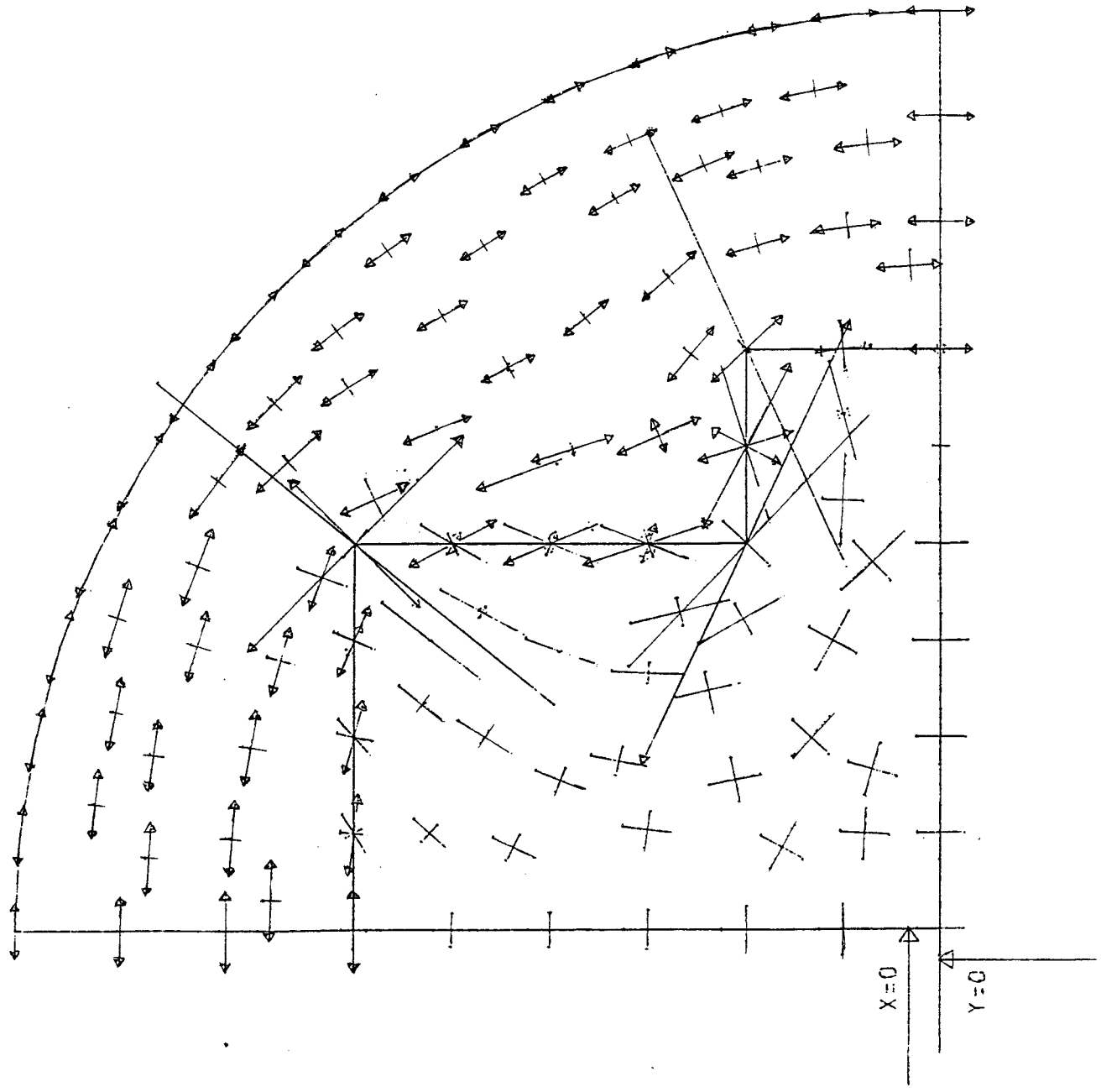


SIGMA- Z

-5	-250.0	1	50.00	7	350	
-4	-200.0	2	100.0	8	400	
-3	-150.0	3	150.0	9	450	
-2	-100.0	4	200.0	10	500	
-1	-50.00	5	250.0	11	550	?
0	0.	6	300.0	12	600	N/MM

Principal stress

$\longleftrightarrow$ $\triangleq$ 66 N/mm^2



Preliminary safety study of the HIP process

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TAB

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Sammanfattning/Abstract
ABSTRACT

For KBS 3 a preliminary safety assessment has been made primarily of those process steps which are unique for KBS 3, i.e. hydrogen conditioning and hot isostatic pressing (HIP).

The preliminary judgement is that those process steps has such a built-in safety that mishaps are expected to imply only negligible risk for the environment.

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1 INTRODUCTION

The KBS 3 work includes a safety assessment of the encapsulation procedure with hot isostatic pressing, from the receiving in the encapsulation station up to the finished end product.

The HIP procedure has briefly the following steps.

From a receiving and buffer pool the fuel bundles are lifted into a hot cell, where they are placed in a copper canister, which is filled with copper powder and tightened with an inner lid by welding. The copper powder may be clean from oxide, but otherwise a hydrogen conditioning takes place, vacuum suction and sealing of the canister. A main lid and an outer lid are applied. The outer lid is seal-welded to the canister and the space between the lids is hydrogen conditioned and sealed. The canister is then moved to a Quintus press for hot isostatic pressing at 550°C and 150 MPa.

In these conditions the copper powder is fused to solid copper. The canister is cooled after which it is subject to final inspection.

As the process has many steps which are common to KBS 2, aspects on safety measures common to both processes have been limited to qualitative judgements with reference to the corresponding assessment for KBS 2.

The safety analysis is limited to those steps in the process which are unique to the pressed canister in KBS 3, i.e. hydrogen conditioning and hot isostatic pressing in the Quintus press. The analysis concerns the risk for damages on the fuel with radiologic consequences at mishaps in the various steps.

Judgement of the durability of the final product during long time deposition, as a consequence of not fully satisfactory results in the various encapsulation steps, is outside the scope of this analysis.

2 DISTURBANCES DURING THE PROCESS

During the encapsulation different disturbances may occur. The receiving and handling of the fuel before it is loaded into the copper canister is similar to the procedure in KBS 2 and is therefore treated in several studies within KBS. Disturbances, special for KBS 3, may be fire and explosion as hydrogen is handled and high pressures are used.

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3
SAFETY MEASURES AND SAFETY ASPECTS

3.1
General

The station is designed with the following basic criteria

- minimizing the radiation dose to the personnel
- preventing damages on the fuel due to mishaps and erroneous handling
- minimizing the spreading of radioactivity to the environment.

The integrity and managability of the spent fuel is not expected to deteriorate during 40 years of storing in CLAB. A study of potential degrading mechanisms for light water reactor fuel in pool storage is made in reference 1.

In the reference is shown that degrading mechanisms as general corrosion, local corrosion, stress corrosion, hydrogen embrittlement and delayed hydrogen fracture are not expected to result in the commencement of degrading within this time. The managability of heavily burnt-up fuel is good and vast experience and well developed routines for such handling are available in Sweden. The dose burden for personnel who is engaged in fuel handling is low according to the experience. This experience is further based on handling of fuel shortly after finished reactor service, why the handling in the encapsulation station will take place in comparatively favourable conditions from the radiation point of view.

3.2
Radiation protection

The radiation doses are minimized chiefly by the remote handling of the fuel, either below water or in radiation shielded cells. The handling in water takes place with a minimum of 2.5 m water coverage over the fuel, which gives a quite satisfactory radiation shielding for both gamma and neutrons.

The handling and equipment in the shielded encapsulation cells are remotely operated and controlled from the control room or from adjacent rooms. The ventilation air or nitrogen passes through filters if measurements show a content of activity.

All active cells are subject to a continuous underpressure relative to control areas, other station rooms and surrounding space.

The amount of fuel, which simultaneously is handled in KBS 3 is about the same as in KBS 2, why radiation protection and shielding aspects are similar in the two processes.

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3.3 Handling

In KBS 3 one rack of fuel with either 8 BWR or 2 PWR and 2 PWR bundles is handled. The complete bundles are placed in the rack and the rack is loaded into the copper canister. The handling procedure is thoroughly analysed in reference 2.

3.4 Hydrogen conditioning

The use of hydrogen implies generally a risk for explosions and fire. As the hydrogen conditioning is unique for KBS 3, the problems are discussed exhaustively in chapter 4.

3.5 The HIP process

The hot isostatic pressing is achieved by pressurization with gas and heating. The HIP process is analysed in chapter 4.

3.6 Criticality

The BWR bundles are transported in their boxes to the encapsulation station. In the work of assembling the fuel into encapsulation units, the BWR fuel is lifted out of the boxes. The boxes are transferred to a separate cell for embedding into concrete. The boron glass rod bundles of the PWR fuel are lifted out of the fuel bundles. They are also transferred to the separate cell for embedding into concrete.

The geometry of the individual fuel bundles is maintained during the encapsulation process. During storage in water, the fuel is arranged in a geometry which is similar to that employed in the fuel pools at the nuclear power plants. This provides a very wide margin to criticality, even assuming an enrichment corresponding to that of new fuel, when the fuel is standing in water. When the unit is lifted into air or nitrogen, the moderating function of water disappears and no criticality is possible.

3.7 Fire protection

The fire load is low throughout. Apart from an almost total absence of burnable material in the cells, where fuel and copper are handled openly, this is also indirectly achieved by the cells being filled with nitrogen.

The station has also been divided in fire cells and provided with active fire fighting systems.

The probability for a fire to break out and spread into areas where fuel is kept is extremely low due to the fact that such areas contain very little of flammable material.. The division into fire cells of the station with separated ventilation systems will also contribute to a decrease of the risk of fire. Spreading of fire is hence prevented and the probability of fuel damages due to fire is exceedingly low.

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3.8
Fuel heating

The evacuation of the copper canister impairs the transportation of residual heat from the fuel before the pressing is fulfilled. Calculations show that the heating of the fuel is reasonable and that this factor is judged not to contribute to the risk for cladding damage.

4
SAFETY ANALYSIS OF THE HYDROGEN CONDITIONING AND THE HIP PROCESS

4.1
Explosion in the hydrogen conditioning process

When hydrogen is used it is generally known that unfavourable mixtures of hydrogen and oxygen can give ignition by temperature or formation of sparks. In KBS 3 hydrogen conditioning will be made of the space between inner and outer seal lid. A process of conditioning of the interior with copper powder is possible but not yet decided.

The hydrogen conditioning is made under subatmospheric pressure. A possible leakage results in an in-leakage of the surrounding atmosphere, which will disturb the process. The forming of explosive gas in the furnace and apparatus cell is eliminated by the nitrogen atmosphere in these volumes. Outside the apparatus cell parts of the hydrogen conditioning system is working with overpressure. These parts of the station are equipped with efficient ventilation. The risk for oxy-hydrogen explosions should thus be extremely low.

In spite of this the following sections discuss the consequences of an oxy-hydrogen explosion in the inner of the canister and between the seal lids.

4.1.1
Explosion in the interior of the canister

An explosion in the canister could be a result of air in some way being mixed with the hydrogen during the conditioning. An other possible way would be connected with the conditioning of the volume between the lids, whereby except an explosive mixture between the lids also a defect seal weld of the inner lid is required. The probability of obtaining an explosive hydrogen mixture in this later way in hence utterly low.

The risk of a rapid combustion of hydrogen in the interior is small since the copper powder acts as an effective flame barrier. Powder with a grain size of less than one mm has been proved to be very efficient flame barriers. The reason is that the thermal losses are so big that the flame front is effectively damped. These facts are well known and used in the off-gas systems of reactor power plants.

If a pressure increase is reached in the canister interior, the pressure relief will most probably take place by bursting of the weld of the inner seal lid. If no pressure relief should occur, then the fuel should be subject to an outer overpressure, which it withstands.

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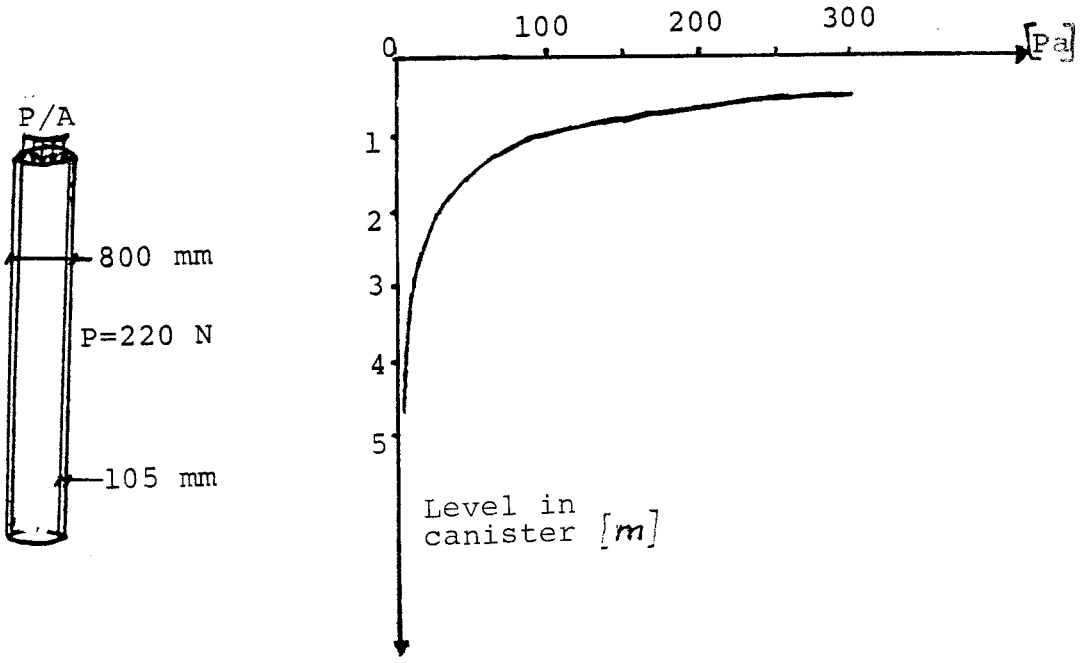
4.1.2
Explosion between the seal lids

The space between the lids has a volume of ca 5 dm^3. The energy which can be generated is about 240 kJ/mol gas mixture. As the hydrogen conditioning is made at about 400°C, the heat generated in the volume 5 dm^3 is maximum 22 kJ. With an assumed acceleration length of 1 cm the force is 220 N.

The most probable event is that the pressure is relieved by bursting of the weld of the outer seal lid and the consequence regarding the enclosed fuel would be negligible.

If the outer seal lid is assumed not to be deformed at a hydrogen explosion between the lids, the pressure will act also on the inner lid. If a further assumption is made that the weld of the inner seal lid has a bad strength, the pressure force is transmitted to the copper powder. A poor degree of filling in the copper powder has normally been discovered in the earlier process steps. By using the stress equation of Boussinesq, well known in geotechnique, the stress increase can be determined. The stress increase as a function of the depth below the seal lid is presented in the figure below.

Figure 4.1.2.A
Vertical stress increase from a 220 N force



The horisontal stress increase is less than the vertical.

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It can be seen that even with conservative assumptions the stresses on most of the fuel will be moderate, why additional fuel damages are unlikely.

As a summary hydrogen explosions are very improbable as the conditioning takes place in a nitrogen atmosphere. If a hydrogen explosion should occur in the canister internal the pressure increase is moderate. Should the explosion occur when the space between the lids is conditioned, the most probable result is that the pressure is relieved via the outer lid. In any case no influence is expected on the enclosed fuel.

4.2
Mishaps during the HIP process

4.2.1
General

Each copper canister contains 8 BWR or 2 PWR and 2 BWR bundles. The previous process steps have implied drying, filling of copper powder, welding of seal lids and hydrogen conditioning.

From the canister wagon the canister is lifted together with the plunge, on which it rests and which is formed as the bottom of the pressure retaining cylinder in the Quintus press, into the cylinder after which the pressing can start.

The pressing procedure is briefly as follows:

The bottom plug is locked to the bottom of the cylinder
The Quintus frame is moved to a position around the cylinder
The top and bottom pieces of the frame are applied hydraulically to the top and bottom of the cylinder
The cylinder is evacuated
The pressure medium (argon) is supplied at a pressure up to about 1000 atmospheres.
Heating is switched on. At the same time, the cylinder is cooled. The temperature increases to approx. 550°C and the pressure rises to 1500 atmospheres.
These conditions are maintained for a few hours.
Canister cooling is then started and the pressure medium is returned to the storage equipment.
The frame is moved away and the canister wagon takes over the pressed cylinder.

The Quintus process has so far only been tested with inactive material, but no difficult technical complications are assumed when the process is used on active material and built-in in a concrete cell and remotely operated. The following safety-related incidents are logically conceivable.

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4.2.2
Cladding fracture due to gab between pellets

The stresses on the fuel appearing in a normal HIP process, e.g. increased fission gas pressure, will not lead to an exceeding of the strength of the fuel cladding, even if the outer pressure from the copper powder is not credited.

One source of cladding fracture could be a gap between full pellets, however. Such a gab may be obtained in the reactor operation. Fuel rods with simulated pellet gaps have been used in the tests, which have been made by ASEA, Robertsfors. The results are reported in ASEA TR KX3 83-002. The tests show no fracture in the cladding.

4.2.3
Failed fusing due to defective seal welds

As a result of defective seal welds in both the inner and the outer lid the fusing may fail. The probability for a defective weld is estimated to 10^{-2}. The probability for both welds to be defective is thus 10^{-4}. A totally failed fusing is discovered in the subsequent inspection procedure.

One possible consequence of a failed fusing is that fission gas due to the heating might leak out to the Quintus press from fuel, damaged already before the process.

The gas from the fuel is insignificant, however, at the moderate heating used in the process. Significant release of fission gas, bound to the fuel material, occurs only at considerably higher temperatures.

4.2.4
Loss of vacuum due to defective seal welds

A consequence of defective welds could be the loss of vacuum when the Quintus press is pressurized. In a normal process this will lead to failed fusing, but for the completeness of the analysis it is assumed that the process tightens the leaking welds due to the fusing in the subsequent heating.

The pressure increase in the copper canister due to heating may result in yielding of the copper which is now rather ductile. In the following pressure and temperature reduction in the Quintus press an expansion of the canister can occur until the strength of the copper balances the inner overpressure. Even in this postulated scenario no radioactivity is released, as the canister is not expected to rupture. The end product would probably not be accepted for long term deposition, however, and therefore rejected in the final inspection.

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4.2.5
Overpressure explosion in the Quintus press

The pressure vessel in the Quintus press is provided with rapidly operating safety valves preventing the normal service pressure to be exceeded. If the pressure should be exceeded the wiring in the frame and vessel would prevent an explosion. Also if there should be a manufacturing fault in a part of the wiring the pressure relief will be rather slow, which has been shown in the ASEA analysis of the Quintus press.

4.2.6
Gasket rupture in the Quintus press

Rupture of a gasket might result in a quick pressure relief in the press cylinder. The consequence would be that the fusing of the copper canister would not be completed.

The cell, where the Quintus press is located, is dimensioned for the overpressure arising from the relief of the energy stored in the Quintus press.

4.2.7
Summary

To sum up the preliminary judgement of the Quintus step in the encapsulation process is that neither mishaps in the press nor faults in the copper canister are expected to result in such an influence on the enclosed fuel, that significant quantities of radioactive products will be released from the process.

5
RADIOLOGIC ASPECTS

Normal operation

The judgements made regarding activity release during normal operation in KBS 2 are also applicable to KBS 3.

Copper powder filling is unique in KBS 3. When the copper powder is poured into the canister it may be assumed that activity attached to the cladding surface is rubbed off and may appear as dust in the nitrogen. It is chiefly corrosion products and possibly also small amounts of fissile material from leaking fuel, that may be present on the cladding surface. The radiation after 40 years is dominated by Co-60. By means of filtering of the cell nitrogen atmosphere such radioactive dust from the copper powder filling can be collected.

Mishaps

It has been shown that the worst consequence of the disturbances, which are discussed in this report and which are unique to the pressed canister in KBS 3, involves only negligible risks for radioactive radiation in the environment.

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6
REFERENCES

Reference 1 — Degrading mechanisms in pool storaging and handling of spent power reactor fuel (In Swedish)
KBS TR 68, G Vesterlund, T Olsson

Reference 2 — Encapsulation of spent nuclear fuel - Safety analysis
KBS TR 83-30, ES-konsult AB

Denna handling får ej utan vårt medgivande kopieras. Den får ej heller delgivas annan eller eljest obehörigen användas. Överträdelse härav bevrias med stöd av gällande lag. **ASEA-ATOM**

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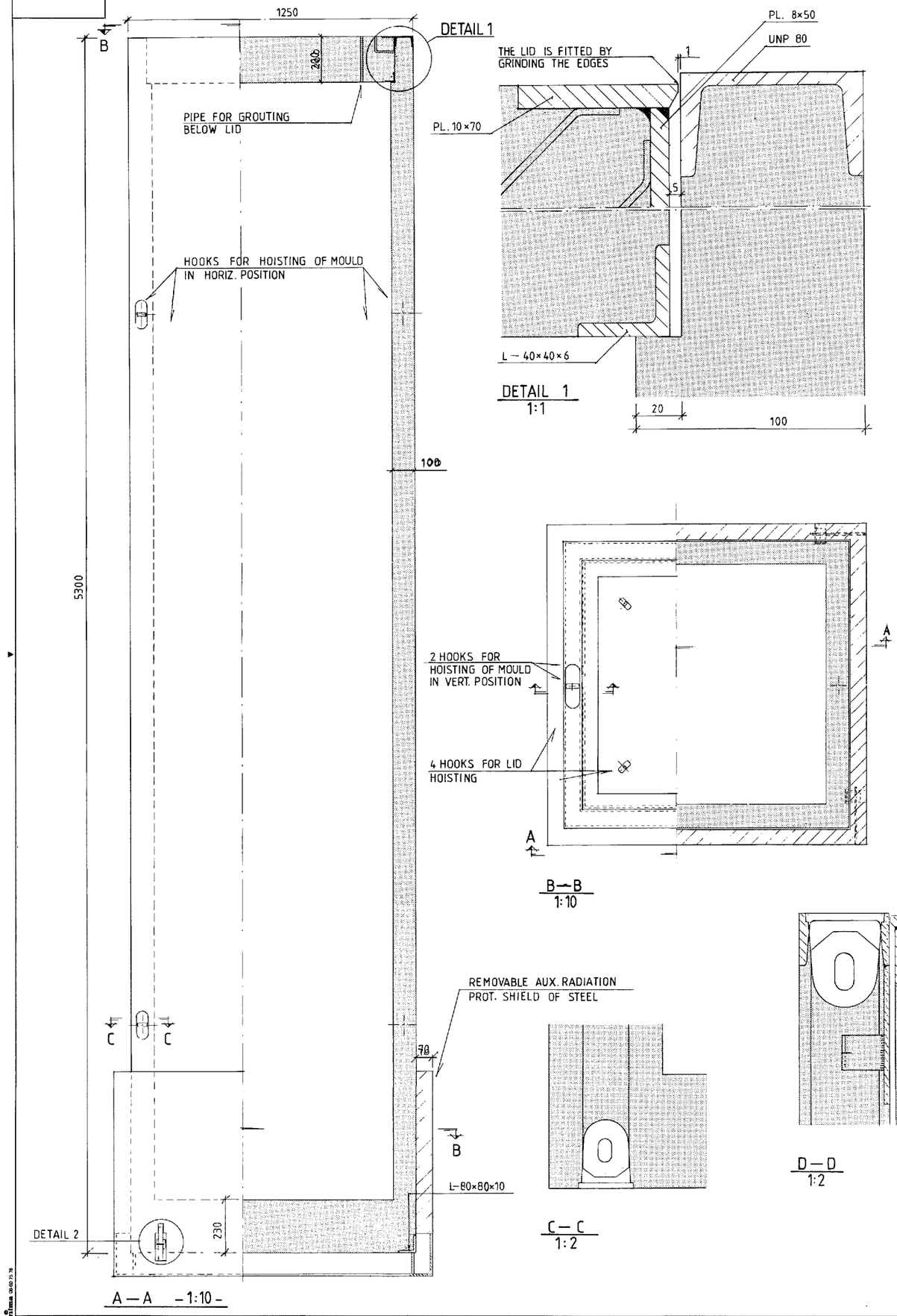
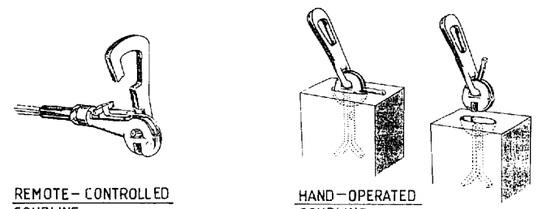
Bl. 2024 50.000 83.02 Västra Aros

KBS - Concrete mould for embedding of fuel channels

VBB, Lars Ageskog

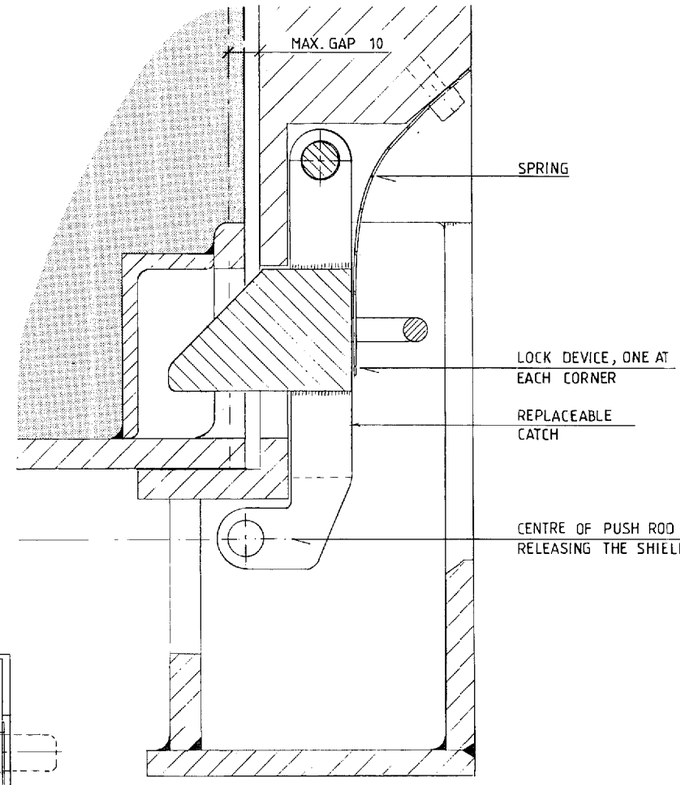




REMOTE – CONTROLLED
COUPLING

HAND – OPERATED
COUPLING

EXAMPLE OF QUICK COUPLING FOR HOISTING



WEIGHT

MOULD INCL. LID BUT EXCL. RAD. PROT. SHIELD	7 TONNES
DITTO FILLED	20 TONNES
RADIATION PROTECTION SHIELD	2 TONNES
TOTAL	22 TONNES

REV.	ANT.	REVIDERINGEN AVSER	RITAD	GRANSK.	DATUM

KBS
CONCRETE MOULD FOR EMBEDDING
OF FUEL CHANNELS

KONSTRUERAD	RITAD	GRANSKAD	REG.NUMMER
LEA	EDL		B 8795
SKALA		RITNINGSNUMMER	REV.

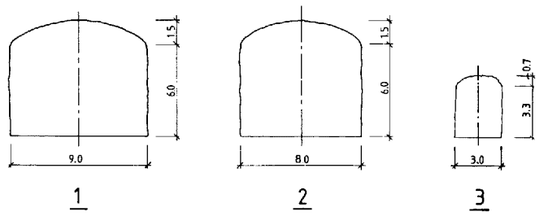
STOCKHOLM

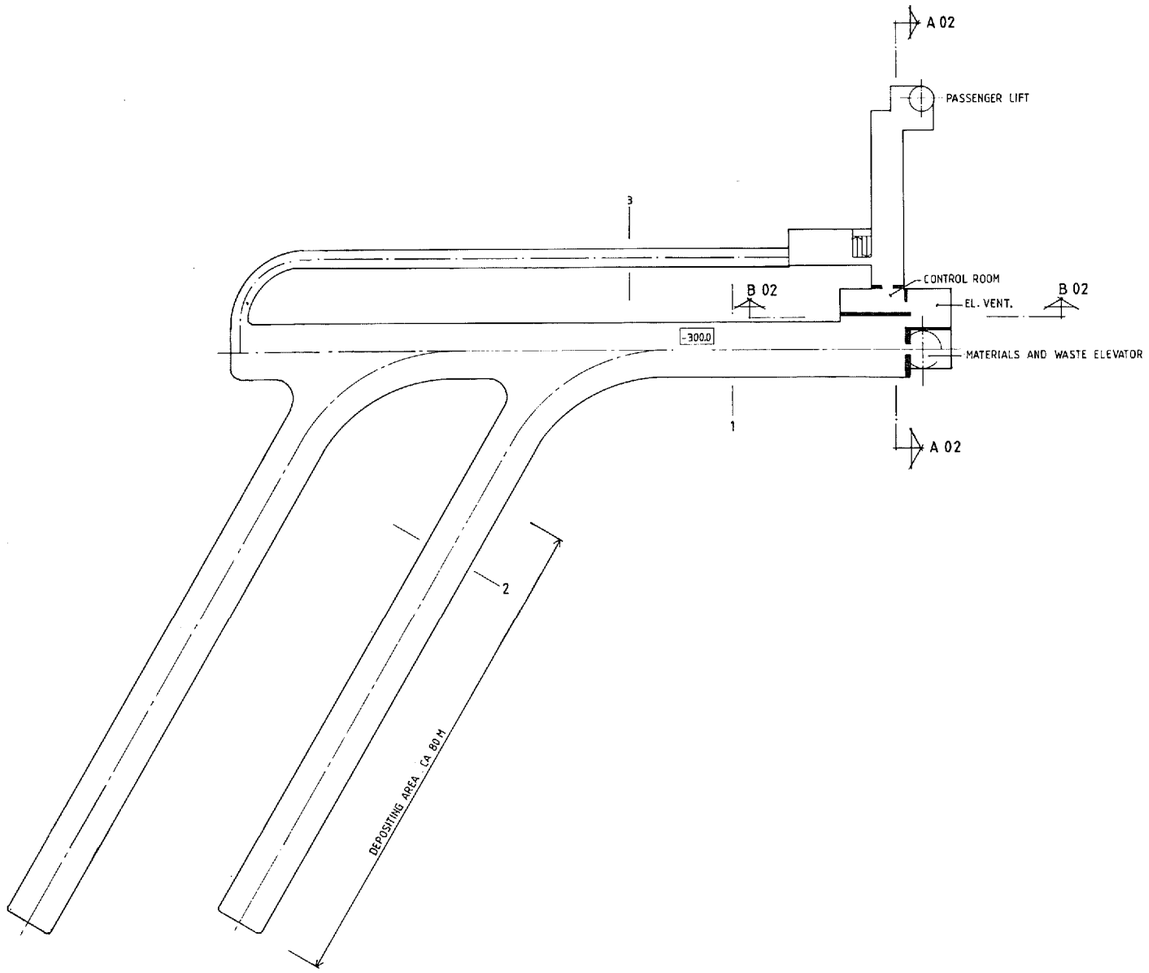
VBB
BOX 5038
102 41 STOCKHOLM 5
TEL. 08-22 85 80

VBB 66-51

KBS - Final repository for embedded fuel channels

VBB, Lars Ageskog





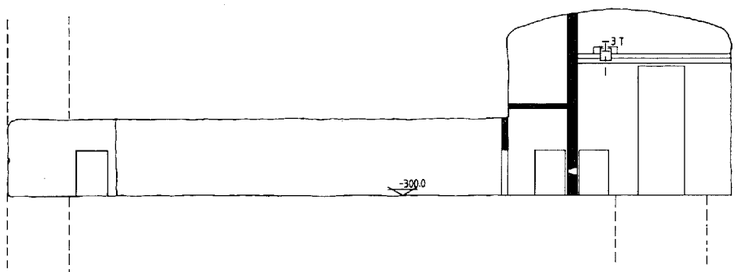
REV.	ANT.	REVIDERINGEN AVSER	RITAD	GRANSK.	DATUM

KBS
FINAL REPOSITORY FOR EMBEDDED FUEL CHANNELS
GENERAL LAYOUT
PLANE -300

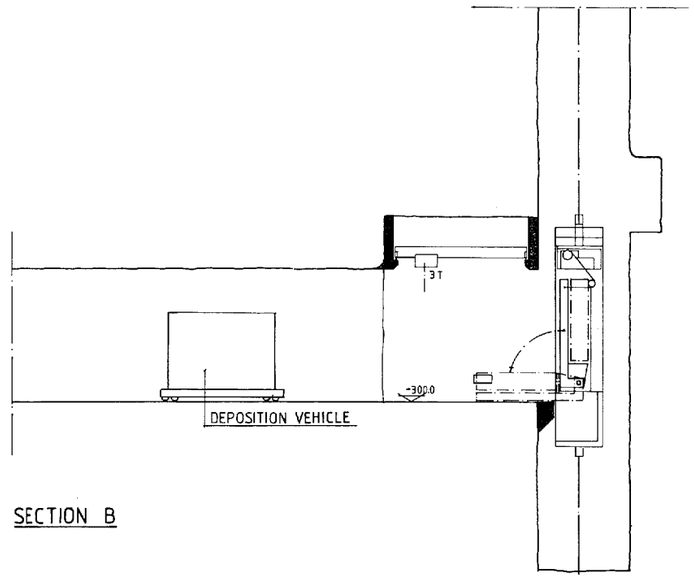
KONSTRUERAD	RITAD	GRANSKAD	REG-NUMMER
LEA	NIR		B 87 95
SKALA		RITNINGSNUMMER	REV.
		01	

STOCKHOLM
VBB
BOX 5038
10241 STOCKHOLM 5
TEL. 08-7627000

VBB 86:51



SECTION A



SECTION B

REV.	ANT.	REVIDERINGEN AVSER	RITAD	GRANSK.	DATUM

KBS
FINAL REPOSITORY FOR EMBEDDED FUEL CHANNELS

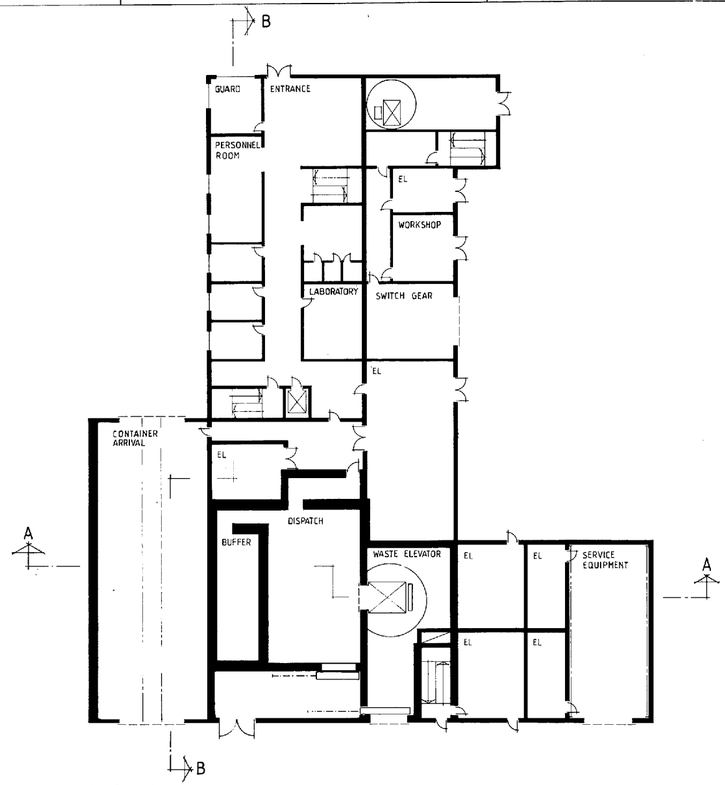
SECTIONS

KONSTRUERAD	RITAD	GRANSKAD	REG.NUMMER
LEA	WHF		B 87 95
SKALA		RITNINGSNUMMER	REV.
		02	

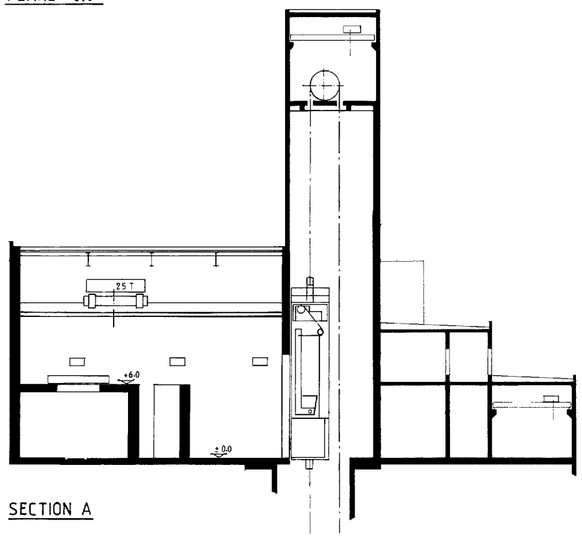
STOCKHOLM DEN

VBB
BOX 5038
102 41 STOCKHOLM 5
TEL. 08-782 70 00

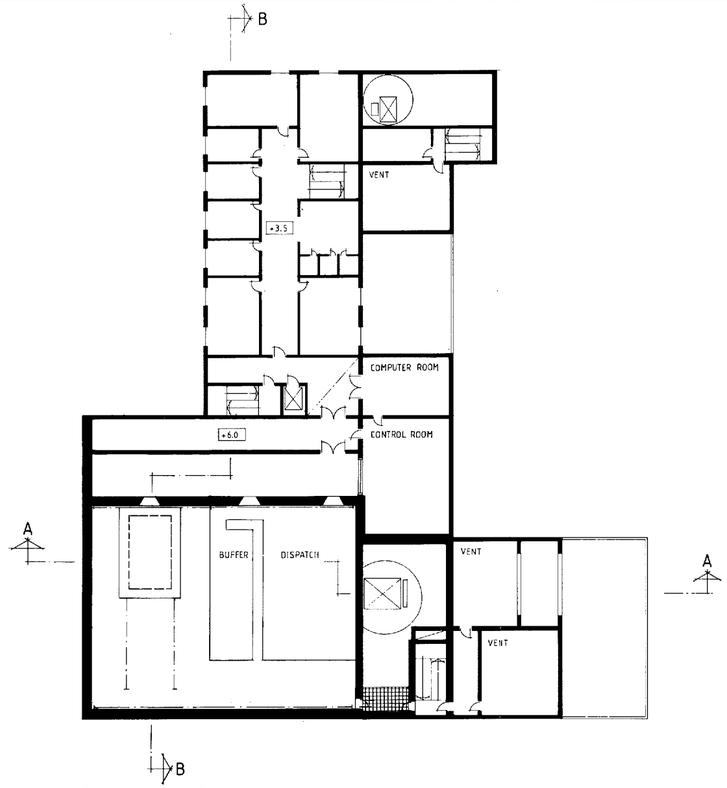
VBB 76-91



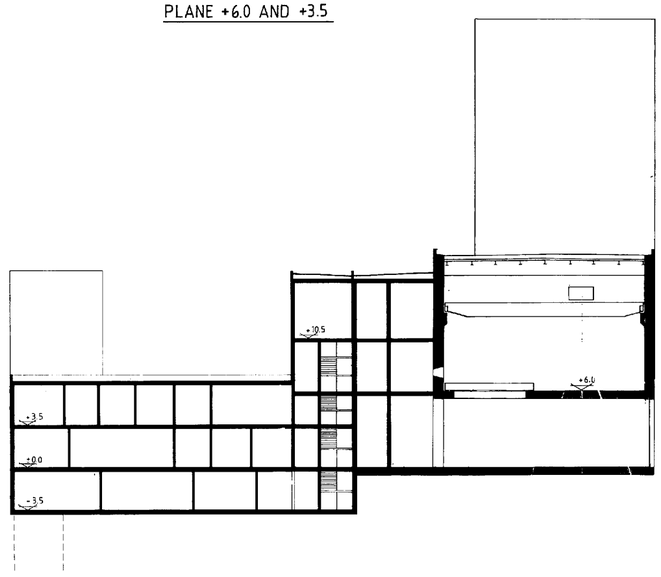
PLANE +0.0



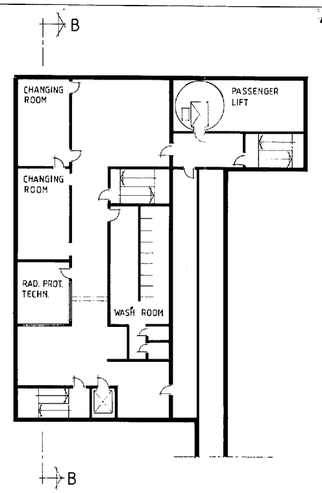
SECTION A



PLANE +6.0 AND +3.5



SECTION B



PLANE -3,5

REV.	ANT.	REVIDERINGEN AVSER	RITAD	GRANSK.	DATUM

KBS

FINAL REPOSITORY FOR EMBEDDED FUEL CHANNELS

RECEIVING STATION ON GROUND

LAYOUT

KONSTRUERAD	RITAD	GRANSKAD	REG.NUMMER
LEA	NIR		B 8795
SKALA		RITNINGSNUMMER	REV
1:		03	

STOCKHOLM DEN

VBB

BOX 5038
102 41 STOCKHOLM 5 TEL. 08-7627000

Oce-Ingvi 9112

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TR 121 — KBS Technical Reports 1 - 120.
Summaries. Stockholm, May 1979.

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TR 79-28 — The KBS Annual Report 1979.
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TR 81-17 — The KBS Annual Report 1981.
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A laboratory study
Trygve E Eriksen
Department of Nuclear Chemistry
The Royal Institute of Technology
Stockholm, Sweden 1983-01-19

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I Grenthe
I Puigdomènech
J Bruno
Department of Inorganic Chemistry
Royal Institute of Technology
Stockholm, Sweden January 1983

TR 83-03 — Smectite alteration
Proceedings of a colloquium at State University of New York at Buffalo, May 26-27, 1982
Compiled by Duwayne M Anderson
State University of New York at Buffalo
February 15, 1983

TR 83-04 — Stability of bentonite gels in crystalline rock - Physical aspects
Roland Pusch
Division Soil Mechanics, University of Luleå
Luleå, Sweden, 1983-02-20

TR 83-05

Studies of pitting corrosion on archeological bronzes
Åke Bresle
Jozef Saers
Birgit Arrhenius
Archeological Research Laboratory
University of Stockholm
Stockholm, Sweden 1983-02-10

TR 83-06

Investigation of the stress corrosion cracking of pure copper
L A Benjamin
D Hardie
R N Parkins
University of Newcastle upon Tyne
Department of Metallurgy and Engineering Materials
Newcastle upon Tyne, Great Britain, April 1983

TR 83-07

Sorption of radionuclides on geologic media - A literature survey. I: Fission Products
K Andersson
B Allard
Department of Nuclear Chemistry
Chalmers University of Technology
Göteborg, Sweden 1983-01-31

TR 83-08

Formation and properties of actinide colloids
U Olofsson
B Allard
M Bengtsson
B Torstenfelt
K Andersson
Department of Nuclear Chemistry
Chalmers University of Technology
Göteborg, Sweden 1983-01-30

TR 83-09

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U Olofsson
B Allard
Department of Nuclear Chemistry
Chalmers University of Technology
Göteborg, Sweden 1983-02-15

TR 83-10

Radiolysis in nature:
Evidence from the Oklo natural reactors
David B Curtis
Alexander J Gancarz
New Mexico, USA February 1983

TR 83-11

Description of recipient areas related to final storage of unreprocessed spent nuclear fuel
Björn Sundblad
Ulla Bergström
Studsvik Energiteknik AB
Nyköping, Sweden 1983-02-07

TR 83-12

Calculation of activity content and related properties in PWR and BWR fuel using ORIGEN 2
Ove Edlund
Studsvik Energiteknik AB
Nyköping, Sweden 1983-03-07

TR 83-13

Sorption and diffusion studies of Cs and I in concrete
K Andersson
B Torstenfelt
B Allard
Department of Nuclear Chemistry
Chalmers University of Technology
Göteborg, Sweden 1983-01-15

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The complexation of Eu (III) by fulvic acid
J A Marinsky
State University of New York at Buffalo, Buffalo, NY
1983-03-31

TR 83-15

Diffusion measurements in crystalline rocks
Kristina Skagius
Ivars Neretnieks
Royal Institute of Technology
Stockholm, Sweden 1983-03-11

TR 83-16

Stability of deep-sited smectite minerals in crystalline rock - chemical aspects
Roland Pusch
Division of Soil Mechanics, University of Luleå
1983-03-30

TR 83-17

Analysis of groundwater from deep boreholes in Gideå
Sif Laurent
Swedish Environmental Research Institute
Stockholm, Sweden 1983-03-09

TR 83-18

Migration experiments in Studsvik
O Landström
Studsvik Energiteknik AB
C-E Klockars
O Persson
E-L Tullborg
S Å Larson
Swedish Geological
K Andersson
B Allard
B Torstenfelt
Chalmers University of Technology
1983-01-31

TR 83-19

Analysis of groundwater from deep boreholes in Fjällveden
Sif Laurent
Swedish Environmental Research Institute
Stockholm, Sweden 1983-03-29

TR 83-20

Encapsulation and handling of spent nuclear fuel for final disposal
1 Welded copper canisters
2 Pressed copper canisters (HIPOW)
3 BWR Channels in Concrete
B Lönnerberg, ASEA-ATOM
H Larker, ASEA
L Ageskog, VBB
May 1983

TR 83-21

An analysis of the conditions of gas migration from a low-level radioactive wste repository
C Braester
Israel Institute of Technology, Haifa, Israel
R Thunvik
Royal Institute of Technology
November 1982

TR 83-22

Calculated temperature field in and around a repository for spent nuclear fuel
Taivo Tarandi
VBB
Stockholm, Sweden April 1983

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TR 83-24

Corrosion resistance of a copper canister for spent nuclear fuel
The Swedish Corrosion Research Institute and its reference group
Stockholm, Sweden April 1983

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Feasibility study of EB welding of spent nuclear fuel canisters
A Sanderson
T F Szluha
J Turner
Welding Institute
Cambridge, United Kingdom April 1983

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The KBS UO_2 leaching program
Summary Report 1983-02-01
Ronald Forsyth
Studsvik Energiteknik AB
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Trygve Eriksen
Royal Institute of Technology
Stockholm, Sweden April 1983