



Working Report 2004-49

Further Development of the Structure and Fabrication of the Final Disposal Canister

Fabrication and Costs of the Canister

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Heikki Raiko**

November 2004

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November 2004

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coincide with those of Posiva.

Further Development of the structure and fabrication of the final disposal canister

Fabrication and costs of the canister

ABSTRACT

During the last nine years Posiva Oy and Outokumpu Copper Oy have been jointly working with the development of a canister for the final disposal of spent nuclear fuel. Several processes, some with Svenska Kärnbränslehantering Ab (SKB), have been tested to produce the copper canister included pierce and draw process, backward extrusion and open forging. One of the processes, pierce & draw can produce a canister with an integrated bottom. The other fabrication routes require a separate bottom to be processed and welded to the cylinder. The bottom is practically the same as the lid, but it can have another manufacturing route as well.

The cylinder hot deformation processes available and tested cannot reach closer to the final wall thickness than about 75 mm, irrespective of the final wall thickness, 50, 40 or 30 mm. Consequently rather limited yield of material can be gained remaining a lot of machining work for the cylinder. The bottom and lid have a few alternatives and better yield might be possible.

The reliability requirement set for ndt methods for the inspection of the canister integrity is high. Decreasing the length of welded joints and the recent development of both radiographic and ultrasonic techniques to meet the requirements will also ease the costs and working hours of the inspections.

For the moment the resources to carry out especially the heavy workshop processes are few and scattered. This increases the transport costs included in the fabrication. At the moment there are no plans to invest for the heavy presses and technology required for the extrusion of the copper cylinder.

The test manufacture of a cast iron insert has been carried out both in Metso Foundries Jyväskylä Inc and by the SKB in corresponding Swedish foundries.

It is not finally decided where the canister will be assembled. In this case some guidance of the SKB Canister Manufacturing Workshop concept is utilised in estimation of the assembly costs. This is not seen as much misleading the total cost estimate.

Comparing to the former estimate (Posiva 97-24) the total costs have not been changed much, but the background knowledge of the affecting factors is considerably closer to the reality.

Keywords: Final disposal, Copper canister, Cast insert, Pierce and draw, Fabrication costs

Loppusijoituskapselin rakenteen ja valmistusmenetelmän edelleenkehittäminen

Käytetyn polttoaineen loppusijoituskapselin valmistus ja kustannukset

TIIVISTELMÄ

Posiva Oy:llä ja Outokumpu Copper Oy:llä on ollut yhteisiä kanisterin kehityshankkeita viimeisen yhdeksän vuoden aikana. Näissä sekä SKB-yhteistyöhankkeissa on testattu useiden valmistusmenetelmien, pisto ja veto, taaksepäin pursotus ja avotaannon soveltuvuutta saumattoman lieriövaipan tuottamiseen. Vain yhdellä menetelmällä, lävistys ja veto voidaan saada pohjallinen sylinteri. Muut menetelmät vaativat erillisen pohjan valmistus- ja hitsausreitit. Se on lähes identtinen kannen kanssa, mutta voidaan tehdä toisinkin.

Käyttökelpoisilla kuumamuokkausmenetelmillä päästään parhaimmillaan noin 75 mm:n seinämänpaksuuteen, riippumatta valmiin kanisterin mitoista. Koneistustyötä jää runsaasti eikä materiaalin käyttöä päästä tässä juurikaan tehostamaan.

Rikkomattomien tarkastusmenetelmien luotettavuusvaatimukset ovat erittäin ankarat. Kustannusvaikutusta helpottaa hitsimetrien väheneminen aikaisemmista vaihtoehtoista sekä radiografia- että ultraäänimenetelmien viimeaikainen kehitys.

Toistaiseksi kuumamuokkaus voidaan toteuttaa varsin harvoissa paikoissa. Tähän liittyy suurehko kuljetuskustannukset. Tarvittaviin raskaisiin puristimiin ja muuhun teknologiaan ei tämänhetkisen suunnitelman mukaan ole aiottu investoida.

Sisäosan pallografiittivaluja on tehty Metso Foundries Jyväskylän valimossa sekä SKB:n toimesta ruotsalaisissa valimoissa.

Kapselin kokoonpanon toteutuksesta on vasta alustava suunnitelmaa. SKB:n 'Kapselitehtaan' mallia hyväksikäyttämällä luotu kustannusarvio on suuruusluokaltaan paras arvio, joka ei lisää kokonaiskustannuksen epävarmuusmarginaalia.

Lopullinen kokonaiskustannusarvio ei poikkea paljonkaan aiemmasta (Posiva 97-24), mutta tieto taustatekijöistä on varmemmalla pohjalla.

Avainsanat: Ydinjätteen loppusijoitus, kuparikapseli, sisäosa, pisto ja veto, valmistuskustannukset

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1 INTRODUCTION

The most recent published estimate of the industrial fabrication costs of the final disposal canister has been made in 1997 (Raiko, 1997, in Finnish). Since then three development projects in co-operation between Posiva and Outokumpu have been carried out to further develop the fabrication steps of the canister components. As a result of these development efforts the design of the canisters for spent nuclear fuel from Olkiluoto, 2x840 MWe BWR and Loviisa, 2x488 MWe VVER 440 PWR nuclear power plants has not been changed in the exception of a few fabrication tolerance remarks.

The design is based on a massive cast iron insert with places for 12 fuel bundles. The heavily protected package is covered by a 50 mm thick copper cylinder with corresponding bottom and lid. The bottom can be integrated in one cylinder manufacturing process or it can be welded later. The canister will be closed with the lid at the encapsulation plant either by electron beam welding or friction stir welding.

The cast technology for the nodular cast iron insert has been developed so that the bottom of the insert can be integrated at the same cast with the steel profiles of the 12 cassettes.

In this report the most potential manufacturing processes, hot extrusion and a variant called pierce & draw and open forging are briefly summarised. The lid and the bottom are made by hot pressing. The copper components require a lot of machining after the hot deformation processes so that a yield of more than 55 - 65 % of the cast material cannot be reached with the present technology.

It has not been possible to take into account any possible effects of the future OL3 nuclear power plant to the fabrication bases. It is, however, expected that the procedures developed can be applied to slightly longer canisters as well.

The inspection of the cast billet for the lid and for the cylinder are given in the corresponding Quality Plans. The ready deformed and machined components will be carefully tested through an ultrasonic survey, partly using X-ray techniques and partly surface inspection methods.

There are only a few heavy workshops providing equipment to do the copper hot deformation. Transport costs are therefore an essential part of the total costs. The logistics involved bites a great deal of the time on the floor as well. The low yield makes it even less productive. Many of these costs factors will be reconsidered in due course.

2 CANISTER DESIGN AND THE MATERIALS

2.1. The canister components

The final disposal canister for the spent nuclear fuel is based on a massive cast iron insert with places for 12 fuel bundles. The heavily protected package is covered by a 50 mm thick copper cylinder with corresponding bottom and lid. The basic design is the same for both reactor types fuel bundles. The length and the cassette form are separately adapted for the both types, Olkiluoto, BWR and Loviisa, VVER 440 fuel. The main dimensions of the canisters are, outer diameter 1050 mm and the length 4.80 m and 3.60 m, respectively. The corresponding canister weights without the fuel assemblies are 21.5 and 16.5 tons. The ready assembled canisters are illustrated in figure 1 (Raiko & Salo, 1999). The same report gives the detailed masses and dimensions. The copper canister dimensions and masses with OL 3 EPR reactor are presented in tables 1 and 2.

The nodular cast iron insert (Raiko, 2003) acts as a load bearing part, as cassettes for the fuel assemblies, partly also as radiation protection and as thermal conductor to create a sufficient mass. The cassettes for the fuel assemblies are very tight to both dimensional and shape tolerances. The cast will be made with an integrated bottom. The insert lid will be bolted.

The copper canister is carefully machined from both sides to make a 50 mm thick cylinder. The requirements for circular and dimensional accuracy are high, because the gap between the copper canister and the insert is only 1 mm due to a minimised allowance for creep deformation in the raised temperature conditions.

The bottom can be integrated in the cylinder hot deformation process or it can be welded later. The canister will be closed with the lid at the encapsulation plant either by electron beam welding or friction stir welding.

2.2. The copper canister

The choice of material composition in the copper canister is determined by corrosion resistance, creep properties and manufacturing requirements. Corrosion properties would favour very pure copper. The same applies melt mode weldability. Reduced creep ductility at elevated temperatures can be improved with small addition of phosphorous. Hot or cold working or machining will not be a restrictive factor in manufacturing.

As a result of extensive material testing phosphorous micro-alloyed oxygen free copper (Outokumpu nomination, Cu-OFE P) has been chosen as the canister material. For the oxygen free base material the maximum oxygen content has been reduced to 5 ppm. Also the hydrogen content, max 0.6 ppm and sulphur, max 8 ppm has been determined to be lower than OF copper standards normally require (SKB Technical Specification KTS001). The phosphorous addition is 50 +/- 20 ppm. A typical chemical composition is given in table 3.

The quality plans set for the composition as well as fabrication steps, are applied already at the ongoing test manufacturing.

Table 1. Copper canister dimensions.

Cu canister dims / mm	VVER-440	BWR	EPR
Du	1 050	1 050	1 050
Di	950	950	950
(Cast iron insert, Du)	948	948	948
L	3 550	4 750	5 150
L (welded bottom)	3 600	4 800	5 200

Table 2. Copper canister masses.

Cu canister weight /kg	VVER-440	BWR	EPR
Bottom (welded)	380	380	380
Bottom (integrated)	320	320	320
Lid	420	420	420
Shell, 1 400 kg/m	4 900	6 600	7 200
Total copper canister weight with lid	5 700	7 400	8 000



Figure 1. BWR and VVER 440 final disposal canisters (Raiko & Salo, 1999).

Table 3. Typical canister material cast chemical composition.

Units ppm	3-001/1	3-001/2
Cu %	99,995	99,997
P	54	56
Ag	14.3	13.8
As	1.2	1.2
Bi	0.42	0.46
Cr	0.16	0.17
Fe	0.6	0.9
H	0.15	0.28
Ni	0.9	0.8
O	2	2.5
Pb	0.37	0.44
S	6.8	6.2
Sb	0.17	0.18
Se	0.7	0.7
Si	0.4	0.4
Sn	0.2	0.22
Te	0.39	0.42

2.3 Insert variations for BWR, VVER 440 and EPR fuel

The insert is made of nodular graphite cast iron in one piece. The cast material is according to specification EN-GJS-400-15U (SFS-EN 1563). The positions for fuel assemblies are open holes, which are dimensioned and formed according to data given in Table 4.

The insert with integral bottom is made of nodular graphite cast iron in one piece. The positions for fuel assemblies are open holes, circular or square, which are dimensioned and formed for respective fuel assemblies. The insert has a flat end lid made of 50 mm steel plate on top end. The lid is fixed with one central pin screw and there is a gasket between the lid and the insert body. The gasket can be a double O-ring. The purpose for the gasket is to keep the gases inside the insert during the electron beam welding of the lid of the copper overpack. The EB-weld is made in vacuum. The insert types for BWR, VVER 440 and EPR fuel assemblies are described in Table 4 and in Figures 2 - 5.

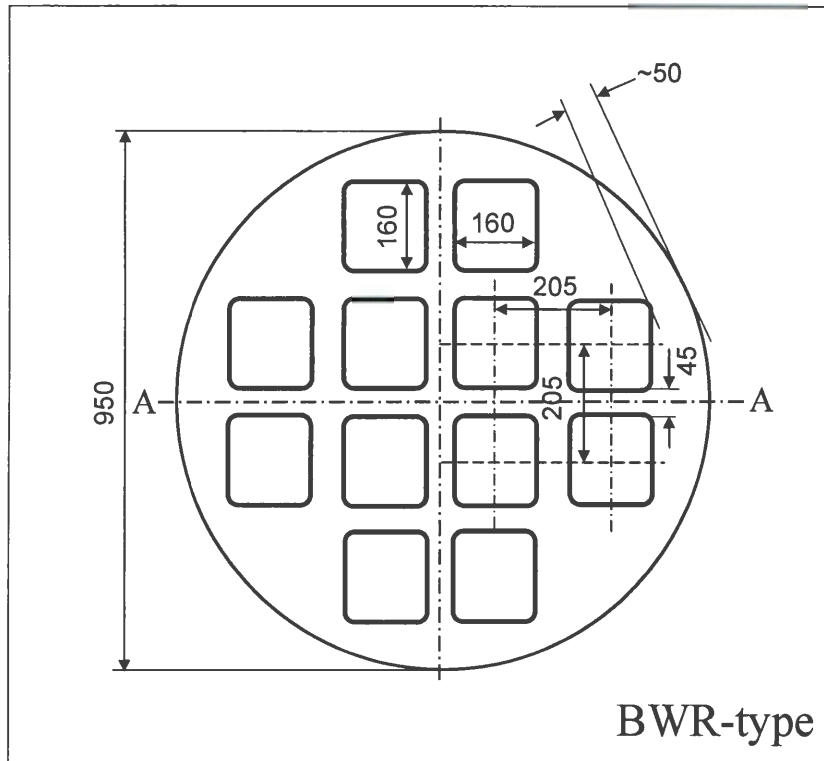


Figure 3. The canister insert section for Olkiluoto 1-2 reactor fuels.

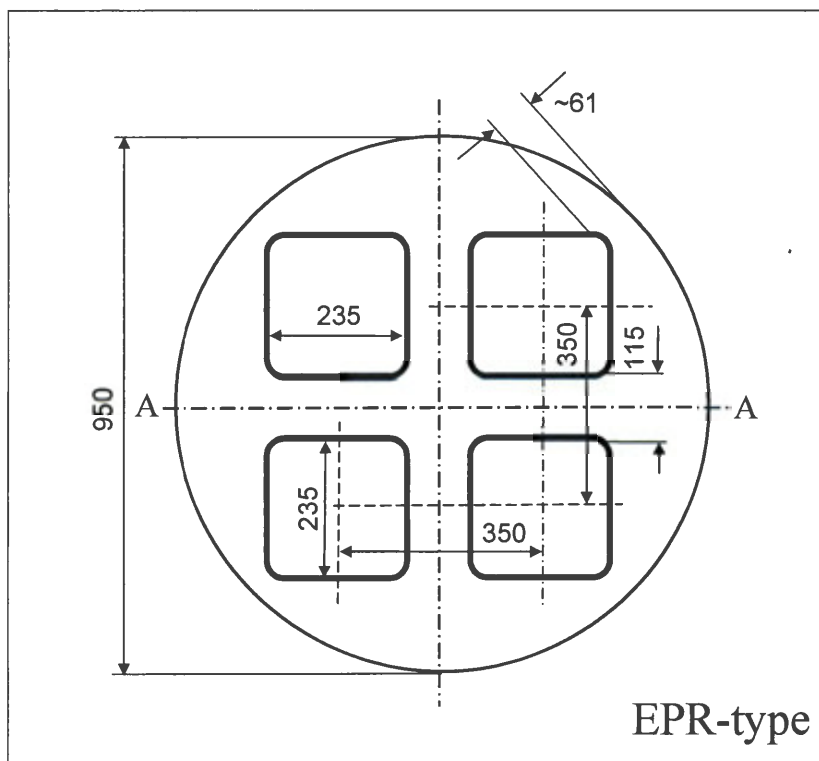


Figure 4. The canister insert section for Olkiluoto 3 reactor fuels.

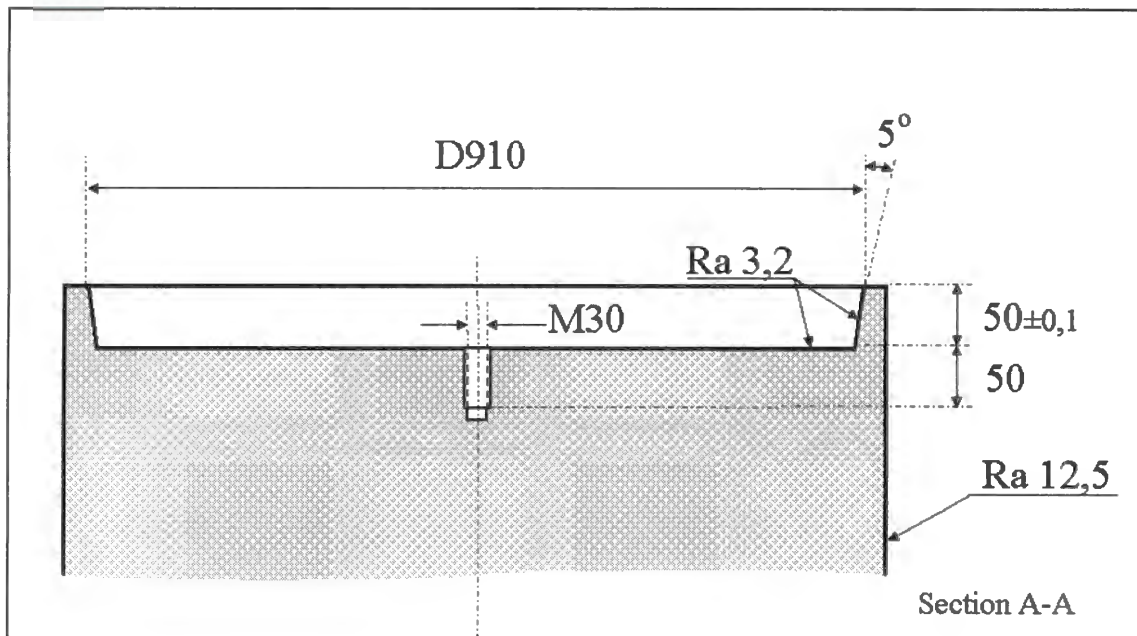


Figure 5. The fitting for gasket and lid in the canister insert top.

3 CAST OF THE BILLET

Outokumpu Poricopper oxygen free casting line has been earlier described i.e. in Aalto et al, 1996. Recently the billet canister casting procedure has been developed towards constant quality by

- redesigning the mould
- redesigning the phosphorous feed
- optimising the mould and secondary cooling
- optimising the cast table with insulation

The aim for the hot working processes, whether pierce & draw, extrusion or forging, is semi-continuously cast, \varnothing 850 mm solid billet about 2700 mm long weighting about 14 tons. Figure 6 presents an as cast billet for the encapsulation canister.

At the moment after about a dozen of completed casts for the development of the seamless canisters most of the problems, like the cast surface quality, variation of oxygen content and phosphorous content have been solved.



Figure 6. The big billet cast. The start end dovetail pointed out in the down left hand corner.

4 FABRICATION OF THE SHELL

From several possible methods to produce cylindrical components the fabrication route rolling, bending / longitudinal seam welding has been developed to a state of industrial manufacturing of used nuclear fuel disposal canister (Aalto et al.,1996, Andersson, 1998, Raiko et al.,1999).

Later the development work has been concentrated to seamless tubes to reduce the length of welded joints in the canister preferably only to the closing of the lid in the encapsulation plant.

There are three processes, which are available in Europe. They are *pierce & draw (called punch & draw with integrated bottom)*, *backward extrusion* and *open forging*. All of these have produced acceptable tubes for canisters. The big advantage of pierce & draw process is that it has proved to be able to produce a canister with an integrated bottom. These are described in the following to give background information for the cost analysis.

4.1. Pierce and draw

'Pierce and draw' process, also known as the Ehrhardt method by its inventor, is described in detail in Nieminen & Pihlainen, 2001. Besides the tube produced for Posiva Oy P&D-process has been used in test production of seamless copper tubes for the disposal canisters of spent nuclear fuel earlier for the Swedish SKB.

The billet is first hot worked in a 40 MN vertical piercing press in three upsetting blows to increase the diameter up to 1135 mm. Figure 7 shows the billet being positioned into the upsetting pot.

After the third upsetting, cooling down to room temperature and examinations the billet is reheated and pierced at about 760 °C using a 690 mm diameter mandrel. The piercing produces an elongated hollow body with integral bottom. It is important that the piercing produces tube without eccentricity so that there is minimum variation of the wall thickness (figure 8.). In case of eccentric tube, the deformation of the wall during expanding would concentrate to **the thinnest region** thus increasing the eccentricity. It is therefore a normal practice at this point to machine the tube to have an even wall thickness for the **further** deformation steps.

The hot deformation takes altogether 15 steps. One of the piercing and one of the drawing steps are shown in figures 9 and 10, respectively.

In case intermediate machining reveals surface defects, they can be smoothly ground away. Also possible bottom holes can be ground or even drilled away. The effect of grooves to the following expansion has been simulated by material flow models and acceptable defect sizes have been established. The process has produced canisters, which have proved acceptable in every other respect but the bottom grain size, which has to be < 360 µm.



Figure 7. Positioning the billet into the container for upsetting.



Figure 8. After the first piercing the cup was too much eccentric



Figure 9. One of the successive expanding phases in the pierce and draw process.



Figure 10. One of the successive drawing phases in the pierce and draw process .



Figure 11. *The canister with integrated bottom after final machining to be inspected manually by ultrasound during the development to verify the automatic inspection.*

After hot working operations the canister is bored inside and turned outside for final dimensions. At the pre-industrial phase the bottom was inside milled in sectors of about 30 mm each. A special tool must wait until the production numbers will reach a volume, which can justify the required investment.

The minimum wall thickness, which can safely be reached with the horizontal drawing and expanding is 75 mm, thus causing relatively much milling and turning work.

The gain of the pierce & draw process is at the moment only about 55%, hence a billet size of minimum 13.4 ton is required.

The straightness, dimensions and surface roughness has been acceptable when compared to SKB Technical Specification.

It is a standard procedure for these workshops to carry out dye-penetrant testing for the tubes. So far the cylinder and the bottom has additionally been tested with mechanised and manual ultrasonic techniques (figure 11).

4.2. Backward extrusion

The 1050 mm diameter canisters are outside the range of most hot extrusion presses available in the world, but can be found both in the US and Europe.



Figure 12. A 9 000 ton blocking press.

The required cylinder can be produced using three vertical presses, a 3000 ton, and a 9 000 ton blocking press and a 30 000 ton extrusion press (figures 12 and 13). The process starts in rotary furnaces to heat the material. Once the billets are heated to the required temperature, they are placed in the 3 000 ton press. At first the scale is removed from the billet surface. When clean the heated blocking dies are moved into position and the upper slide assembly applies downward pressure to compact the billet into a pot. This procedure, known as potting, refines the cast structure. Next the piercing punch is positioned over the billet in the 9 000 ton press. Piercing is the first step to dimensionally form the inside diameter towards the final shape. The whole blocking sequence is presented in figure 14.

After the blocking sequence the pierced tube is machined on all surfaces, heated in the oven and placed on a pedestal of the extrusion press. First the mandrel is extended up through the tube to shape the inside diameter. Next the upper bolster and preheated dies are lowered over the blocker. The extrusion container is forged through the die. When the tube reaches its final length, the upper bolster is raised and the extrusion is completed. The whole extrusion sequence is presented in figure 15.



Figure 13. A 30 000 ton extrusion press.

Extrusion is reasonably well controlled operation. Problems, which might occur and defects, which can be brought to the final product are connected to friction or variation of cooling of the billet during the extrusion. The varied friction can cause changes in material flow pattern. This variation of the flow pattern can lead to surface oxides immersing into the canister wall. Incomplete recrystallisation can lead to locally increased grain size.

The gain of the backward extrusion process is also low, like above about 55%. Their requirement for the billet size is 12.1 to 12.4 tons. The machining and inspections are the same as in case of pierce and draw.

4.3. Open forging

There is a 4 000 ton forging press, which is said to be the biggest in Scandinavia. It can handle up to 70 tons components. The solid \varnothing 850 mm cast copper billet about 12 ton is placed standing in the press. It is pressed down in a few steps to more like a cake. Then it will be pierced with a mandrel. Then the ring formed block is placed horizontal where it will be hot forged to enlarge the hole in the middle (Lagerblad, 2003).

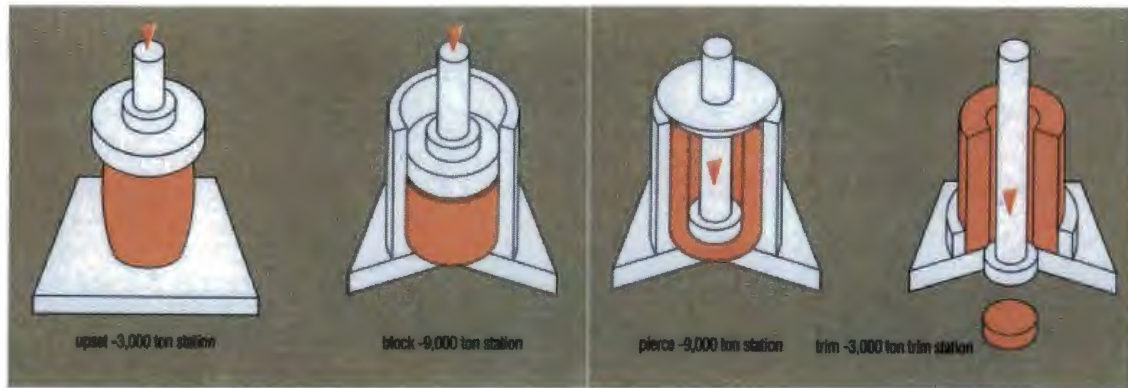


Figure 14. Start of the extrusion process, potting and piercing.

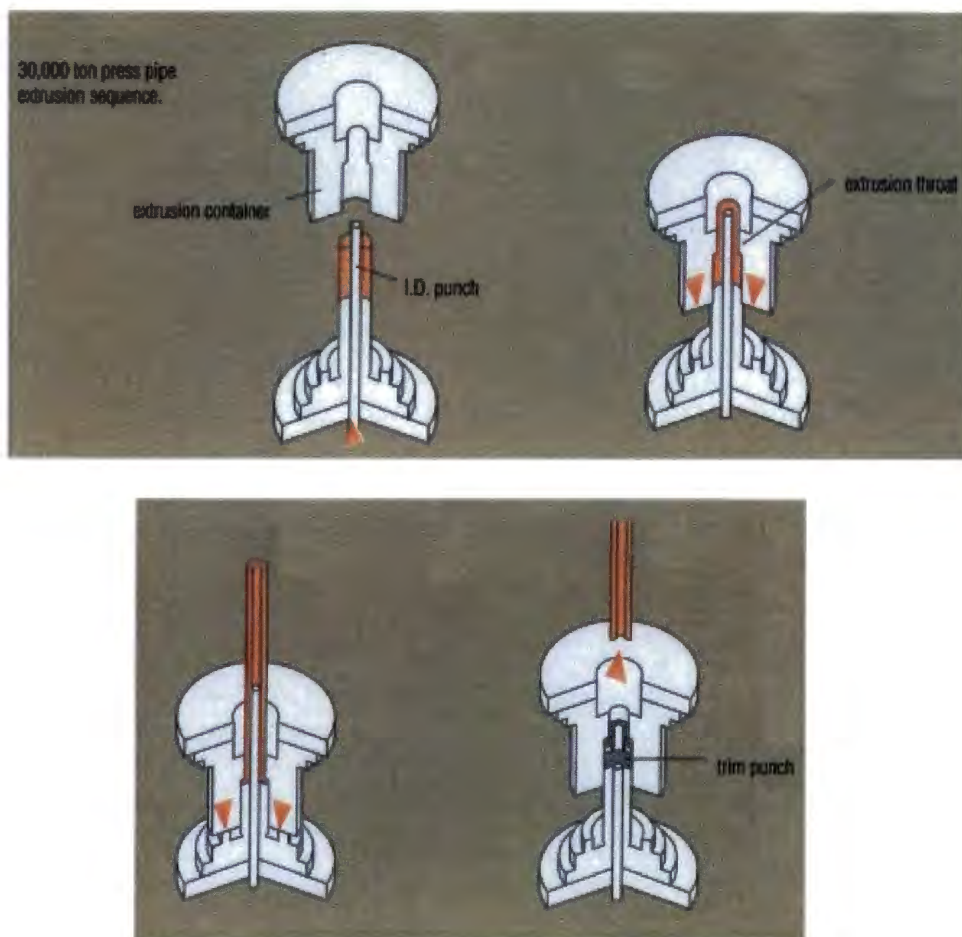


Figure 15. The backward extrusion phase.



Figure 16. A nearly ready forged cylinder. The semi-circular tools are in the press.

In the next step the shell will be hammered with a specially designed forge tool until it is long enough for a 5 m long cylinder (figure 16) after the both rather irregular ends have been machined straight. The semi-circular press heads are used in this most difficult phase to get the cylinder exactly circular. Hot forging is all manually controlled. The process requires a lot more working hours than the extrusion, but the fixed assets are lower and the transportation is easier and cheaper.

SKB has reported that the dimensional tolerances can be met and the nd testing has proved the cylinder to be acceptable.

5 FABRICATION OF THE LID (AND THE BOTTOM)

Lids and bottoms to the canister are machined from blanks preformed by hot forging. It gives the material the desired homogeneous and fine-grained structure. A conventional forging press can do the job. Such workshops are close in hand. The forging will give the blank such a shape and dimensions, that the machining work would be minimised.

The starting block for this process is cylindrical, 350 - 500 mm diameter, copper ingot (figure 17). For the lid, and similarly for the bottom, if required this continuously cast ingot is cut to 1.4 - 0.65 m pieces. First the ingots are pressed in several steps down to a flat cake (figure 18). The final forging operation takes place in a specially designed die and a formed presser head (figure 19).

The way to improve the yield, i.e. to further decrease the machining work after the hot forging, is to optimise the copper ingot and the design of the forging die by modelling. The work has been carried out by Hamzah (2004).



Figure 17. The 350 mm casts for the copper lids and bottoms.



Figure 18. The cast block is hot pressed down to a cake.



Figure 19. Finally the cake will be die forged.

6 BOTTOM WELDING

In the two cases, the backward extrusion process and the open forging the bottom must be welded to the cylinder to make the copper overpack. The pierce & draw process has been tested to give an integrated bottom. For the bottom welding electron beam welding procedure has been developed. Alternatively friction stir welding has been developed by SKB for the joining of the bottom. Both processes are briefly described in the following.

6.1. EBW

Electron beam welding is a well established mass production method ever since 1960's. For thick copper welding it is described ao. in Aalto et.al, 1996. The procedure development work has been reported in Aalto, 1998, Salonen & Meuronen, 2000 (in Finnish).

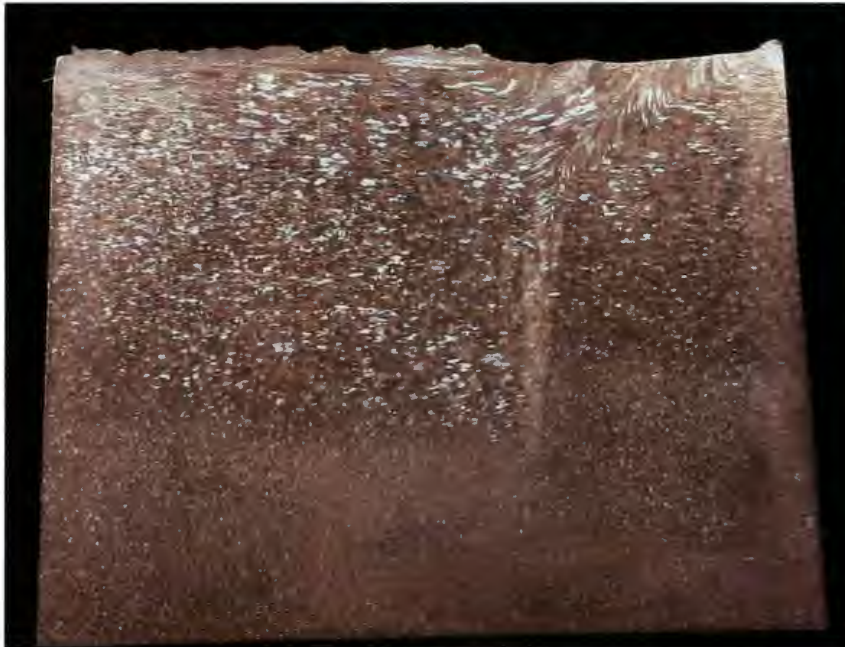


Figure 20. An overlapping EB weld from a plate welding test. A 150 kV EB generator has been used with 45 kW beam power.

Joining the bottom is similar to final closing of the canister lid and requires at least 60 mm weld penetration. It is a complicated task to copper, because the material is heavy and needs a lot of energy to melt. In Finland the development work is based on commercial high voltage technology with state of the art EB generator electron optics and beam deflection control. In such a deep penetration welding, which is not a pure keyhole welding, it is wise to use vertical beam to be able to control the melt behaviour and the evaporation channel. The well known complications of the root area spiking effect, the slope down cavity and the spatter and bursts of melt caused by differences in vacuum level when overlapping, have all been successfully tested during the several years of development work. Figure 20 shows that a sound finish can be achieved.



Figure 21. Ready lid closing EBW test at Steigerwald GmbH, 150 kV, beam power 40 kW.

The electron beam welding procedure developed for the circumferential weld to close the lid (figure 21) can be directly applied to bottom joining as well. It is easier in a few aspects like the open canister, which will not cause a pressure difference problem and the workshop environment, which makes the inspection and a possible repair welding much easier. The problem faced so far is the every time changing test environment not allowing repeatable production type welding to be carried out.

6.2. FSW

Friction stir welding (FSW) is a very new process invented only about 12 years ago by The Welding Institute (TWI). It was at first meant solely for aluminium welding finding its first 'industrial' application within space craft manufacture. There is still a long way to go from light, easy to 'stir' soft aluminium alloys to tough, thick copper sections. The problem of the process is culminated to finding a tool geometry and material to last the long welds in copper. The friction stir welding process is described a.o. in Cederqvist & Andrews, 2003.

It has been proved by SKB and TWI that the required penetration can be achieved and a good quality joint produced with FSW. Two full size machines have been built for the circumferential lid joining tests. The later one is specially meant for lid closing (figure 22).

One of the key issues is the stiffness of the machine frame and the tool head to keep up a steady down force. Working in extreme conditions the parameters to follow the process are the down force control and the temperature at the welding head.



Figure 22. A canister lid closing FSW machine (SKB Canister Laboratory).



Figure 23. A complete lid closing FSW weld (TWI).

A hole is left at the end of a FS weld. The lid and bottom must be designed so that these holes can be brought to safe places or machined away after welding (figure 23).

The problem is like in EB welding that the acceptable parameter window is extremely narrow and it is still not finally established, which would be the controlling parameters in order to keep the constant conditions for a defect free weld throughout the entire circumference of 3.2 meters. Nevertheless, the latest news is, that a complete canister was successfully closed using FSW in May 2004.

7 INSPECTION OF THE SHELL AND THE BOTTOM

Posiva has started a programme together with SKB, for developing qualifying procedures for canister manufacturing, welding and inspection. Generally the quality assurance of the canister pre-fabrication will be carried out according to procedures adapted for the nuclear power plant component manufacturing.

According to the present plans, the lid weld will be inspected volumetrically by a mechanised and automated ultrasonic system and alternatively or additionally with a computerised X-ray system. The surface of the weld will be inspected by an eddy current device, in addition the outer surface will be inspected using liquid penetrant testing or visually.

The same procedures will be applied to the pre-fabrication of the canister components and bottom welding to a degree applicable and verified within the test fabrication and development of the manufacturing methods.

For estimating the cost of the pre-fabrication it is assumed that the shell and the bottom will be ultrasonically surveyed using an automatic inspection station. A complete dye-penetrant testing will also be applied.

In case of welded bottom the joint will be completely inspected both by surface inspection methods and volumetrically using automated X-ray technique and mechanised ultrasonic system. Phased Array ultrasonic technique has been developed for this purpose. A manual version is shown in figure 24. A good resolution has been proved with SKB 9 MeV linear accelerator (figure 25) equipped with a state of the art computerised detector system (figure 26).



Figure 24. Manual Phased Array Ultrasonic inspection of the lid weld (Inspecta Oy).



Figure 25. A linear accelerator, 9 MeV for the lid weld radiographic inspection.

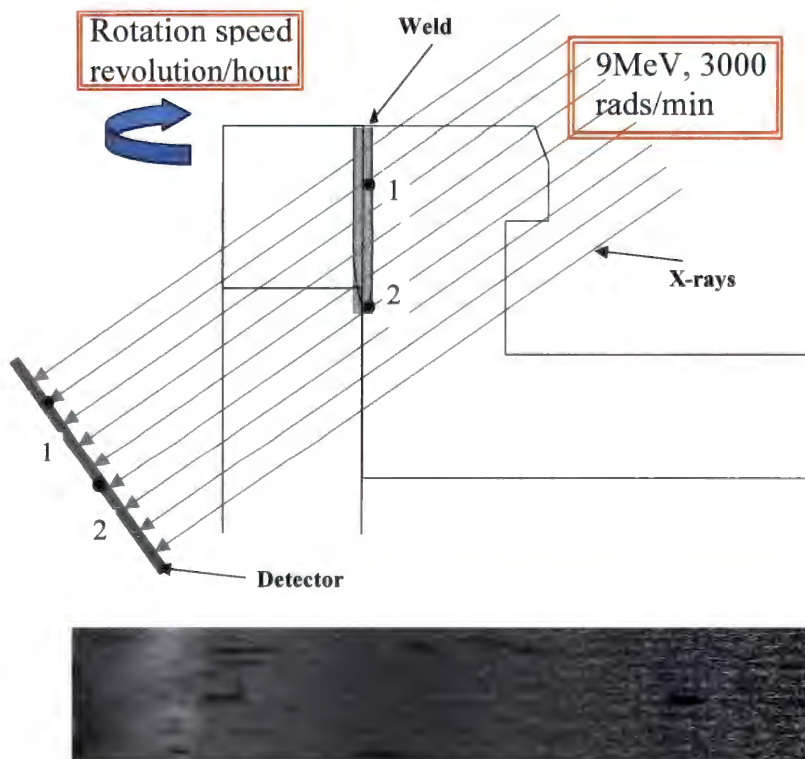


Figure 26. The interpretation of the beam is made by a detector slice by slice. The resolution is extremely good as shown with an example.

8 CANISTER INSERT FABRICATION

The insert is cast in a foundry, and no additional thermal treatment is needed. The openings for fuel assemblies are formed to the cast body by setting an equivalent steel structure into the mould. The prefabricated steel structure is welded together from steel tubes with strict dimensional tolerances. The bottom of the insert is cast as a 60 mm thick integral bottom, thus the positions for fuel bundles are open from top end only. After casting the cast block is cleaned up by sand-blasting, cut into the right length and the outer surfaces are machined. In addition, three drilled holes are made and threaded into the top end of the insert. One is used for the central lid fixing screw and the two other are used for fixing the lifting eyes.

Then a volumetric ndt examination is made. In addition, the dimensions and machined surfaces are examined. The outer circumference is examined with ultrasonic test not to include large buried indications within the 50 to 60 mm depth measured from the outer circumference. The machined top face including the fitting for gasket and lid is surface tested with liquid penetrant or magnetic particle examination for surface cracks. The gasket can be a double O-ring. The purpose for the gasket is to keep the gases inside the insert during the electron beam welding of the lid of the copper overpack. The EB-weld is typically made in vacuum.

The top lid is manufactured by machining from rolled steel plate. The M30 pin screw is installed and the top lid with a gasket system is not assembled until the canister is filled with fuel bundles in the encapsulation plant. The planar lid is surface tested for cracks.

9 TRANSPORT

For the pre-fabrication costs it is assumed that the sites described in the 'Fabrication' chapters are to be used. The logistic routes for the three alternative fabrication procedures are given in tables 5 - 7. Components to one canister have to be transported nine times, two of them shipping abroad and the rest lorry transports inside Finland. This is assuming that the forging sites or the machining sites have got the automatic inspection facilities required for the quality assurance.

Table 5. Pre-fabrication of the canister.

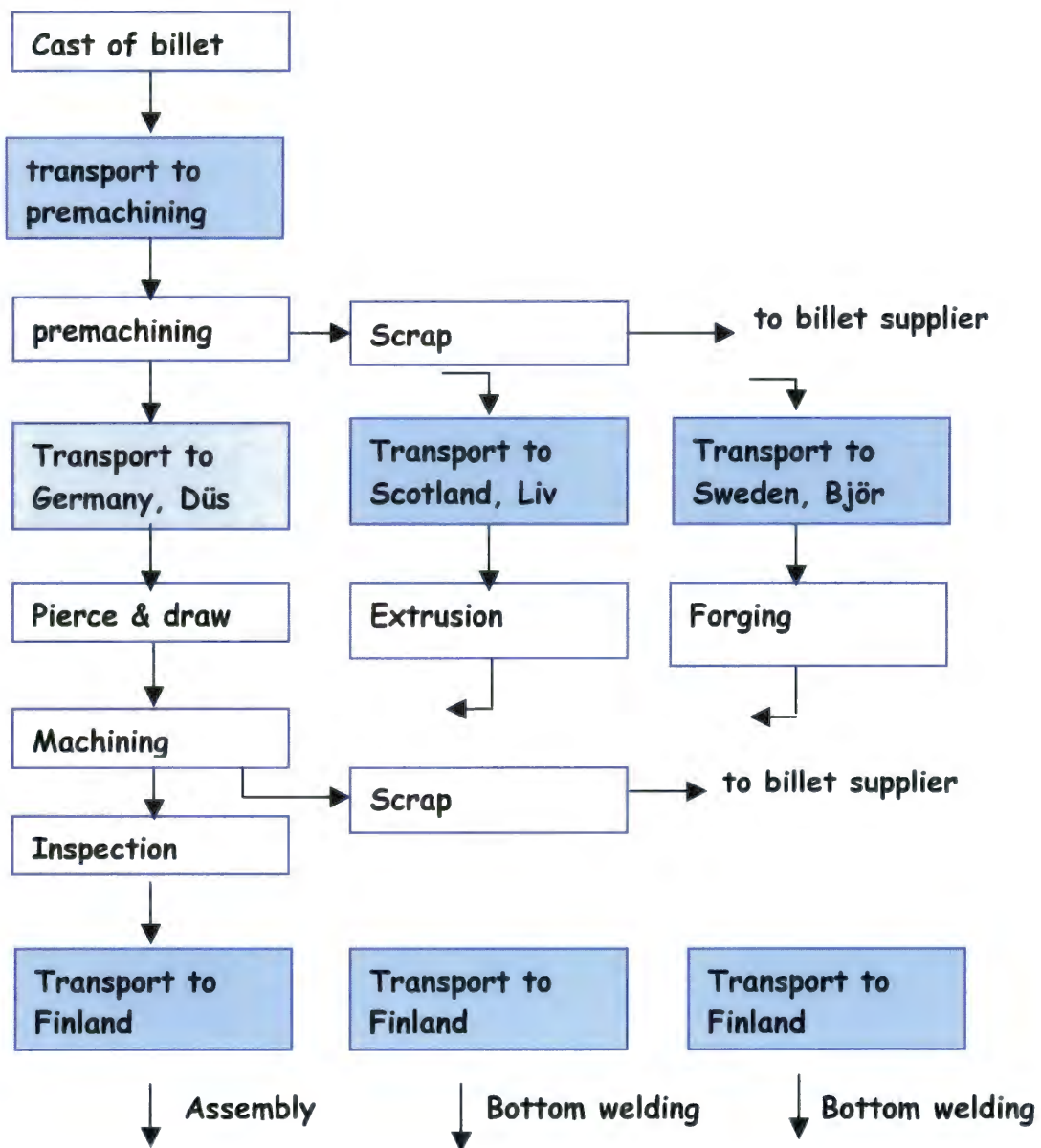


Table 6. Pre-fabrication of the insert and the bottom / lid.

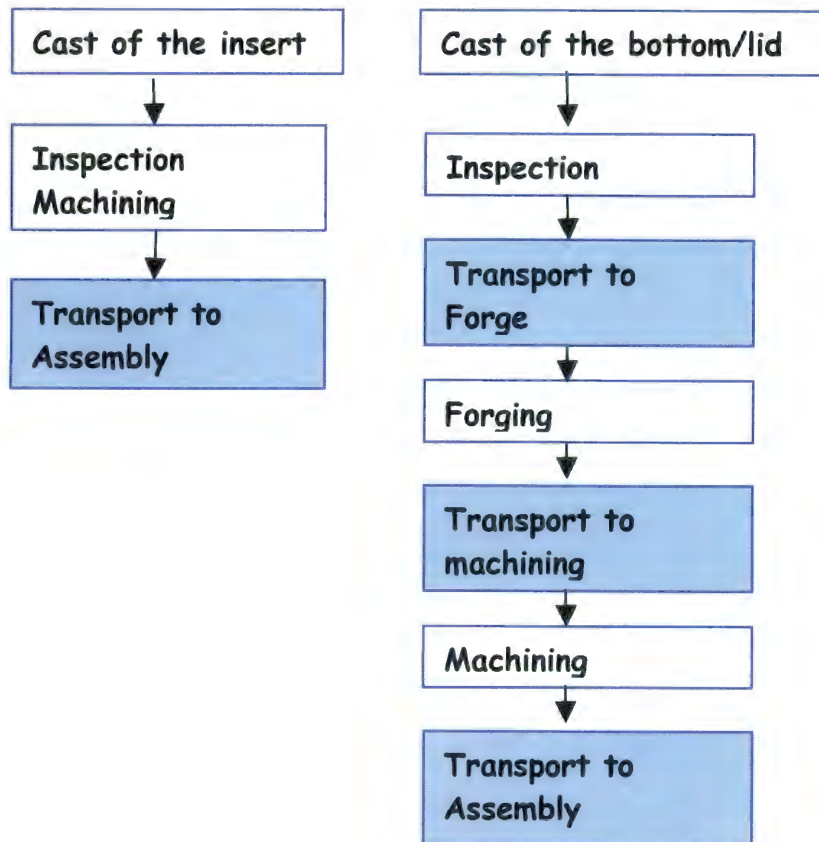
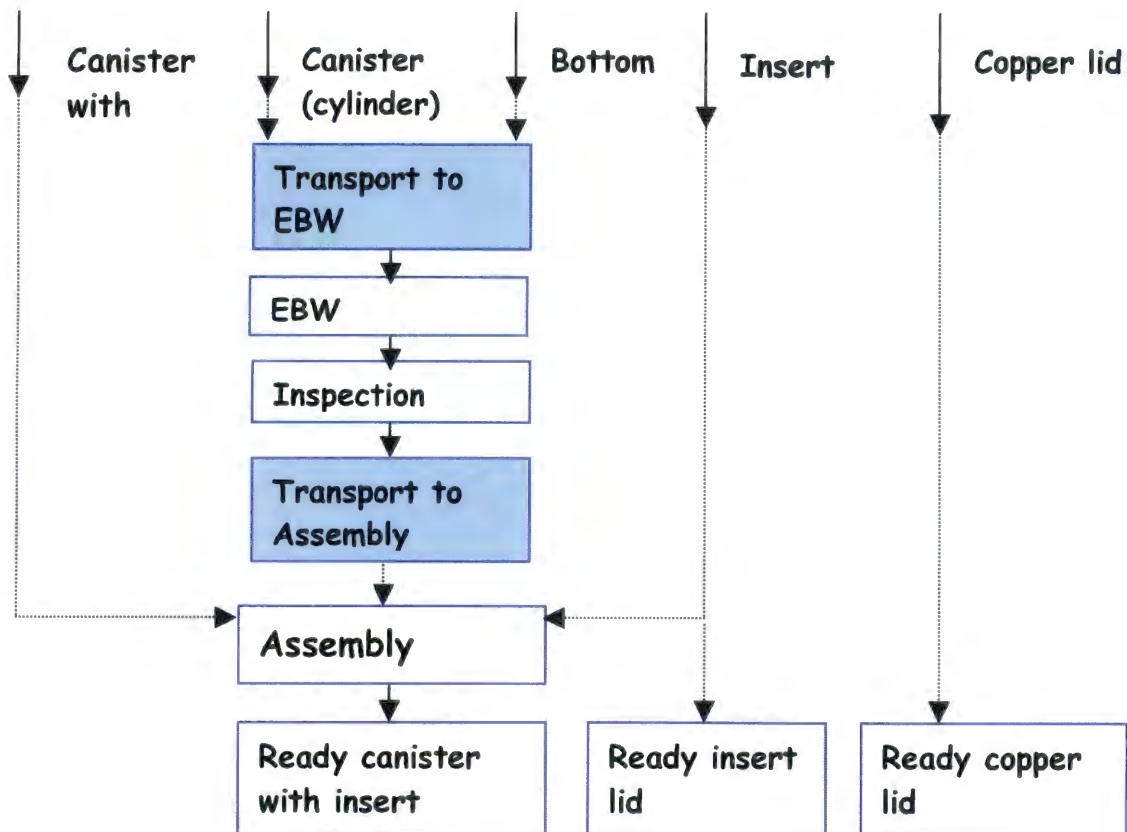


Table 7. Assembly of the pre-fabricated components.



10 ASSEMBLY OF THE CANISTER PARTS

It is assumed that a separate assembly hall with normal heavy workshop component handling systems like min a 25ton lift and high enough room for the hoisting is available. Alternatively the cast iron insert can be assembled in connection to the encapsulation plant.

A ready hot deformed and machined canister with integrated bottom will be brought to the assembly. In case the bottom is welded to a cylinder the ready welded and inspected canister will be brought from the welding site. Thirdly the insert is transported from the foundry / workshop ready machined and accepted. At the assembly there will be yet a separate acceptance inspection, verification of the inspection certificates.

The main task is to put the machined cast iron insert inside the copper overpack. It will require a handling system for both 6 to 8 ton copper canisters and 10 to 17 ton cast iron inserts and a station where the copper canister is placed on a lying platform for the delicate assembly where the insert outer diameter is only 2 mm smaller than the copper canister inside diameter.

Together the package is rigid for the transportation, but will need a protective cover and a transport cradle for a safe lorry transport.

The whole operation is mostly logistics oriented routine work well established and does not incur a great deal of costs. As it is assumed that the assembly is made continuously evenly spread throughout the year, it will not cause any wider storage problems nor any special handling capacity requirements.

11 CANISTER MANUFACTURING COSTS

The final disposal canister test fabrication has been spread out to companies and workshops, which have got the required special know how and processes. The main manufacturing steps were described in Chapter 9. The number of companies available in Europe with the required status is very limited. Therefore competing quotations could not be received. The tenders started from a yearly production of about 100 canisters grouped in monthly batches of 8 canisters.

The test manufactured components were always single products and the tools and processes used were only tuned for those single pieces. It was therefore not possible to approach a real industrial price. Actually, it is probable that the equipment and processes to be used in series production starting around year 2015 will be different to what were used as the quotations now received. A long term planning of fabrication costs could be easier if there were any co-operation or co-development agreements between the fabricators and the buyer.

The component prices are direct prices at the time of reporting. The transport prices are based on long term agreements with the logistics companies. Copper material price is selected and fixed to match a long term development. The assembly of the components is planned to be carried out at a domestic workshop. It is assumed that the quality assurance, inspections and documentation are included to the component and assembly prices.

11.1. Copper canister cost

Starting from the cast of the big billet the price is formed by the copper material price and cast procedures, inspections and premachining of both ends and the surface. During the last 8 years time the LME price of copper has changed on extremely wide scale and lately very dramatically (figure 27). Still for this estimate a fixed copper price is selected to represent a long time average, 2.5 Euros/kg. It is estimated at Outokumpu that a change from semi continuous casting to a continuous oxygen free casting line would require about 2 M€ investment. Continuous casting process could increase the yield, improve quality of cast billet and considerably reduce casting costs.

Based on the lately delivered test billets it is assumed that the pierce & draw process requires 13.4 tons ready cleaned billet. The extrusion requirement is 12.4 tons and a slightly smaller size, 12 tons is used for the forging.

The cast billet, both ends and surface cleaned is transported to hot deformation workshop to be pierced and deformed to seamless cylinders either with or without an integrated bottom. The raw processed cylinders will be ready machined at the sites. The considerable amount of copper chips will be compensated towards the credited price using quoted LME copper price, normally LME – 10%. The net masses delivered from the workshops are 7 000 kg with integrated bottom and 6 600 kg without the bottom. Total theoretical volumes of scrap will be 6 400 kg for the pierced & drawn, 5 800 kg for the extruded and 5 400 kg for the forged cylinder. A similar counting is applied to the casting and premachining

phase. The starting cast size is 14.8 tons. It is premachined to 13.4 tons for the pierce & draw process and to 12.4 and 12 tons for the other processes. The factors towards the **handling** prices increase slightly with increased machining work. The scrap price is readily subtracted from this processing price.

After the machining the cylinder will be automatically nd tested, which is also included to the budget price received from the potential suppliers. They have informed of investment programme to the critical points like annealing and the first piercing, which will have an influence on the canister price in future. The other prices are estimated by Posiva.

The prices shown on Table 8 are based on Olkiluoto 1-2 BWR-type canisters. The difference to a slightly lighter canister required for the Loviisa VVER-440 fuel is about 7% less. Olkiluoto 3 EPR-type uses longer fuel rods and hence longer canister is required with respectively higher costs.



Figure 27. Development of copper LME price during last 8 years in USD without inflation correction.

Table 8. Cost estimate for a BWR-type fuel final encapsulation copper cylinder of the canister. M stands for the delivered billet size, M_c is the Cu canister mass.

Item	Cost (€)		
	Pierce&draw	Extrusion	Forging
Raw material, (2.50 x M)	32 750	30 250	30 000
Casting + inspection + premachining	37 050	39 550	40 550
Billet sizes delivered, (M)	13 400 kg	12 400 kg	12 000 kg
Hot forming + machining + inspection	35 750	32 175	17875
Canister sizes delivered, (Mc)	7 000 kg	6 600 kg	6 600 kg
Scrap value,(2.25x(M – Mc))	- 14 400	- 13 050	- 12 150
Transport	3 000	4 400	1 300
Copper canister total	94 150	93 325	77 575

11.2. Cost of the insert

The estimated cost for a BWR-type canister insert in serial production is 36 000€. The price is based on the experience gained from the manufacturing tests of a few prototype inserts made in Finland and Sweden during the past years. The estimate is based on the assumption of serial production of 50 to 60 inserts annually. The price estimate does not include the value-added tax, as is the case throughout the present review.

The insert for Loviisa type fuel is some 20% cheaper, 29 000€ and the insert for EPR-type fuel is some 10% more expensive, 39 600€ than the BWR-type insert referenced here. Inserts for Loviisa-type fuel or for Olkiluoto 3 EPR-type fuel are not, so far, test manufactured in Finland.

11.3. Cost of the copper canister bottom and the lid

In case of extruded or forged cylinder a bottom needs to be welded. Made as described in Chapter 5 the cast must be 800 kg. The final machined bottom is about 380 kg. The lid start size is 1 200 kg and after final machining about 420 kg. It is assumed, as in case of canister processing that the machining chips can be recirculated at LME – 10% price. The price formation is summarised in Table 9.

11.4. Cost of the assembly

The assumed assembly conditions are described in Chapter 10. Electron beam welding or friction stir welding of the bottom to the extruded and forged cylinders are here included to the assembly.

So far, the lid closing tests with EB welding have been carried out abroad. It can be assumed that, in future, facilities in Finland will be available and hence the transport costs will be considerably lower than sending the components to Western Europe to be joined. The Patria Aviation facility is under rearrangement, but still not capable of inserting the whole canister. Therefore there are no possibilities to get calculated estimate of the welding costs. The only figures available from the lid closing tests are based on small chamber size and individual experimental handling, which can give a far misleading estimate.

11.5. BWR-type canister total costs

Collecting the total costs of the main components and the assembly from the appropriate tables 5 to 8 and adding them together the total canister costs with the lids are presented in table 9 for the optional main copper shroud deformation process.

Table 9. Cost estimate for a BWR-type canister bottom and the lid.
Mc stands for the delivered billet size, Md is a ready lid/bottom.

Item	Cost (€)	
	Bottom	Lid
Raw material, (2.5xMb)	2 000	3 000
Casting	240	360
Billet sizes delivered, (Mb)	800 kg	12 00 kg
Hotforming + machining + inspection, (1.5xMb)	1 600	1 800
Sizes delivered, (Md)	380 kg	4 20 kg
Scrap value (2.25x(Mb - Md))	- 945	- 1 755
Transport	50	50
Bottom / Lid total	2 945	3 455

Table 10. Cost of the assembly of BWR-type canister components.

Item	Cost (€)		
	Pierce&draw	Extrusion	Forging
EB welding	-	6 000	6 000
Insert to copper canister	1 500	1 500	1 500
Transport	-	200	200
Copper canister total	1 500	7 700	7 700

Table 11. BWR-type canister total cost.

Item	Cost (€)		
	Pierce&draw	Extrusion	Forging
Insert + lid	36 000	36 000	36 000
Copper canister + lid	97 605	99 725	83 975
Assembly	1 500	7 700	7 700
A ready canister + lid	135 105	143 425	127 675

12 CONCLUSIONS

Posiva Oy, Outokumpu and SKB have made considerable investment to test and implement fabrication steps of the spent nuclear fuel canister. As a result the nodular iron insert is cast with an integrated bottom and the copper overpack is being made of a 15 ton cast billet, which is extruded or forged to a seamless cylinder. One of the optional processes can produce a canister with an integrated bottom. A more conventional route is to use hot rolled copper plate, bend it and weld the required longitudinal joints. But that has not been considered in this cost analysis.

Here pierce & draw, backward extrusion and open forging have been selected as possible fabrication methods. For the moment it is difficult to see any other process to appear as more potential to produce seamless copper cylinders.

The present analysis of the canister costs is based on well established procedures. The cast iron insert has been made in four workshops. Together they have produced tens of casts. The total number of big copper billet casts approaches 20. The lids and bottoms have been produced by a few fabricators in tens of pieces.

The calculation resulted in 135 105 euros total costs to a complete canister for a BWR-type used fuel in case of pierce and draw process, which gives an integrated bottom to the copper canister, thus simplifying the manufacturing route. Extrusion way would be 6% more expensive, whereas open forging as a non automatic craftsmanship work would be 6% cheaper.

The other options, a canister to Loviisa-type (VVER 440) fuel or the fuel left after several tens of years from the new EPR-type reactor have not been counted exactly. An estimate is that Loviisa-type smaller canister would be about 10% cheaper than the BWR-type.

Because of many confidentiality reasons and because of experience only on a few individual tests, real component prices have been extremely difficult to get in many, even significant steps of fabrication. It is not possible to get an estimate of the inbuilt uncertainty of the price. The given price is based on present available information of production cost level. A part of the costs is incurred to logistics, not only the direct transport costs but also the extra time consumed tends to increase the total costs.

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