POSIVA-96-08

Production methods and costs of oxygen free copper canisters for nuclear waste disposal

Harri Aalto
Hannu Rajainmäki
Lenni Laakso
Outokumpu Poricopper Oy

October 1996

POSIVA OY
Annankatu 42 D, FIN-00100 HELSINKI, FINLAND
Phone (09) 228 030 (nat.), (+358-9-) 228 030 (int.)
Fax (09) 2280 3719 (nat.), (+358-9-) 2280 3719 (int.)

ISBN 951-652-007-3
ISSN 1239-3096

ISBN 951-652-007-3
ISSN 1239-3096

Posiva-raportti - Posiva report

Posiva Oy
Annankatu 42 D, FIN-00100 HELSINKI, FINLAND
Puh. (09) 2280 30 - Int. Tel. +358 9 2280 30

Raportin tunnus - Report code
POSIVA-96-08

Julkaisuaika - Date
November 1996

Tekijä(t) - Author(s) Harri Aalto, Hannu Rajainmäki, Lenni Laakso, Outokumpu Poricopper Oy	Toimeksiantaja(t) - Commissioned by Posiva Oy

Nimeke - Title

PRODUCTION METHODS AND COSTS OF OXYGEN FREE COPPER CANISTER FOR NUCLEAR WASTE DISPOSAL

Tiivistelmä - Abstract

The fabrication technology and costs of various manufacturing alternatives to make large copper canisters for disposal of spent nuclear fuel from reactors of Teollisuuden Voima Oy (TVO) and Imatran Voima Oy (IVO) are discussed. The canister design is based on the Posiva´s concept where solid insert structure is surrounded by the copper mantle. During recent years Outokumpu Copper Products and Posiva have continued their work on development of the copper canisters. Outokumpu Copper Products has also increased capability to manufacture these canisters.

In this study the most potential manufacturing methods and their costs are discussed. The cost estimates are based on the assumption that Outokumpu will supply complete copper mantles.

At the moment there are at least two commercially available production methods for copper cylinder manufacturing. These routes are based on either hot extrusion of the copper tube or hot rolling, bending and EB-welding of the tube. Trial fabrications has been carried out with both methods for the full size canisters. These trials of the canisters has shown that both the forming from rolled plate and the extrusion are possible methods for fabricating copper canisters on a full scale.

ISBN ISBN 951-652-007-3	ISSN ISSN 1239-3096
Sivumäärä - Number of pages 30	Kieli - Language English

Posiva-raportti - Posiva report

Posiva Oy
Annankatu 42 D, FIN-00100 HELSINKI, FINLAND
Puh. (09) 2280 30 - Int. Tel. +358 9 2280 30

Raportin tunnus - Report code
POSIVA-96-08

Julkaisuaika - Date
Marraskuu 1996

Tekijä(t) - Author(s)

Harri Aalto,
Hannu Rajainmäki,
Lenni Laakso,
Outokumpu Poricopper Oy

Toimeksiantaja(t) - Commissioned by

Posiva Oy

Nimeke - Title

KÄYTETYN POLTTOAINEEN LOPPUSIJOITUSKAPSELI HAPETTOMASTA KUPARISTA - VALMISTUSMENETELMÄT JA KUSTANNUKSET

Tiivistelmä - Abstract

Raportissa käsitellään Teollisuuden Voima Oy:n (TVO) ja Imatran Voima Oy:n (IVO) käytetyn polttoaineen loppusijoituskapselin kuparivaipan valmistusmenetelmiä ja -kustannuksia. Kuparivaipan kustannuksista tehdyissä arvioissa on oletettu, että Outokumpu toimittaa valmiita kuparikapseleita.

Viime vuosien aikana Outokumpu on tehnyt kapselin valmistukseen liittyvää tuotekehitystyötä ja valmiuksia on lisätty kapselien teollista tuotantoa ajatellen. Täyden mittakaavan kuparikapseleita on tehty nykytekniikkaa soveltaen kahdella eri valmistusmenetelmällä. Nämä kuparikapselit on valmistettu kuumavalssaukseen, taivutukseen ja pitkittäissauman elektronisuihkuhitsaukseen sekä kuumapursotukseen perustuvilla valmistusreiteillä. Tutkimuksissa on osoitettu, että näitä nykyisiä valmistusmenetelmiä soveltaen voidaan valmistaa hyvälaatuisia kuparikapseleita.

ISBN
ISBN 951-652-007-3

ISSN
ISSN 1239-3096

Sivumäärä - Number of pages
30

Kieli - Language
Englanti

Contents

1. Introduction

In Finland the spent nuclear fuel has been planned to be encapsulated into canisters and deposited into the bedrock about 500 m below the earth surface.

Oxygen free copper is being considered as the corrosion resistant material for these canisters. The quality requirements of these large and thick wall canisters are high. The present survey is continuation for earlier work /25/ and it addresses the alternative manufacturing techniques and the cost of producing large copper canisters.

In addition to this survey, Outokumpu Poricopper Oy and Posiva Oy have a joint project “Development of EB-welding method for massive copper canister manufacturing”. This three year project (1994-1997) is focused on increasing knowledge of EB-welding and inspection of welded joint. The project is a part of the national technology program “Weld 2000” and it is supported financially by Technology Development Centre (TEKES).

2. Canister designs and materials

2.1 Copper canister designs

There are two alternative canister models which differ in the length. The main dimensions and masses of the canisters are given in Tables 1 and 2 for TVO´s and IVO´s fuel bundles. Total length of TVO´s canister is 4,5 m and IVO´s canister 3,55 m due to grip fixture in the copper lid. The design of these canisters are described in detail elsewhere /2/.

There is an external pressure directed to the canister and thus the copper mantle is supported by an integral insert structure made of nodular cast iron. The nominal diameter of the inside of the outer copper mantle and the outside diameter of the insert has a nominal tolerance of 2 mm, which corresponds to a 1 mm gap between the cylinders maximum. The tolerance has set to be close in order to minimise the maximum creep strain in the copper parts below 5 %. This will also allow a friction free installation of the inserts into the copper mantle. The copper lids of the canisters have the same minimum wall thickness (50 mm) as the cylindrical parts.

Table 1. Mass and dimensional data for TVO´s canister /2/.

	Cast insert	**Steel lid**	**Copper cylinder**	**Copper lid**	**Fuel bundle**
Outside diameter [m]	0.880	0.880	0.982	0.982	
Wall thickness [m]		0.050	0.050	0.050	
Length [m]	4.200		4.400		4.130
Density [kg/m^3]	7200	7850	8900	8900	8555
Material volume [m^3]	1.515	0.0304	0.644	0.050	0.030
Mass [kg]	10908	239	5733	445	257
Number of items	1	2	1	2	11
Total mass [kg]	10908	478	5733	890	2827

Table 2. Mass and dimensional data for IVO´s canister /2/.

	Cast insert	Steel lid	Copper cylinder	Copper lid	Fuel bundle
Outside diameter [m]	0.880	0.880	0.982	0.982	
Wall thickness [m]		0.050	0.050	0.050	
Length [m]	3.250		3.450		3.200
Density [kg/m^3]	7200	7850	8900	8900	8555
Material volume [m^3]		0.0304	0.505	0.050	0.0262
Mass [kg]	8287	239	4495	445	214
Number of items	1	2	1	2	11
Total mass [kg]	8287	478	4495	890	2354

2.2 Material properties

The choice of the material composition in the copper canister is determined by requirements on corrosion resistance, creep properties and the manufacturing aspects of these canisters.

The primary strategy for material selection has been corrosion resistance, because the main function of the nuclear waste canister is to keep the radioactive waste confined for a sufficiently long time in order to avoid the risk on the biosphere /1/. The design lifetime of the canister is 100 000 years. This strategy has been concluded to select a copper quality which is as pure as possible. If the conditions in the vicinity of the repository located at Posiva´s investigation sites remain roughly similar to what they are today at the depth of 500 m in the bedrock, the copper canister will be preserved intact for several million years /18/.

The important area from the corrosion point of view is the weld joint because it is a microstructural inhomogeneity. The copper canister contains at least one seam (if HIP technique is excluded), namely the final closure of the lid. This closure must be done in the hot cell condition since the canister includes then the radioactive fuel bundles. The best and most reliable welding method (at present) for thick copper sections is electron beam welding. It is also an advantage that it is a fully automated process and in case of improper joint quality the joint can be repaired by another EB-welding.

The joint quality can be inspected in the hot cell condition by the ultrasonic inspection or radiography. Ultrasonic inspection is most sensitive when the grain size of the material to be inspected is small.

The mechanical load of the canister is mainly carried by the solid insert structure. Thus no special requirements on the strength of the copper part are needed. The only criteria is that the canister must withstand the handling and the external pressure load caused by hydrostatic pressure of the groundwater and the swelling of the surrounding bentonite clay. The 0.2 % proof stress of the hot worked oxygen free copper is around 50 MPa and it is sufficiently high.

Copper can easily be both hot worked and cold worked and the desired shape is achieved normally without problems. The machinability of copper is sufficient to obtain the required tolerances of the inner diameter of the canister.

2.3 Material composition

The copper content of Outokumpu`s oxygen free copper is always above 99,99 %. The impurity contents are below the requirements of ASTM and other standards /20-21/.

The impurities present in the raw material are also present in the castings and semifabricated products. Consequently, when producing oxygen free copper, only cathodes classified as A-grade should be used. Nearly every single impurity element content is below 1 ppm. However, there are some impurities which are difficult to remove from the raw material. One of these impurities is sulphur.

Result of test series has showed that sulphur has deleterious effect on creep strain at elevated temperatures (200-300°C) /17/. Sulphur has very low solubility in copper and it precipitates at the grain boundaries where it has a harmful effect on the creep ductility. Tests has shown that also very low sulphur content reduce creep strain. Consequently, it is advisable to keep sulphur level at the minimum. The OF-Cu line in Outokumpu is capable of producing copper having sulphur level below 8 ppm at continuous operation.

Reduced creep ductility at elevated temperatures can be improved by the addition of 40 to 60 ppm phosphorus according to material investigations /17/. Consequently an oxygen-free copper with approximately 40-60 ppm phosphorus is chosen as the canister material at the moment. This grade is specified as phosphorus microalloyed oxygen free copper (Cu-OFP). The phosphorus addition can be done in the oxygen free casting line without any special arrangement. The nominal phosphorus content of 40-60 ppm is sufficiently high to improve creep ductility at elevated temperatures /17/. The weldabilities of Cu-OF and Cu-OFP are similar in general, although the tendency towards microporosity and root defects is slightly greater for the Cu-OFP /22/.

The term oxygen-free means that the material contains only trace amounts of oxygen. In practice the oxygen content is typically 1-3 ppm. This level is sufficiently low to ensure that oxygen free copper is immune to porosity during casting and EB-welding. The maximum oxygen content is set by ASTM B170-93 to be 10 ppm for Cu-OF /21/.

The solid solubility of hydrogen is 1.8 ppm at melting point of copper. The solubility of hydrogen decreases rapidly when temperature is below melting point. In the copper products internal hydrogen might cause internal cracking during hot working when the hydrogen level is above 1 ppm. The Cu-OF line in Outokumpu is capable of continuously producing copper having gas content less than 0.7 ppm hydrogen /23/.

3. Basic Production Methods

3.1 Casting

Oxygen free copper is produced by melting and casting the copper cathodes in reducing atmosphere. The highest purity (A-grade) copper cathodes are used as the raw material. The reduction of oxygen from the melt can be done either by carbon or vacuum. Both methods result in a low oxygen content. The casting can be either continuous or semicontinuous which both have their advantages. The addition of phosphorus can be done during the casting without any special arrangements.

The maximum dimensions needed to be cast for the manufacturing of the nuclear waste canisters are 850 mm (diameter) for the billets to be hot extruded and 1200 x 250 mm for the cakes to be hot rolled. The suitable dimensions can be sawed from the ingot for different canister lengths.

Outokumpu Poricopper Oy (Finland) has an oxygen free copper casting line (Fig. 1), which is capable of producing the ingots needed for the canisters.

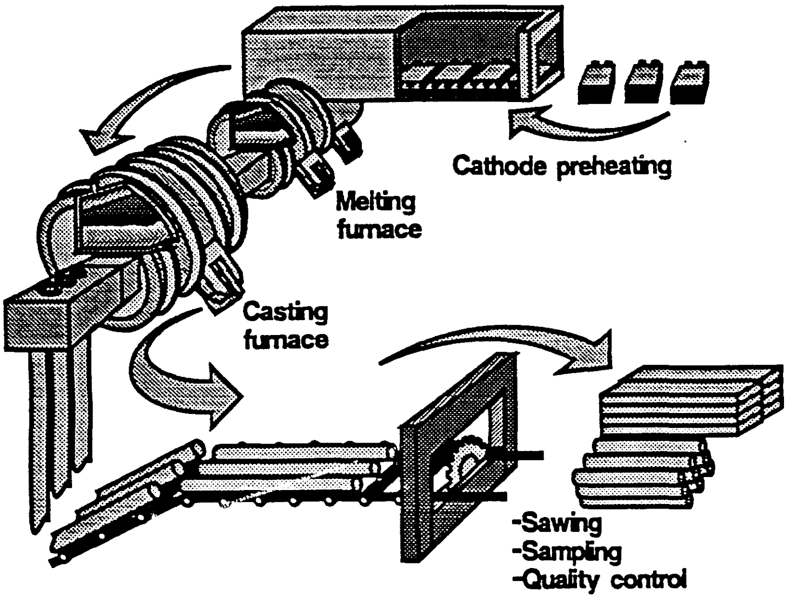

Fig. 1. The oxygen free copper casting line.

The line has a semicontinuous 10 m casting unit which can cast ingots up to 15 tons. The other dimensions can be obtained after some modifications. The casting line contains also a preheating unit in order to remove moisture and impurities from the surfaces of the cathodes. The preheating unit and carbon used for the oxygen reduction from the melt result in a very low oxygen content of 1-3 ppm. The oxygen free copper capacity of the casting line of Outokumpu is much higher than the amount of oxygen free copper needed for the Finnish nuclear waste canisters (100 canisters per year maximum).

Two examples of 850 mm diameter ingots of oxygen free copper with 50 ppm of phosphorus added were produced by semi-continous casting line for SKB at Outokumpu in the 1995. The nominal weight of the ingots was 10 tons and length 2 meters. The casting of these ingots was a considerable technical achievement because the diameter of these billets were significantly larger than former fabricated billets /24,26/.

3.2 Extrusion methods

Although there seems to be no possibility of choosing between different extrusion methods the basic methods will be briefly reviewed. In direct or forward extrusion the stem and the extruded product move in the same direction and in the indirect or backward extrusion the stem and product move in opposite directions (Fig. 2).

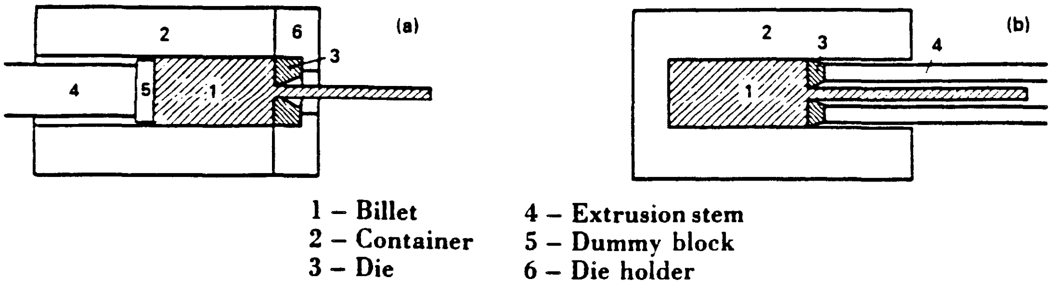

Fig. 2. Direct extrusion (a) and indirect extrusion (b) /7/.

The 982 mm diameter canisters are outside the hot extrusion range of all existing presses except the world's biggest presses of Wyman-Gordon Ltd in Houston, USA and Livingston, Scotland. The 35 000 ton press extrudes pipe up to 1219 mm in diameter and up to 177 mm in wall thickness. Length can vary from 3 to 13 meters. The maximum billet weight is 18 tons /5/.

The Wyman-Gordon process employs two vertical presses, a 14 000 ton blocking press and 35 000 tons extrusion press. The process starts in rotary furnaces which heat the material. Once the billets are heated to the required temperature, they are placed on the pedestal of the 14 000 ton blocking press. Next, the scale is removed from the surface of the billets. When all of the scale has been removed, 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, represents the second working of the material to further refine the structure of the metal. Next the piercing punch is positioned over the billet. Piercing is the first step in dimensionally forming the inside diameter of the finished piece. The whole blocking sequence is presented in Fig. 3.

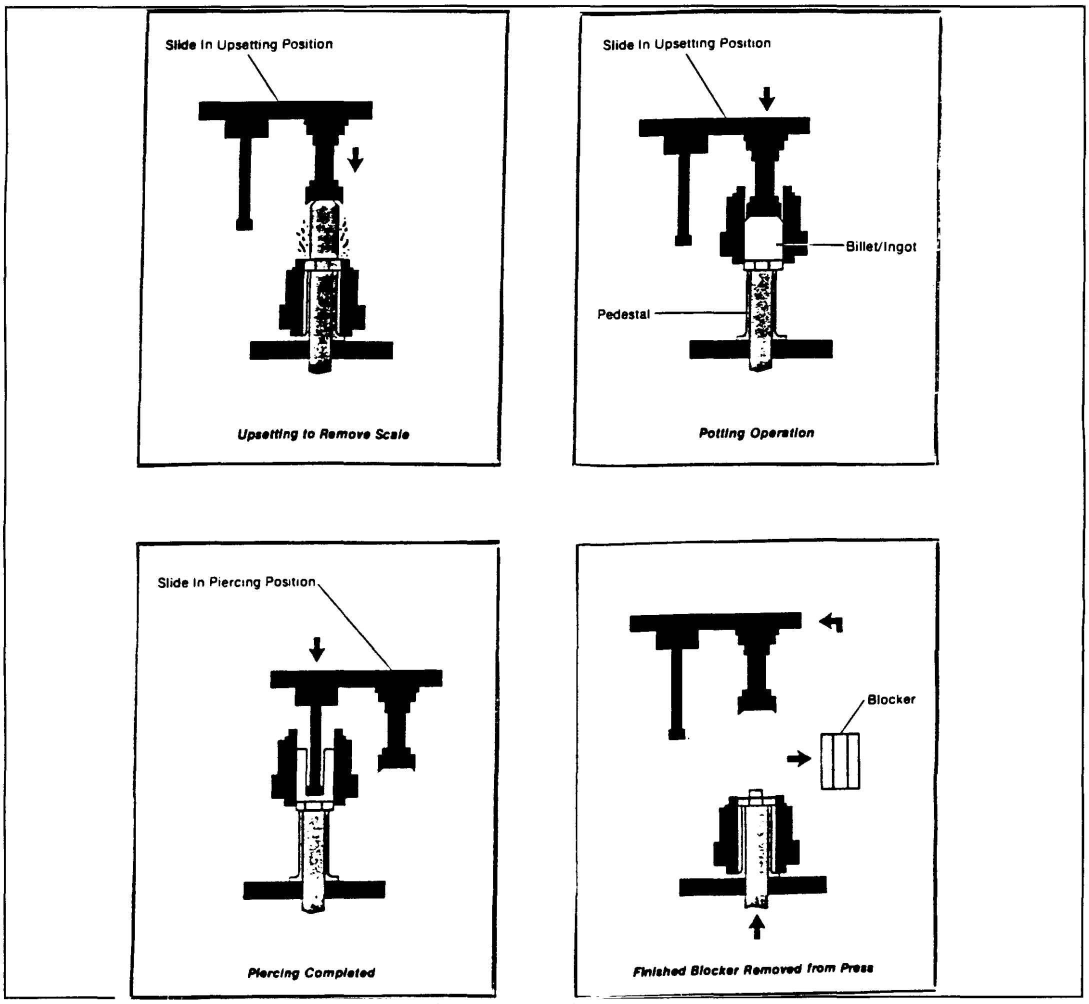

Fig. 3. The blocking sequence before extrusion /5/.

After the blocking sequence has been completed, the blocker is placed on the pedestal of the extrusion press. First the mandrel is extended up through the blocker to shape the inside diameter of the finished product. Next, the upper bolster and pre-heated dies are lowered over the blocker. The extrusion is forged through the die. When the pipe reaches its required length, the upper bolster is raised and the extrusion is completed. The whole extrusion sequence is presented in Fig. 4.

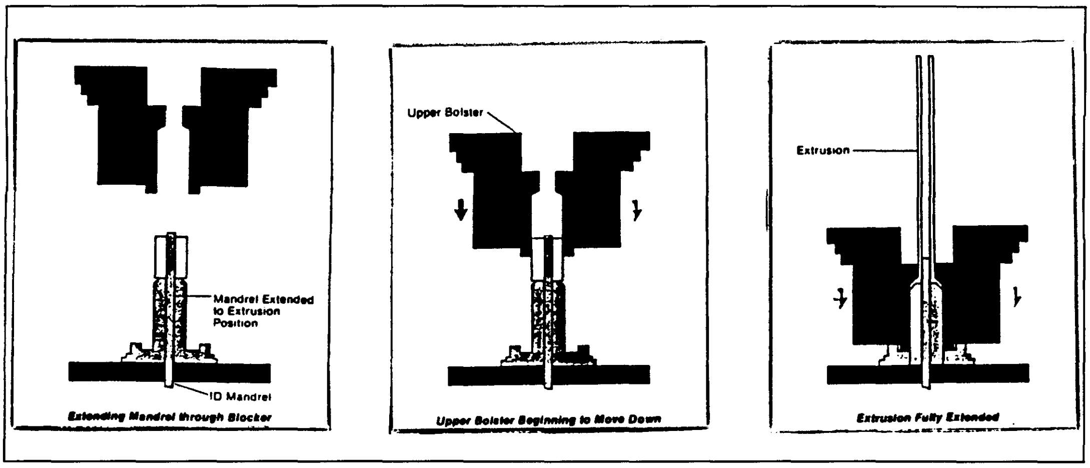

Fig. 4. The extrusion process /5/.

In the hot extrusion processes the copper billet is preheated to 700-950 ^{o}C. Extrusion is a reasonably well controlled operation. The friction is the significant parameter that is not fully possible to control. The variation of the friction during the extrusion results in the variation of the material flow pattern. This variation of the flow pattern can lead to introduction of the oxidised billet surface, sub-surface scale, into the material. The sub-surface defect can exist either in the outer or inner surface.

The product goes upward in this process which is not a common extrusion direction but quite useful for handling of the massive pipes. Weakness in this process is that extrusion into cooling water is not possible. This can be compensated by compressed air or nitrogen cooling of the tube during extrusion.

In indirect extrusion there is a possibility of incomplete recrystallization at the upper end of the cylinder. This can happen if there is too little deformation in the area. The result may be cracking of the material. This can be avoided by significant upsetting prior the extrusion.

Another, more possible reason for defect is the large variation of cooling (or heating) of the billet during the extrusion.

One can also consider a too large grain size as a defect when the small grain size is needed. Grain growth is the process that starts immediately after the dynamic recrystallization already inside the tool. The higher the temperature, the faster the grain growth is. Thus, it is very important to maintain the extrusion temperature as low as possible.

The yield in the Wyman-Gordon extrusion process is 60-65 %, which means that the billet must weight about 10 tons. The preferable billet diameter is 850-1000 mm and the length of the billet is thus 1400-2000 mm.

The two ten ton test ingots supplied by Outokumpu Copper were extruded to tubulars for SKB by Wyman-Gordon in May 1995 /24,26/.

3.3 Rolling and bending

Hot working is necessary to reform the large cast grains into smaller recrystallized grains. The small grain size is a crucial factor in the ultrasonic testing of the welds. If the grain size is small, the ultrasonic inspection is easier. However, the ultrasonic inspection of the thick copper plates is a challenge but development of computer-driven ultrasonic imaging techniques has recently made inspection more sensitive.

The fabrication of tubulars by rolling and bending requires heavy plates. The individual plates need to be 60 to 70 mm thick depending on the machining allowance. Other dimensions are 1.8 m wide and 3.5-4.5 m long depending on final canister size.

Rolling and press bending are conventional methods for fabricating tubes from the plates. The most important factor in the forming operation is to fabricate the tube halves with such tolerances that they can be finish-machined without excessive machining allowance and can be joined together by means of EB-welding.

The principle of rolling is shown in Fig. 5. Hot rolling of copper is done in temperatures of 650 - 900 °C. Several passes through the rolling stand are needed to obtain the desired thickness. The coarse grain structure is effectively broken and a finer grain size is obtained. Since this is a hot working operation the copper is in soft condition after rolling. Water cooling can be used to keep the grain size small.

Hot rolling with bending and EB-welding involves the longitudinal weld seam which can be avoided with extrusion. Also, the longitudinal seam requires edge preparation before welding.

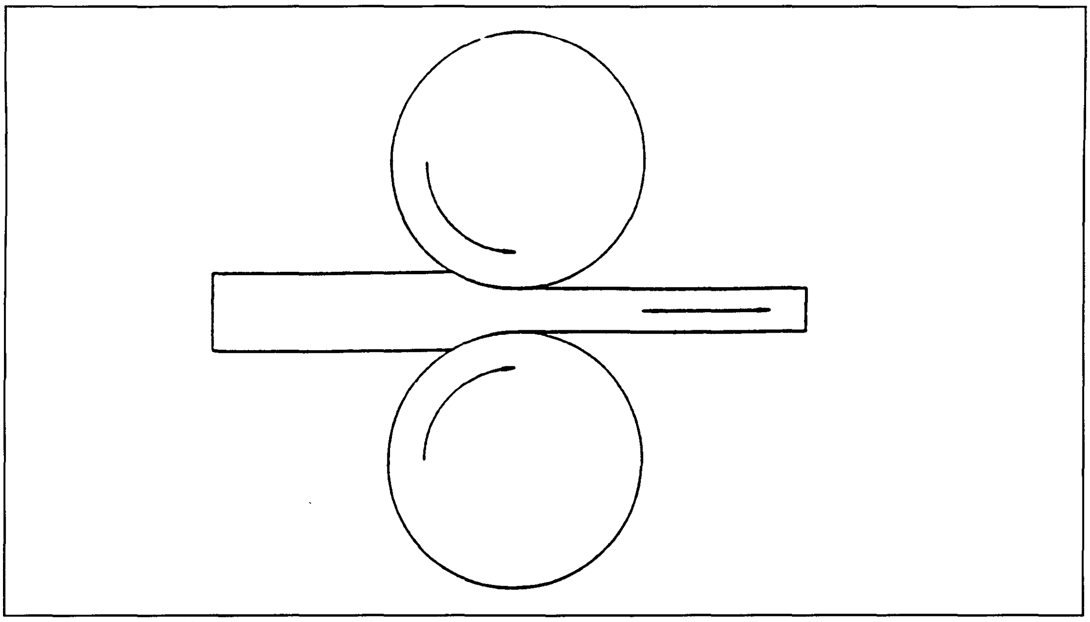

Fig. 5. The principle of rolling.

The trial rolling of the full-size copper canister has been demonstrated in USA and in Germany. Also one pair of plates have been roll formed at Vickers Shipbuilding and Engineering Limited (VSEL) in England /24,26/.

Internal stresses left after bending may need to be relieved before machining. This means additional stress releaving annealing at 250 °C before gap machining for EB-welding. The stress realieve annealing doesn't effect on internal structure of copper because temperature is well below recrystallization temperature. Thus, it doesn't cause any grain growth in copper.

3.4 Welding

Electron beam welding is a feasible method to join thick materials (Fig. 6). A beam of high-energy electrons is focused into the welded seam where electrons loose their energy and heat the seam. The heating causes melting and proper joining of the sections. The penetration and the depth of the weld depends on the power of the electron beam. The welding must be performed in vacuum and the sections to be welded together must be machined.

Main difficulty of circumferential and large thickness welds is the manufacturing of a defect free end of the weld. Because the weld end remains in the workpiece, its metallurgical and geometrical soundness is decisive for the quality of the entire weld. The main feature of the slope-out is the downward adjustment of the beam power and a suitable variation of other parameters.

An important criterion for a good slope quality is the minimal occurrence of spiking and inclusions of pores in the weld root. Degasification and spiking can be reduced when steps are taken, to create weld roots with a rounded tip.

In the Finnish EB-welding test program for copper the first welding trials were concentrated on attempts to achieve 50 mm penetration in thick copper. Some difficulties were experienced with formation of root defects and cold-shut defects. Some defects were also found on the surface area because of spattering during welding. However, these problems were reduced by parameter optimisation and at the moment we have been able to optimise the welding parameters to produce sound weld for longitudinal seams for the copper canister. /22/

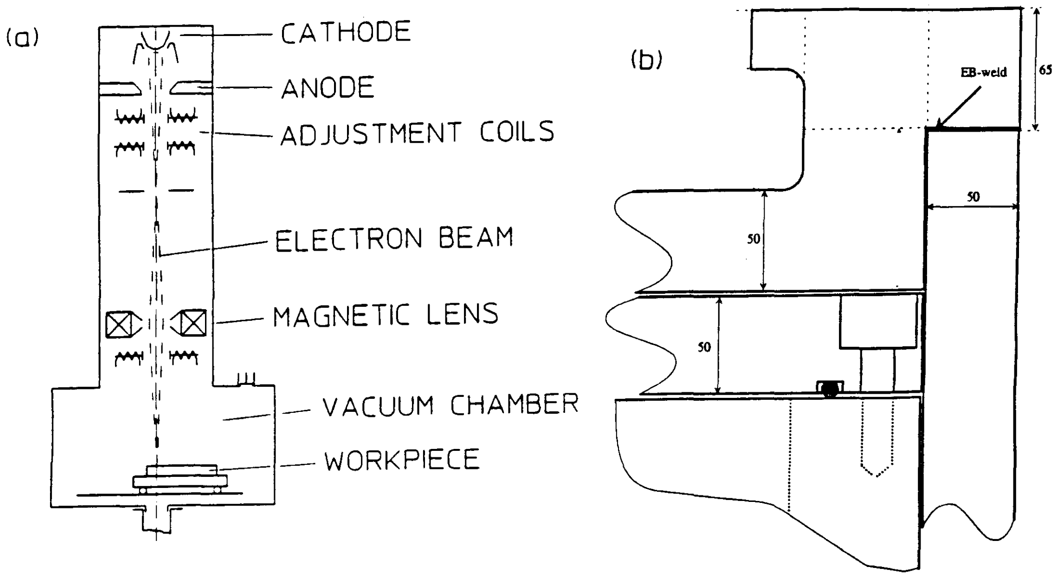

Fig. 6. (a) Electron beam welding equipment /10/, (b) canister lid weld joint using horizontal beam /5/.

3.5 Machining

The machinability of oxygen free copper is characterised by long chips and therefore it is not the best possible. Good results can be achieved by using special cutting tool constructions /9/. Because of laborious machinability it is desirable to keep the machining at a minimum. This is also important in order to minimise material losses. The machinability of phosphorus alloyed oxygen free copper is similar to the machinability of oxygen free copper.

Two full-size canister has been machined at VSEL in England. The target dimensions were achieved on the one tubular which was fabricated. The problems during machining were related to canister supporting, controlling of the scarf and residual stresses /24/.

3.6 Alternative manufacturing processes

Hot isostatic pressing (HIP) has been considered for use as encapsulation process. In HIP process heat and isostatic pressure are applied to compact and densify a structure. This method allows the use of oxygen free copper powder as a filling material. The process converts the copper powder, through diffusion and sintering of the particles, into a solid mass of copper. The powder, tube, fuel elements and end pieces are bonded into a seamless integral monolith. Hot isostatic pressing eliminates the need to weld ends on the canister. The joints are formed by diffusion bonding. The size of canister is a problem, however. There is currently no HIP press in the world long enough to process a full-length canister.

Roll extrusion is another alternative. This process is more commonly known as tube spinning. Other names for this process are shear forming, flow turning, spin forging, rotary extrusion, flow forming, hydrospinnig, rotoforming and flowturning. Tube spinning is used to reduce the wall thickness and increase the length of tubes without changing their inside diameters.

The spinning can be done hot or cold. There are two different techniques, backward and forward. Spinning can also be done internally. These processes are shown in Fig. 7. The method has been used to produce very thin wall large-diameter tubing such as rocket cases. Estimates of the suitability and costs of this method are not presently available and the applicability of the process needs further study.

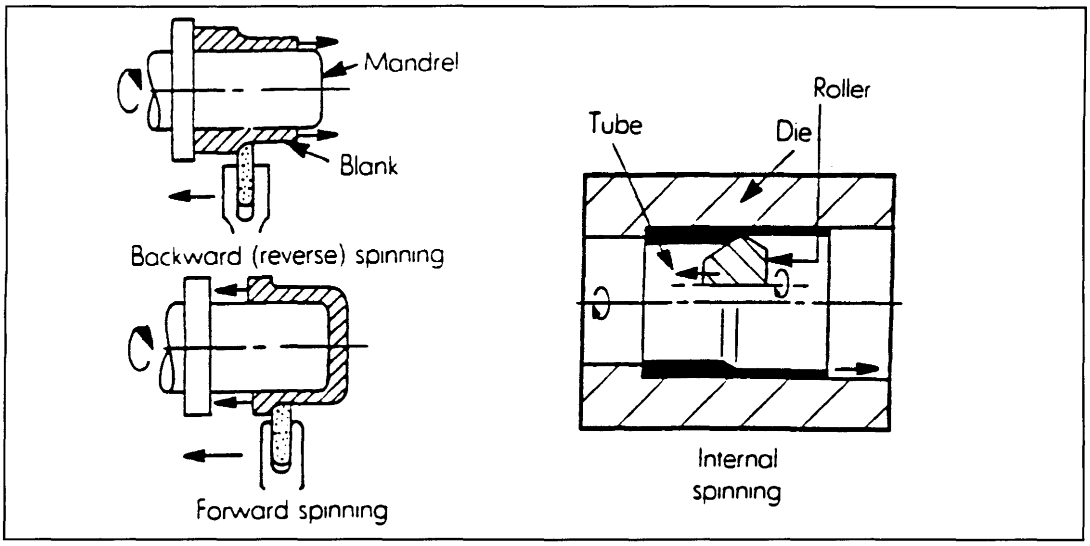

Fig. 7. Types of tube spinning processes /12/.

Centrifugal casting could be a promising production method with its advantages of metallurgical cleanliness and homogenous microstructure. Unfortunately the method is not suitable for OF copper if performed in air. Centrifugal casting in vacuum is not yet developed to mass-production volumes /6/.

The Osprey process is a relatively new method for the manufacture of tubes. It involves spray deposition of inert gas atomized molten metal stream on a recipient, Fig. 8.

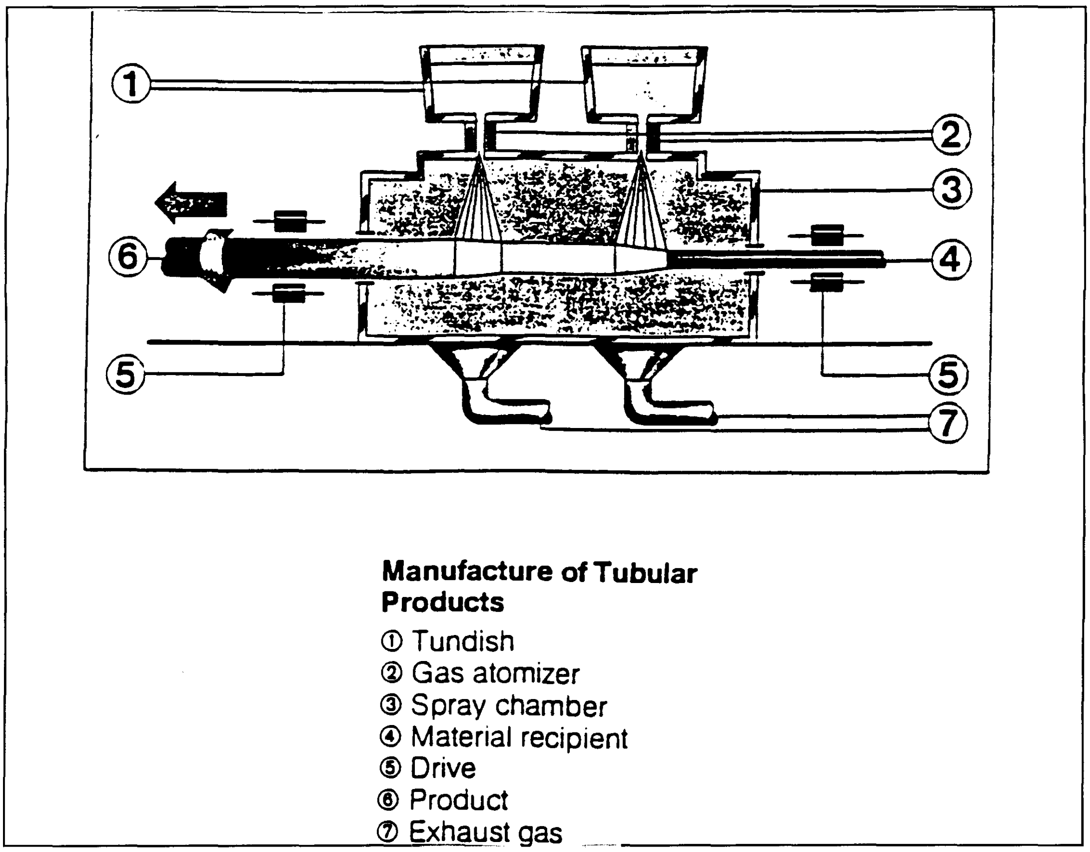

Fig. 8. Spray deposition of tubular products /13/.

Sandwik Steel in Sweden produces high alloy special steel blanks with dimensions up to 400 mm diameter and up to 8 000 mm in length. The method is interesting because multilayer materials can be produced. Copper could be spray deposited directly on steel tube. This alternative is well worth considering for the production of waste canisters. However, at the present stage it still needs strong development work.

Electroforming is defined as the production of an article by electrodeposition on a mandrel that is subsequently removed. In case the mandrel is not removed the process is called electrodeposition. Electroforming is best suited for producing thin products, such as foil for printed circuit boards. To avoid excessive nodular growth and porosity the deposition rate must be sufficiently slow. A typical value is only 0.03 mm/h. So this appears not to be a suitable production method for canisters with wall thicknesses of 50 mm.

Radial forging is a process used to reduce the cross-sectional area of the workpiece by typically four radially aligned hammers, as shown Fig. 9. Between strokes of the hammers the workpiece is rotated and fed in. Tubes are hot forged over a water cooled mandrel (Fig. 10). Radial forging is not widely used for the working of copper since copper is easily extruded. The possible applicability of this method needs further study.

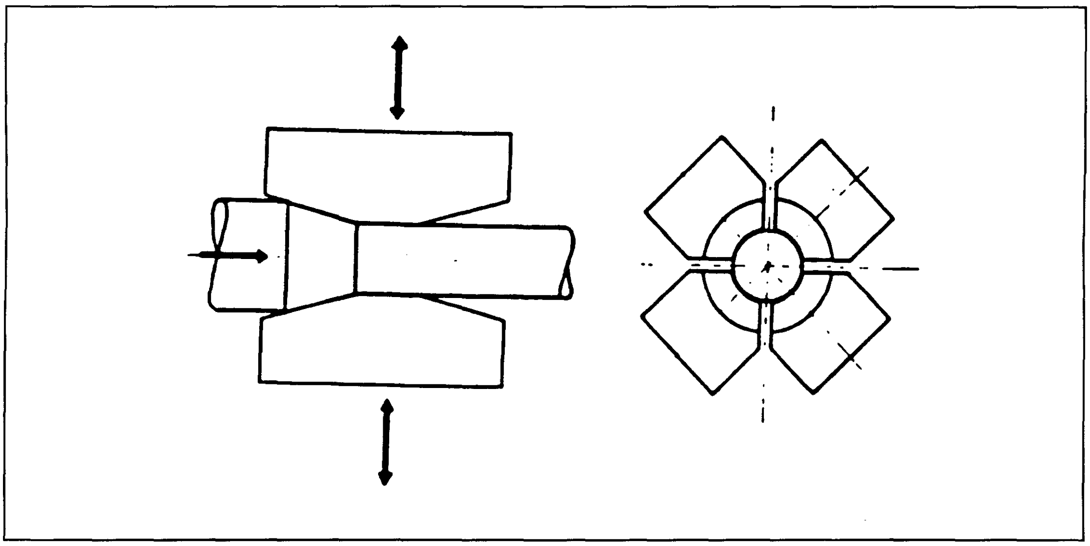

Fig. 9. Four-hammer radial forging /15/.

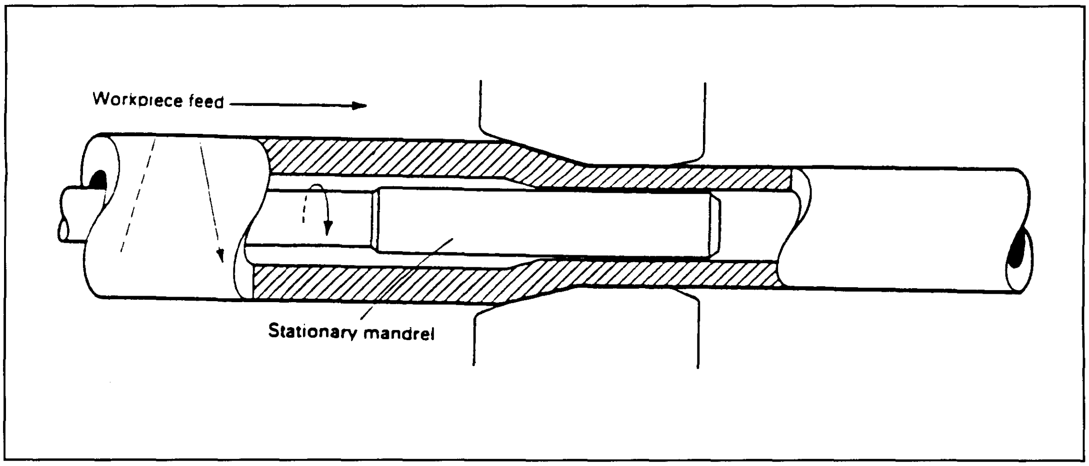

Fig. 10. Radial forging of tube over a mandrel /16/.

4. Manufacturing Routes and Their Costs

At the moment two routes are considered as alternatives for the manufacturing of the copper mantle of the canisters (Fig. 11). There may appear better alternatives in the future but according to the present knowledge these two manufacturing routes are the most feasible at present and in the near future.

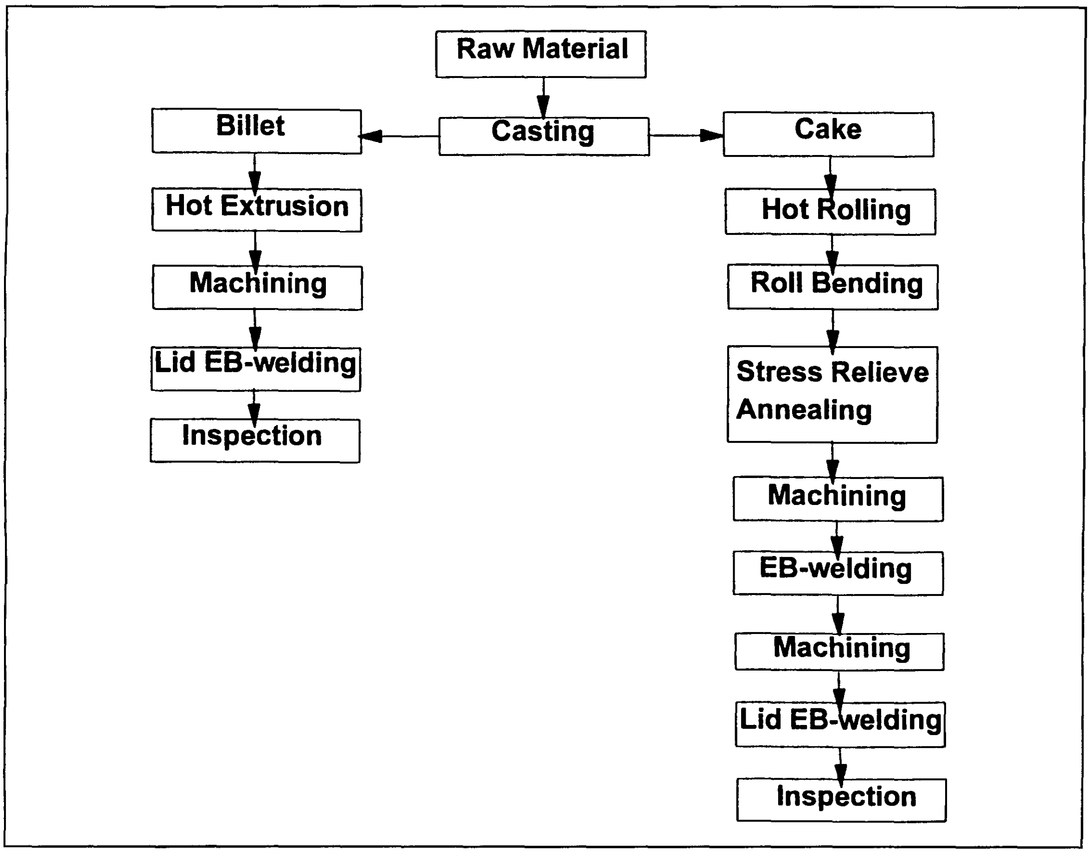

Fig.11. Alternative manufacturing routes.

4.1 Raw material need and costs

The amount of raw material needed (Table 3) is deduced by taking into account the yield obtained in each manufacturing stage. Outokumpu introduced on January 1, 1996 a new reference type copper price quatation, MPK. The MPK copper price is based on official LME (London Metal Exchange) cash price of copper. It includes costs for taxes, transportation and storage costs (excluding value added tax). The MPK price is published in Kauppalehti and in Reuters finance system heading Nordic Semi Metals.

The MPK copper price on April 16, 1996 (according to Kauppalehti) 13.54 mk/kg has been used in the cost estimates.

The availability of copper is excellent. The consumption of oxygen free copper for the Finnish nuclear waste represents below 1 % of the annual oxygen free copper production in the world during the estimated disposal period of 20 years.

The price of copper expressed in Finnish marks has increased during the past 40 years (Fig. 12), but the price in general has decreased during last 25 years (excluding statistical fluctuations). The real price of copper will likely decrease in future because of technical development of the manufacturing processes.

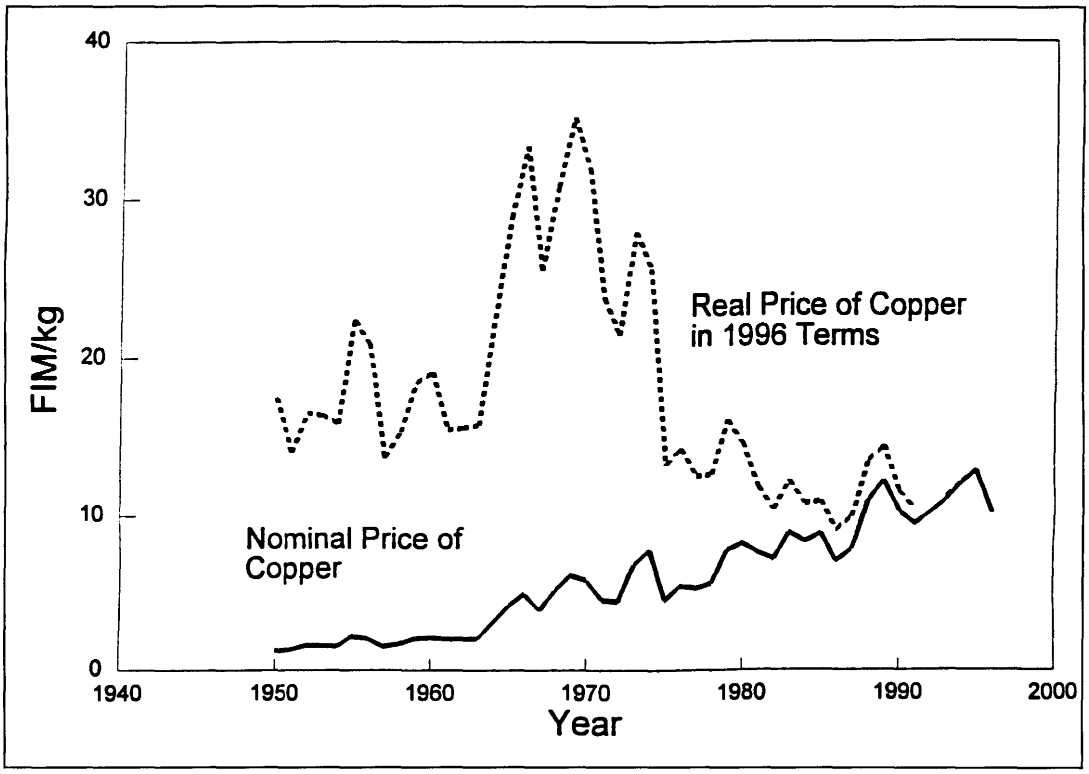

Fig. 12. The nominal and the real price of copper.

Since material loss during the process, the value of scarp is significant. At least approximately 85 % of all scrap is returned as high quality (not containing impurity particles). Probably the return percent is even higher. The price of the high quality scrap is LME-price minus 3 %. The return value of the scrap on April 16, 1996 was 11,79 mk/kg.

Table 3. Raw material need (tons of copper) for canisters extruded as a tube or produced by rolling and bending.

	Tube Extrusion		Roll & Bend	
	TVO	IVO	TVO	IVO
Mantle	10.5	8.2	9.2	7.2
Lid (s)	2.3	2.3	2.3	2.3
Total	12.8	10.5	11.5	9.5

4.2 Casting

The casting costs includes investments and development work for casting large diameter billets. Also additional work has to be done to prepare casting line before operations.

4.3 Extrusion

The ingot sizes and costs of extrusions are based on the estimates given by the manufacturer. According to the manufacturers the ingot weight must be nearly twice the final weight due to extrusion scrap and tolerances, i.e. the yield is only about 60 %. The freight costs are also significant since extrusion presses suitable for this purpose are available only in USA and in Scotland.

4.4 Hot rolling and bending

The hot rolling should be done in a copper hot rolling mill. The nearest copper mills capable of rolling sufficiently wide plates are in Russia and in Germany.

If the hot rolling were done in a steel mill the cost would be several times higher due to the capacity losses in the transition period from steel heating and rolling to copper heating and rolling (heating temperature 800-900 ^{o}C for copper and 1300 ^{o}C for steel).

The bending of the hot rolled plate is performed in a three roll bending machine. From both ends of the plate about two times thickness, i.e. 100 - 150 mm, remains typically unbent. However, the unbent region can be reduced to about 50 mm by prebending the ends. This method reduces the necessary width of the plate and increases the yield so that only 50 mm from each edge of the plate need to be removed. The yield of rolling and bending is then very good, about 95 %.

4.5 Stress Relieve Annealing

Internal stresses left after bending may need to be relieved before machining. Stress relieving annealing is to be carried out by heating at 50 ^{o}C/h to 250 ^{o}C and maintained at that temperature for 2 hours followed by cooling in the air. The stress releaving annealing can be done in appropriate annealing furnace.

4.6 EB-welding

Electron beam (EB) welding is a good and reliable method for joining thick copper plates. The high quality of the weld seams requires the material to be oxygen free copper or microalloyed oxygen free copper. The vacuum chamber must be large enough to weld 1 m diameter and 4.5 m long canisters. A sufficiently large vacuum chambers can be found in France and in UK at the moment. Before production of full-size canisters, the trial welding is required to quarantee the quality of the welded structure.

The operating costs of the EB-welding machine are not high but the starting costs are significant because of trial welding. A sufficiently large vacuum chamber can be found in Central Europe meaning significant freight costs also. In the cost estimates these costs has been taken into calculations.

The cost estimates includes required test welding, transportation and EB-welding of the canisters with one end closed.

4.7 Machining

The extruded tube requires machining to achieve required outer and inner surface tolerances because after extruding the tube has got thickness variations in the walls and the tube is eccentrical. After EB-welding of the lid it is recommended to machine weld surface before inspection to qurantee optimal circumstances for defect control.

The final machining of the copper mantle is recommended to be done after welding to achieve required surface quality. The inner diameter tolerances can be obtained using modern machining unit.

The machining costs includes transportation and machining to required tolerances. Machining is possible to be performed in Finland.

4.8 Inspection

There are two viable inspection techniques for the welds in thick copper plates: ultrasonic inspection and radiography.

In practice 100 % inspection of the weld seam is not necessary but control of the EB-welding machine and the inspection of the critical regions is sufficient. The inspection of the weld seams made in workshops is easier than inspection of canister lid in encapsulation plant because the inspection can be also done inside of the canister.

The exact inspection costs are still difficult to estimate before defining e.g. the minimum detectable defect size and acceptable defect size. For this study the inspection costs are based on automated ultrasonic inspection technique and suitable probes to detect defects from base material and EB-welds.

In the radiographic method a special high voltage equipment ($>$ 1 MeV) is required for detecting defects from thick copper. It is possible to detect several kinds of defects, especially volumetric defects. The main difficulties are crack-like defects which are running perpendicularly to the inspection direction. The inspectability of these defects can be improved by tilting the inspection direction so that the possible crack is not perpendicularly to the inspection direction any more. There are not enough knowledge to estimate inspection cost for digital radiography or radiographic tomography at the moment.

The cost estimates includes conservatively the 100 % ultrasonic inspection of the welds of the copper mantle.

4.9 Lid manufacture and costs

The most optimal way to produce the lids is casting the cake, forging and machining. The casting can be done with the present casting machine. The continuous processing is forging (hammering or hot pressing at 600 - 800 ^{o}C), which results in a homogenous, recrystallized grain structure and the desired shape.

The cost estimate includes transportation and machining to required tolerances. The machining can be done in many workshops in Finland.

4.10 Total costs of the canisters

The cost estimates of the two routes for canisters and different production routes are summarised in Table 4. The yield of the process is difficult to estimate, i.e. how many of the manufactured canisters must be rejected. Since in practice all the processes are well controlled in the continuous operation and some faults can be corrected (e.g. welding). Therefore the yield is estimated to be high, about 95 %. This means assumption that 5 % (50 pieces) were rejected which means only 2-3 % increase in total costs. The rejected part of the canisters has been taken into account in the calculations in Table 4. The cost estimates in the Table are without value added tax.

Table 4: Total costs/canister for 1 000 canister lot (thousand FIM) extruded both ends open (tube) or produced by rolling and bending.

	TVO canister	IVO canister
Tube Extrusion	455	385
Roll & Bend	394	346

The estimates can be divided in two parts; material costs and processing costs. The values in above Table can be calculated from the formula:

$$M * CP + A*MP*I - MCP*CS$$

where M= mass of raw material needed for process

MP= mass of final product

CP= price of raw material (MPK price from Kauppalehti)

A= addition due to working and forming (includes effect of rejection)

I= suitable index for correcting additional manufacturing costs due to change in production costs, standard of living and taxes.

MCP= mass of scrapped part of the canister (MCP=(M-MP)*0.85)

CS= price of scrapped part (LME-3 %).

The manufacturing costs for the complete copper canisters can be roughly estimated using the formula above and constants which are given in Table 5.

Table 5. Constants for calculation of the total costs of the copper canisters.

	IVO Roll&Bend	IVO Extrusion	TVO Roll&Bend	TVO Extrusion
M	9 500	10 500	11 500	12 800
MP	5 385	5 385	6 623	6 623
CP	13.54	13.54	13.54	13.54
A	48.09	54.57	43.34	51.81
MCP	3 498	4 348	4 145	5 250
CS	11.79	11.79	11.79	11.79
I	1.00	1.00	1.00	1.00

The estimates of the manufacturing costs of the canisters is based on today's prices. The calculations are based on the assumption that Outokumpu supply complete canister mantles (canisters which has two lids and one end is closed). The figures includes also business profit of Outokumpu. The uncertainty of the total costs for 1 000 canisters is within 15 %.

5. References

1. Werme L. 1990. Near-field performance of the advanced cold process canister. Report YJT-90-20, Nuclear Waste Commission of Finnish Power Companies, Helsinki.

2. Raiko, H. & Salo, J.-P. 1996. Design report of the canister for nuclear fuel Disposal. Report POSIVA-96-08, Posiva Oy, Helsinki.

3. Sanderson A., Werme L. O. November 1986. Can high power electron beam welding encapsulate nuclear waste for 100 000 years ? The Welding Institute Research Bulletin, pp. 365 - 370.

4. Wyman W. S., Servi I. S. June 1990. Copper availability and cost considerations, Appendix 5, Background studies in support of a feasibility assessment on the use of copper-base materials for nuclear waste packages in a repository in tuff, Lawrence Livermore Laboratory. 14 p.

5. Cameron Forge Company Extruded Products, 1988 Cameron Forge Company (Brochure).

6. Kundig K. J. A. June 1990. Fabrication alternatives for manufacturing copper and copper alloy nuclear waste containers, Appendix 2, Background studies in support of a feasibility assessment on the use of copper-base materials for nuclear waste packages in a repository in tuff, Lawrence Livermore National Laboratory. 45 p.

7. Laue K., Stenger H. 1981. Extrusion - Processes, Machinery, Tooling, Metals Park, Ohio, American Society for Metals. 457 p.

8. Rowell D. R. 1977. Large tube production by radial extrusion, 1977 Manufacturing Engineering Transactions, 5th North American Metalworking Research Conference Proceedings, Society of Manufacturing Engineers, pp.122-127.

9. 1984. The Machining of High-Conductivity Copper, Project Report 343A, International Copper Research Association.

10. Mantel, W. 1975. Kupferwerkstoffe Scweissen fur Sonderanwendungen. Maschinenmarkt, Wurzburg, 81 (1975) 91, pp, 1816-1818.

11. Steffens H.-D., Sievers E.-R. 1991. Festigkeitseigenschaften von Elektronenstrahlschwissverbindungen aus Kupfer bei erhöhten Temperaturen - analytishe Untersuchunge, Scweisse und Schneiden, 43 (1991) Heft 3, pp. 150-154.

12. Stewart J.D., Sr. 1988. Tube Spinning, Metals Handbook. 9. ed., Volume 14, Forming and Forging, Metals Park, Ohio, ASM International. pp. 675-679.

13. 1989. Spray Deposition. New Method in Material Technology for Metals - The Osprey Process, Mannesmann Demag (Brochure).

14. Goodman E. T. J: The manufacture of waveguide components by electroforming. The Post Office Electrical Engrs Jour, 64 (1971) 3, pp. 160-163.

15. Hojas H. Garrett N. I. 1980 GFM forging and high-reduction machines, Hot Working and Forming Processes, The Metals Society, pp.259-262, London.

16. Hojas H. Radial Forging, Metals Handbook. 9. ed. Volume 14, Forming and Forging, Metals Park. 1988, ASM International, pp. 145-149, Ohio.

17. P.J. Henderson, J-O. Österberg and B.G. Ivarsson: Low Temperature Creep of Copper Intended for Nuclear Waste Containers. Swedish Institute for Metals Research, October 1991.

18. Vieno T., Hautojärvi A., Koskinen L. and Nordman H. 1992. TVO-92 Safety Analysis of Spent Fuel Disposal. Report YJT-92-33E.

19. SKB Annual Report 1995, Report SKB-TR-9S, Stockholm, May 1996.

20. SFS 2905 Standard, Oxygen-Free Copper for Electrical Purposes. Helsinki 1975. Suomen Standardisoimisliitto. pp. 6.

21. ASTM B 170 - 93. 1993. Standard Specification for Oxygen-Free Copper - Refinery Shapes.

22. Rajainmäki H., Aalto H., Raiskio J., Pohjavirta J., Laakso L. and Raiko H. 1995. EB-hitsausmenetelmän kehittäminen massiivisen kuparikapselin valmistamiseen. TVO Work Report TEKA-95-08. pp.45 + app. 22, Helsinki.

23. Rajainmäki H., Helenius A., Kolehmainen M. The Production and Application of Oxygen-Free Copper. JOM, March 1993. pp. 68-70.

24. Bowyer W. H.1996. Design Basis for the Copper/Steel Canister. Stage Two. Final Report. SKI Report 96:47.

25. Rajainmäki, H., Nieminen, M. & Laakso, L. 1991. Production methods and costs of oxygen free copper canisters for nuclear waste disposal. Report YJT-91-17. Nuclear Waste Commission of Finnish Power Companies. Helsinki.

26. Werme, L., Eriksson, J. & Punshon, C. 1996. The swedish encapsulation plant project. Results from test manufacturing of full size copper canister for encapsulation of spent LWR fuel. Proceedings of the 1996 international conference on deep geologigal disposal of radioactive waste. Winnipeg, Canada.

LIST OF POSIVA REPORTS PUBLISHED IN 1996

POSIVA-96-01	Determination of U oxidation state in anoxic (N_2) aqueous solutions – method development and testing Kaija Ollila VTT Chemical Technology June 1996 ISBN 951-652-000-6
POSIVA-96-02	Fault plane solutions of microearthquakes in the Loviisa region in south-eastern Finland Jouni Saari IVO International Ltd Ragnar Slunga Försvarets Forskningsanstalt, Stockholm, Sweden June 1996 ISBN 951-652-001-4
POSIVA-96-03	Thermal optimisation of the final disposal of spent nuclear fuel Heikki Raiko VTT Energy June 1996 (In Finnish) ISBN 951-652-002-2
POSIVA-96-04	On the origin and chemical evolution of groundwater at the Olkiluoto site Petteri Pitkänen Technical Research Centre of Finland Margit Snellman Imatran Voima Oy Ulla Vuorinen Technical Research Centre of Finland June 1996 ISBN 951-652-003-0
POSIVA-96-05	Seismic emissions induced by the excavations of the rock repository in Loviisa Jouni Saari IVO International Ltd June 1996 ISBN 951-652-004-9

POSIVA-96-06	Geochemical modelling study on the age and evolution of the groundwater at the Romuvaara site Petteri Pitkänen Technical Research Centre of Finland Margit Snellman Imatran Voima Oy Ulla Vuorinen Hilkka Leino-Forsman Technical Research Centre of Finland September 1996 ISBN 951-652-005-7
POSIVA-96-07	Boring of full scale deposition holes using a novel dry blind boring method Jorma Autio Timo Kirkkomäki Saanio & Riekkola Consulting Engineers November 1996 (to be published) ISBN 951-652-006-5
POSIVA-96-08	Production methods and costs of oxygen free copper canisters for nuclear waste disposal Harri Aalto Hannu Rajainmäki Lenni Laakso Outokumpu Poricopper Oy October 1996 ISBN 951-652-007-3