SKI Report 02:46

Research

Electron Beam Welding of Thick Copper Material

Bernt von Brömssen

August 2002

SKI perspective

Background

The integrity of the canister is an important factor for the long-term safety of the repository for spent nuclear fuel. There will be high quality requirements on the sealing of the canister and the following testing of the sealing. SKB is developing the Electron Beam Welding (EBW) method as one alternative for sealing of the copper canister. The work is performed at the Canister Laboratory in Oskarshamn and at TWI in Cambridge, England. POSIVA (the equivalent to SKB in Finland) is developing a similar, but not identical method.

Purpose of the project

The purpose of this project was to make a survey of the different variants of EBW methods developed by SKB and POSIVA. The study is focused on the properties on a principle level: how the methods work and which parameters are important for the results of the welding. The differences between the variants are discussed.

Results

The main conclusions by IVF is that both SKB and POSIVA will succeed in their development of EBW within a few years. An advantage with the SKB method is the use of reduced pressure (instead of high-vacuum) to avoid root defects. An advantage with the POSIVA method is the beam oscillation technique, which gives further possibilities to control the weld quality, and may be of importance for closing of the keyhole in the weld.

Effects on SKI work

The study will be one basis for coming SKI reviews of SKB's programme for disposal of spent nuclear fuel, such as review of SKB's RD&D Programme 2004 and review of SKB's application to localise and build the encapsulation plant. The application is planned to be submitted in 2005.

Project information

Responsible for the project at SKI has been Christina Lilja.
SKI reference: 14.9-010927/01177.

Research

Electron Beam Welding of Thick Copper Material

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August 2002

Summary

The purpose of this study was to review the two variants of the Electron Beam Welding (EBW) processes developed (or used) by 1- SKB, Sweden with assistance from TWI, England and 2 - POSIVA, Finland with assistance from Outokumpu, Finland.

The aim was also to explain the principle properties of the EBW method: how it works, the parameters controlling the welding result but also giving rise to benefits, and differences between the EBW variants.

The main conclusions are that both SKB and POSIVA will within a few years succeed to qualify their respective EBW method for welding of copper canisters.

The Reduced Pressure EBW that SKB use today seems to be very promising in order to avoid root defects. If POSIVA does not succeed to avoid root defects with the high vacuum method and the beam oscillation technique it should be possible for POSIVA to incorporate the Reduced Pressure technique albeit with significant changes to the EBW equipment.

POSIVA has possibly an advantage over SKB with the beam oscillation technique used, which gives an extra degree of freedom to affect the weld quality. The beam oscillation could be of importance for closing of the keyhole.

Before EBW of lids, the material certification showing the alloy content (specifying min and max impurity percentages) and the mechanical properties should be checked. The welded material needs also to be tested for mechanical properties. If possible the weld should have a toughness level equal to that of the unwelded parent material.

Specifically some conclusions are reported regarding the SKB equipment. Suggestions for further development are also given in the conclusion chapter.

Sammanfattning

Avsikten med studien var att undersöka de två varianter av elektronstrålesvetsning som utvecklas av 1- SKB, Sverige med assistans från TWI, England och 2 - POSIVA, Finland med assistans från Outokumpu, Finland.

Avsikten var också att förklara principen för elektronstrålesvetsning: hur den fungerar, parametrar som används och som är viktiga för svetsresultatet men som också ger olika möjligheter, samt skillnader mellan de två olika varianterna.

Huvudslutsatserna är att både SKB och POSIVA inom några få år kommer att lyckas med att kvalificera metoderna för svetsning av kopparkapslar. SKB använder för närvarande svetsning med reducerat tryck vilket verkar vara mycket lovande för att undvika rotdefekter. Om POSIVA inte lyckas undvika rotdefekter med hög-vaakum metoden och pendling av elektronstrålen bör de kunna införliva tekniken med reducerat tryck, dock krävs större förändringar hos svetsutrustningen.

POSIVA har eventuellt en fördel över SKB med den s k pendlingstekniken, vilket ger en extra frihetsgrad med möjlighet att påverka svetskvaliteten. Pendlingstekniken kan också vara viktig för att sluta det s k nyckelhålet som används vid svetsningen.

Före det att elektronstrålesvetsning av lock sker bör materialet kontrolleras avseende certifikat, vilket bör visa legeringsinnehåll och mekaniska egenskaper. Även svetsarnas mekaniska egenskaper bör kontrolleras. Om möjligt bör svetsen ha seghet i nivå med det osvetsade grundmaterialet.

Specifikt rapporteras slutsatser angående SKB:s svetsutrustning. Förslag till fortsatt utveckling har också lämnats under kapitlet slutsatser.

Content

Acknowledgment

Especially the author want to thank Sören Claesson - working for SKB as a consultant, Allan Sanderson at TWI in England and Jouko Koivula at Outokumpu in Finland for all information they have given. Thanks are also due to SKI for financing the work.

1 Introduction

IVF has been requested by Swedish Nuclear Power Inspectorate (SKI), Sweden, order reference no. 14.9-010927-01177, and contact person Christina Lilja (Christina.Lilja@ski.se) tel. +46 (0)8-698 8455), to carry out a survey of the different Electron Beam Welding (EBW) methods useful for welding of thick copper material.

The purpose with this study was to review the two variants of Electron Beam Welding (EBW) process developed (or used) by 1- SKB, Sweden (with assistance from TWI, England) and 2 - POSIVA, Finland with assistance from Outokumpu, Finland.

The aim was also to explain the principle properties of the EBW method: how it works, the parameters controlling the welding result but also giving benefits, and differences between the EBW variants.

2 Background

According to plans from SKB, around the year 2005, they will apply for approval to start the building of a plant for encapsulation of spent nuclear fuel. There will be demanding requirements on the joining method chosen for the encapsulation of the copper canisters. The most important aspects for the EBW method will be as follows:

1. To produce welds that not contain discontinuities that exceed the acceptance criteria that SKB will lay down. Examples of discontinuities that can occur are cracks, pores, lack of fusion and incomplete penetration or root defects.

2. That the weld and the heat affected zone (HAZ) should both have sufficient toughness to meet the requirements for safe handling prior to deposition and the necessary properties in terms of mechanical strength and corrosion resistance required in the deep repository.

3. That the welding results can be inspected with sufficient degree of reliability and accuracy to ensure the required quality of the weld.

4. That it is possible to repeat the welding result quite "easy". This means that the most important parameters should have a relatively "large tolerance box". The value for a parameter should for instance normally be able to vary in the order of ± 1 - 5% without affecting the weld quality more than marginally.

Since around 1984 TWI in England has been developing an EBW process for SKB in Sweden. The goal has been to develop a reliable EBW process for thick copper material (50 – 100 mm).

Application developments are going on both at SKB in Sweden, with assistance from TWI in England, and at POSIVA in Finland. Two "methods with similarities" are being developed. The report describes similarities and differences for the two methods.

3 The EBW process

3.1 General Introduction

Experiments with cathode ray devices producing fast moving electrons lead to the discovery of the X-ray (1895). The first person to realize the potential for melting metals with an electron beam was Marcello von Pirani who in 1905 obtained a patent. The breakthrough in EBW of "thick metals" came in 1958 when deep penetration welding on 5 mm thick Zircalloy was performed.

In practice the EBW method can be used for joining of most engineering alloys. Also dissimilar metals can be welded together. The low heat input applied by the EBW process allow even hardened materials to be weld without almost any loss of hardness and component distortion is kept to a minimum. Materials sensitive to oxidation at high temperatures can be readily welded by utilization of the vacuum chamber.

Material thickness of from 0.5 mm to 300 mm and both thin and thick materials can be welded with the same equipment. Butt joint – a seam where normally two sheets with square edges are placed beside each other without any gap - is the most common joint design used. Also lap joint – two sheets placed beside each other but with a small distance overlapping each other - can be used.

EBW is used for applications where high precision and high quality are required. Normally high volume production is needed to recover the high investment costs. It's also necessary to take full advantage of the characteristics of the process– e.g. the low heat input for low distortion, and the possibility of high repeatability and high welding speed.

3.2 The Principles of the EBW Process

What is an electron? The difficulty of providing an answer to this question is that no one can give an answer that is simple and easy to understand and at the same time correct and complete. But, put very simply, an electron is the smallest bit of electrically charged material that can be identified. The electron charge is 1.6×10^{-19} C and the mass of an electron is 9.1×10^{-31} kg.

A simple **atom** model consists of an extremely small, positively charged **nucleus** surrounded by a cloud of negatively charged **electrons**. Although typically the nucleus is less than one ten-thousandth the size of the atom, the nucleus contains more than 99.9% of the mass of the atom. Nuclei consist of positively charged **protons and** electrically neutral **neutrons held** together by the nuclear force. This force is much stronger than the familiar electrostatic force that binds the electrons to the nucleus, but the range of the nuclear force is limited to distances on the order of a few x 10^{-15} metres. The small electrostatic forces between the nucleus and the electrons make it possible to extract electrons from the atom by the use of an externally applied positive charge.
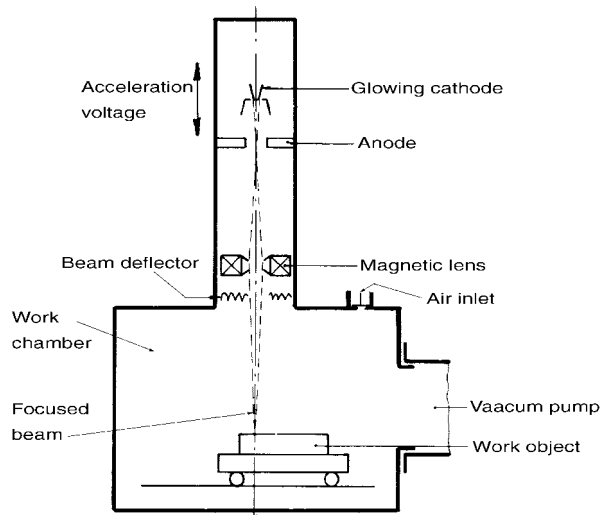
Fig 1. A principle sketch of an Electron Beam equipment (1).

The force that binds electrons to nuclei decreases with increasing temperature of the atom. By resistance heating of a filament the electrons can easily be attracted from the filament to an anode and form a stream of electrons – an *Electron Beam (EB), see Figure 1.*

By use of a hollow anode and a typical accelerating voltage of 150 kV the electrons are accelerated to approximately 2/3 the speed of light (approx. 1.9×10^8 m/s). The electron stream is focused by a shaped electric field, which directs the electrons through the centre of the hollow anode.

The high velocity electrons are subsequently re-focused by one or more electromagnetic lenses and strike the workpiece, causing abrupt deceleration, which converts most of their kinetic energy directly into heat energy. Each electron contains only a small amount of kinetic energy ($W_k = \frac{1}{2}mv^2$) due to the extremely small mass of each electron. It is the incredibly velocity and the vast quantity of electrons that makes it possible to melt and evaporate material.

The workpiece starts to melt when the EB strikes the surface and the melt increases in depth very rapidly. The heat conduction is at the same time not as fast so the total volume of the melt can be kept deep and narrow. When more energy is transferred to the same melt it starts to evaporate and suddenly a deep keyhole is created. The keyhole is held open by the continuous evaporation of material from the walls of the keyhole. Because of this deep penetration phenomenon it is possible to transfer a huge amount of energy to the material in a relative short time. Energy is transferred through the walls of the keyhole in contrast to several other methods like MIG welding where the energy is transferred mainly through the surface of the weld pool. Such methods cannot transfer as much energy per time unit area to the joint interface because they are dependent on the speed of the heat conduction of the parent material.

When the keyhole is displaced laterally by relative motion of the workpiece or the beam, more material melts, evaporates and the melt flows backwards relative the motion of the EB, where the melt material cools, solidifies and a creates the weld.

4

3.3 High Vacuum Welding Machines

For *High Vacuum Welding Machines* the pressure in the work chamber is typically 5 x 10^{-7} bar (4 x 10^{-4} torr). For metals that are prone to oxidation, such as titanium and its alloys, high vacuum EBW is a very good choice. The size of the vacuum chamber decides the size of the parts that can be welded.

Typical applications include
- Nuclear engineering and reactor construction
- Aircraft engineering: turbojet engine components, cell structures, fuel tanks, steering systems
- Electrical engineering: superconductors, relays, contacts
- Saw blades
- Marine repairs

3.4 Partial Vacuum and Reduced Pressure Machines

The pressure in the work chamber of *Partial Vacuum Machines* is typically 100 times higher than in the high vacuum operation mode. This level is best suited for all materials for which high vacuum is not required, such as steel, nickel, copper, aluminium and its alloys and for achieving short cycle times, e.g. in mass production.

Typical products welded by partial vacuum technique are

- Pistons, valves, torque converters, gears, axle boxes for automotive industry

In the case of Reduced Pressure EBW the pressure can be even higher i.e. 10^{-4} to 5 x 10^{-2} bar (0.1 to 50 mbar).

Typical applications include welding of large thick section steel components where rapid evacuation of the work chamber is required in order to achieve the minimum possible weld cycle time whilst employing relatively crude local sealing arrangements.

It also offers special advantages where component out gassing is likely to be a potential problem, since the beam generator is quite immune to fluctuations of pressure in the work chamber.

3.5 Non-Vacuum Welding Machines

The superior advantage of a *Non-Vacuum Welding Machine* is the very short cycle time achievable due to the total elimination of evacuation time for the workpiece chamber. However, in order to achieve welds as narrow as possible, the work is generally carried out at distances ranging from 6 to 30 mm from the base of the gun column to the workpiece.

The somewhat broader beam of Non-Vacuum can tolerate larger gaps. The cost of weld preparation can be by this means kept relatively low.

The essential distinguishing feature of the process (compared with the vacuum variants) is the collision of the beam electrons with the molecules or atoms of the atmosphere. Scattering broadens the beam as it advances. The scatter effect becomes less the lighter the gas particles are and the lower the particle density. Helium is therefore more favourable than air, and argon however much less favourable. For this reason practically all commercial Non-Vacuum EBW machines have a mechanism built into the gun for ejecting a flow of helium coaxial with the EB.

The metal vapour plasma produced during Non-Vacuum EBW can be less troublesome than in the case of laser welding where often gas jets have to be used to blow the plasma away. This is partly because much higher power levels can be produced more readily allowing higher welding speeds to be used. When welding at high speeds the beam effectively outruns the plasma.

Typical products welded by Non-Vacuum technique are

- Torque converters, epicyclical gear units, exhaust gas converters, steering column jackets, measuring cells, pressure reservoirs, car frame parts, gears.

3.6 Pros and Cons for EBW of Thick Copper Material

3.6.1 Advantages with EBW for welding of thick copper material

In comparison with other fusion welding methods the advantages with EBW are as follows:
- The high welding speed possible, due to the high energy density in the beam and the use of a keyhole which makes it possible to transfer more energy in a shorter time to the parent material compared with other methods.
- The deep penetration possible by the use of a keyhole and high power. This simplifies the seam preparation in comparison with many other methods.
- The low distortion created by the use of a keyhole with deep penetration, high power, and high speed welding which means minimized heat-input to the parent material. Lower distortion gives lower residual welds stresses and generally decreases the risk for hot cracking during welding.
- The use of filler material can be avoided which simplifies the welding procedure. The fewer things to control when welding the simpler it is to perform the weld. Avoidance of filler material also means one less thing to check regarding quality, alloy content, surface etc.

3.6.2 Pros and cons of EBW of thick copper in comparison with laser welding

Pros and cons of EBW of thick copper in comparison with laser welding which are true today but probably will be changed considerably within 10 – 15 years. Today the EBW is quite superior to laser, with the seam and thickness chosen for the copper material, but the difference will decrease and could also be the reversed in the time period mentioned above.

Pros with EBW versus laser welding

- Deeper penetration possible with EBW due to the possibility to use higher power and possibly smaller beam diameter.
- Less distortion with EBW possible due to the possibility to use lower heat-input (smaller keyhole and higher speed). With a thin and narrow EBW the shrinkage forces will be relatively lower than for a wide weld, which in turn results in less distortion.
- Higher efficiency, 90 % compared to 10 % for a CO_2 laser. This would be reflected in the diameter of the electrical cable and power systems necessary that have to deliver the power. Higher efficiency means that a cheaper and smaller diameter cable can be used. Fuses with lower capacity can be used. The whole electrical installation will be cheaper with increasing efficiency for the welding method that is to be used.
- Thicker copper material can be welded with the EBW due to the keyhole size/technique and the high power possible to use. Today it is impossible to butt weld 60 mm thick copper material with one laser. The use of several lasers is not recommended due to the complexity of handling such equipment.

Cons with EBW versus laser welding

- Low-pressure vacuum at the workpiece, especially for deep penetration welding. It's time consuming to create a low pressure, especially when the working chamber is big. It also needs more leak-tight sealing when working with lower pressure compared to higher pressure.
- Shielding necessary against the X-ray generated. Not a problem when working with automatic EBW and a thick protection of concrete, but anyway it is a cost that must be considered when installing EBW equipment. The same shielding that protects operators from the radiation coming from the spent nuclear fuel will also be enough protection for the operators from the X-ray generated by the EBW process.

4 An RF Excited Electron Beam Welding System

A conventional power supply system for an indirectly heated triode gun is shown in Figure 2. According to (2) such systems were prone to auxiliary power supply failure, cable inter-lead failures and invariably led to a large diameter inflexible cable quite unsuitable for mobile gun systems.
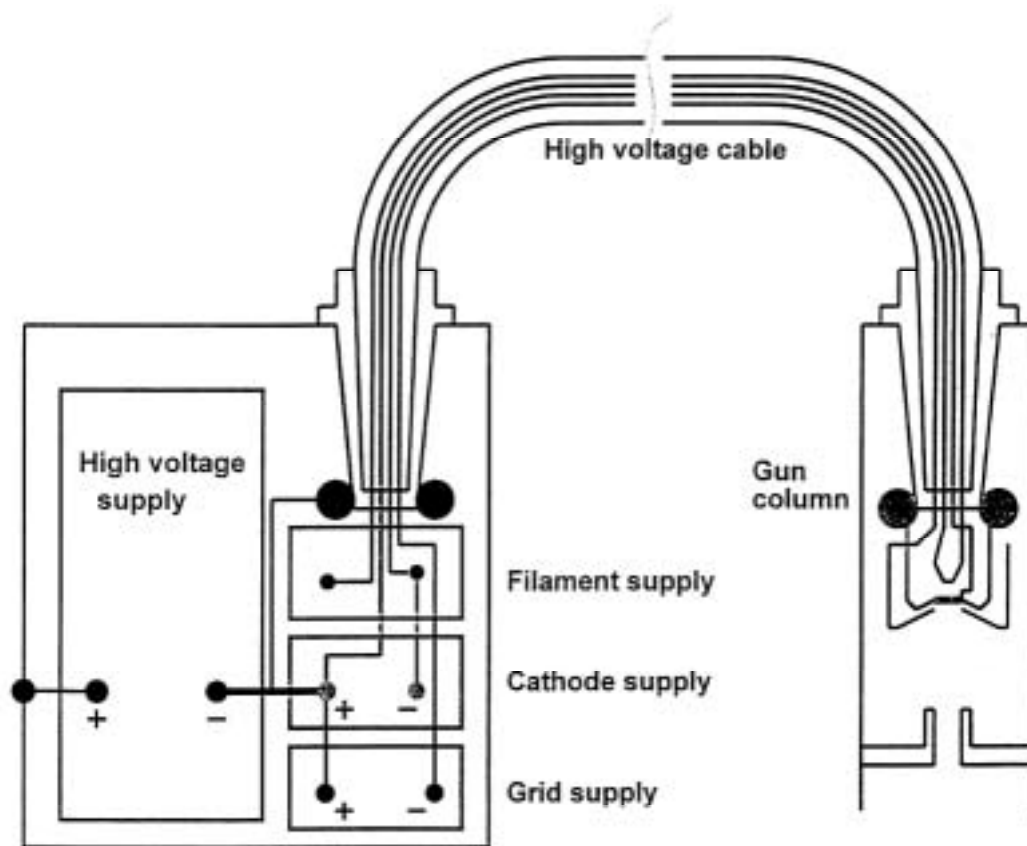

Fig 2. A conventional power supply system for an indirectly heated triode gun (2).

The principle of the Radio Frequency (RF) excited gun development is best described by reference to Figure 3 (8). RF power at a frequency of typically 84 MHz is beamed at the gun cartridge by an aerial enclosed within the gun housing. A secondary winding consisting of a single turn cylinder, housed within the gun cartridge, collects the RF power. This winding, in combination with a small ceramic capacitor is held in resonance at 84 MHz, producing a high current circulating through a ribbon filament. The resistively heated filament emits electrons. As the RF power level is raised the filament is brought to electron emission temperature (<2500 °C). Since a high alternating voltage then exists between the filament and the cathode element, electrons are drawn from the filament every half cycle producing a primary electron beam, which heats the main cathode.

The electrons are then shaped to form a primary electron beam and this beam will heat up the cathode to a rather high temperature (<2000 °C). A high voltage 200 kV between the cathode and the hollow anode then generates the main beam. The electrons pass through the hollow anode and enter the chamber work area with a typical velocity in excess of 2/3 the speed of light.
Magnetic focusing lenses can then focus the beam.
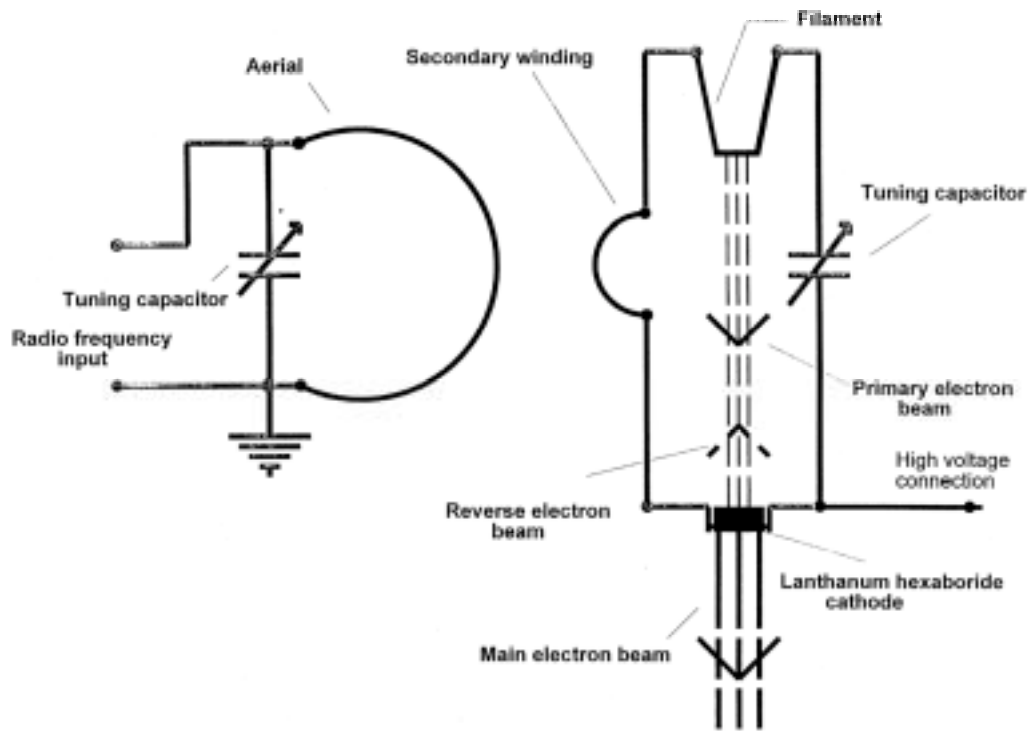
Fig. 3 A principle of a RF excited gun (8).

A power density of over 30 kW/mm^2 can be produced which causes spontaneous evaporation of the workpiece material and leads to the so-called keyhole effect.

Electron beam generators of the type described above can achieve power levels of over 100 kW covering a wide range of EBW applications.

Depending on the application and the related specification, different voltages and pressure levels in the workpiece environment can be used. High and partial-vacuum systems reach output powers of up to 100 kW at acceleration voltages of 200 kV. Commercial atmospheric systems operate at 175 kV and up to 40 kW.

5 Electron Beam Welding of 50 mm Thick Copper

5.1 The EBW Variant at SKB in Oskarshamn

TWI in Cambridge developed the EB equipment. The machine is a Reduced Pressure type. The machine was installed in the year 1997. SKB still purchase development work from TWI, especially regarding the equipment.

In total 21 lid welds have been made since 1999 (4 – 1999, 10 – 2000, 7 – 2001). Also 50 bead-on-plate welds in test pieces of the size of 400 x 180 x 60 mm have been performed.

Normally 65 kW of power have been used with an accelerating voltage of 190 kV and a beam current of approximately 0.34 A.

When all the development work is finished, the welding method including all of the important parameters should be described in a Welding Procedure Specification (WPS). The production of EBW lid welds must then be performed in the way the WPS describes, without any changes of parameters, clamping etc. If anything needs to be changed, a re-qualification of a new WPS must be carried out.

5.1.1 Positioning of the lid

The lid is lowered into the cylinder by lid handle equipment and utilizes its own weight to achieve good fit-up relative the cylinder. The shape of the lid neck is weakly tapered and the gap distances between the lid and cylinder are adapted to fit well; no problems are expected to get the lid in the right position for welding. A mark is engraved on the cylinder wall (giving a 1 mm distance from the final position between the lid and the cylinder), which makes it possible to see if the lid has reached almost the right position. At present, a certain level of uncertainty exists because of the present method of viewing the workpiece. Although in an eventual production machine a laser measurement system will be used to assure the position of the lid relative the cylinder. It should be possible to make the alignment procedure reliable and no problems are expected after a short period of test running.

5.1.2 Position of the EB relative the lid

The cathode is made of a ceramic material called lanthanum hexaboride (LaB_6). Lanthanum is rare earth element with the atomic number 57 and boron has the atomic number 5 in the periodic table and is a metalloid. Metalloids exhibit the properties of both metals and non-metals. This ceramic material is often used in Scanning Electron Microscopes and seems to be a reliable long life cathode. A good choice for an electron beam cathode. During welding the cathode can reach approximately the temperature of 1600 °C. The ceramic material is suitable to withstand this temperature. The high temperature makes the electrons "highly mobile" promoting easy extract and acceleration towards the anode, thereby creating the electron beam. If the beam is

measured regularly any wear or other cathode defects will be detected during the measurements and comparison with earlier performance measurements.

In the SKB case the beam enters the lid essentially horizontally, penetrating through the lid surface and in to the cylinder wall, see Figure 4.

In order to adjust the beam impact position with respect to the cylinder, the gun position is set visually to hit the lid edge support. A beam diameter of approximately 2 mm is used which makes it difficult to achieve the desired accuracy of ±1 mm. *A method (seam finding, seam tracking) giving better accuracy than today would help to improve the repeatability of the welds.*

The choice of a horizontal position affects the welding performance. The viscosity of copper in the molten condition, as in welding, is such that it is very fluid. Because of the fluidity of copper in the molten condition and the horizontal weld position, the melt during the welding must be supported by an edge. This edge is a part of the lid itself, see Figure 4.
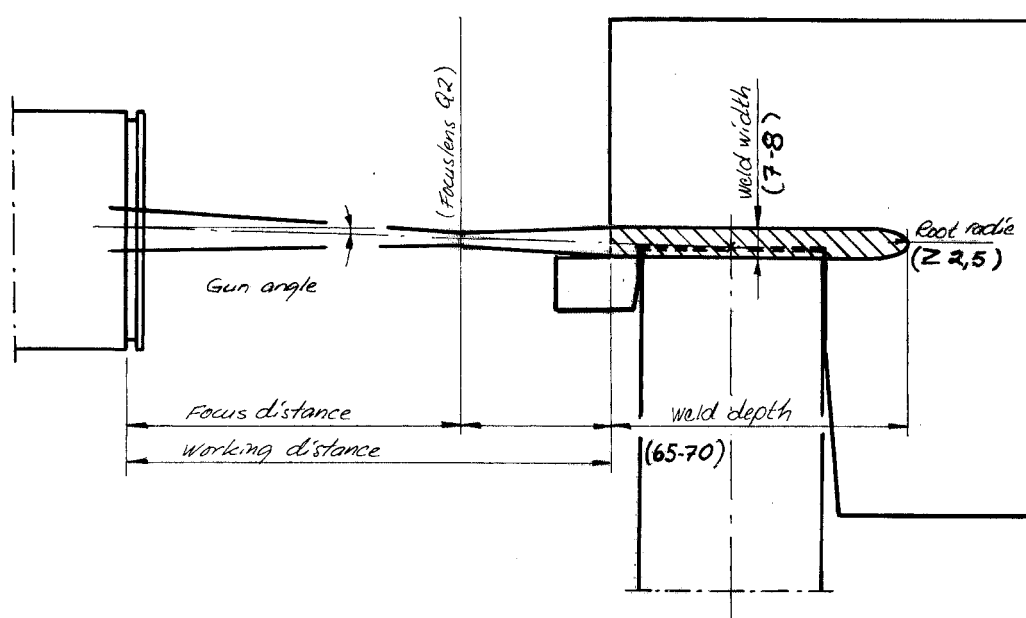
Fig 4. Position of EB relative lid and cylinder.

The most frequently used working distance (Figure 4) for the lid welds so far has been around 125 mm from the column end face to the lid.

The magnetic lenses focus the beam to a small diameter above the lid surface. After the focal plane, the beam diverges. The beam typically generates a weld width of 7 – 8 mm on the surface.

Alternatively the beam focus can be positioned directly on the workpiece surface. Location of the focus on the surface is a very common technique used in laser welding. The idea of this is to use maximum intensity of the beam at the surface giving the opportunity to maximize welding speed, but this also produces a narrower weld. When welding thicker material, as in the "copper canister case", high welding speed and a

narrow weld seem desirable. A long depth of focus seems more desirable in order to give better shielding of the gun and at the same time a wider weld which allows the gas in the weld pool sufficient time to escape from the melt before it solidifies.

A long depth of focus gives a beam with smaller variation of beam intensity along the beam. This is probably more suitable for a weld of that thickness as in the copper case. A large distance, as used in the most of the performed lid-welds, is probably desirable in order to minimise the spatter caught on the extremity of the gun. Especially spatter inside the gun must be avoided in order to avoid discharging inside the gun. If the EB hits Cu-spatter inside the gun, the spatter will evaporate creating plasma, which could cause the beam to spread causing possible damage inside the gun column.

Maybe the gun could be equipped with some better spatter protection inside the gun? EB equipment could be equipped with a magnetic trap device that would prevent spatter entering the gun column. *Maybe something similar or a device with the same spatter protection could be installed at SKB.*

Alignment coils in the lower column are used to centre the beam. This trimming is important to ensure that the beam does not deviate from the joint line.

An instrument for measuring the current density in the beam could be useful, see Figure 5. The instrument should be able to measure the width/diameter and current distribution within the beam. By measuring the beam at different heights the focal point could be found. The width and the current distribution will be a function of the power. The beam will increase in size with increasing power due to the fact that a greater number of electrons in the beam will demand more space because of the repulsion of the negative charges. Measuring of the beam width/intensity should therefore be carried out at high power, if possible the power used for welding. The measurement can be done regularly (before and after the welding) in order to have a kind of calibration of the beam.
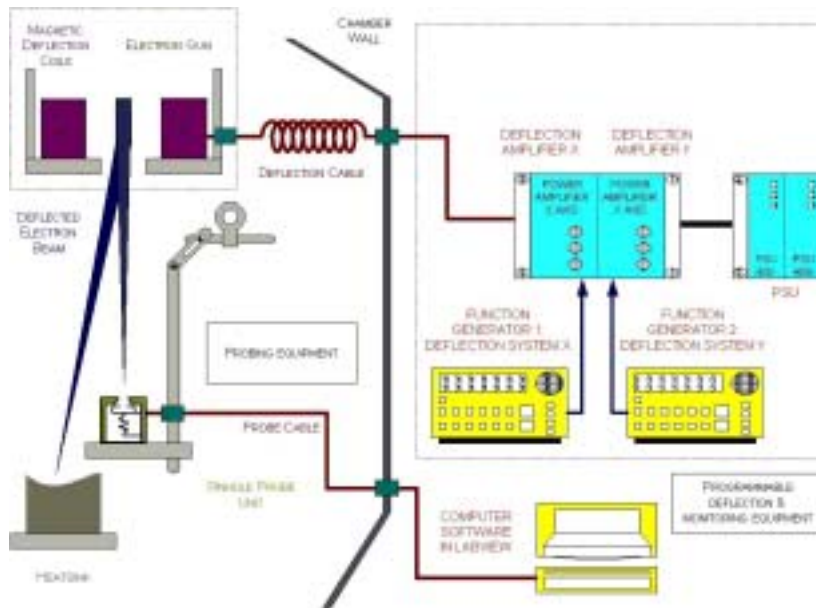
Fig 5. Schematic diagram of probing equipment (from TWI)

5.1.3 Reduced Pressure

SKB today use about 0.2 – 0.25 mbar as the lowest possible pressure. With a very long pumping time (½ day) they can reach approximately 0.18 mbar. There seems to be fewer problems with lower pressure, although there will **probably be an optimum pressure where the desired shape of the weld is reached** and at the same time the welding process will be stable, repeatable and with minimum spatter. SKB recently bought an extra pump in order to reduce the pressure in the welding chamber to around 0.1 mbar. Also pipes and sealing ought to be checked at the same time so that the required pressure can be reached within a reasonable amount of time. The use of lower pressure is probably a step in the right direction: a lower pressure gives less interaction between the electron beam and the remaining gas-atoms or gas-molecules (hydrogen, argon, nitrogen, oxygen and carbon dioxide) in the chamber. Fewer interactions between the beam and the gases (lower pressure) might give a more repeatable welding process.

Today helium is used inside the gun to protect the beam from air and dust coming into the gun and interacting with the beam. The flow used is approximately 1 l/min, and also 2 – 3 l/min has been tested without any noticeable effect. The input of helium in the gun will increase the pressure in the chamber, which also is measured by the instruments in the chamber. The cooling effect from 1 l/min of helium is probably very low and probably not of importance. Higher flow rates could create plasma inside the gun and disperse the beam causing possible gun damage. There will be a maximum flow allowed which will not degrade the beam properties. Mechanical protection of the gun before and after welding in order to avoid dust that penetrates the gun is desirable.

In transit to the copper surface, the electrons pass through the relatively high-pressure region and will interact with some of the atoms/molecules in their path, giving rise to some scattering, which in turn will give a wider weld, see Figure 6. Before the EBW operation is started the electrical lights are switched off giving a dark chamber. The result of the interaction can then clearly be seen – a blue-coloured plasma along the beam path which increases in intensity when the power is increased. Probably electrons from the EB collide with atoms/molecules thus exciting electrons to higher energy levels, which will spontaneously emit visible light (photons) when returning to lower energy levels.
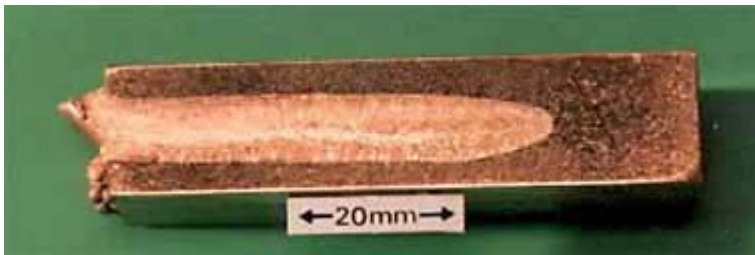

Figure 6. Reduced Pressure EB weld in copper showing round-bottomed weld profile (from TWI).

5.1.4 The welding procedure

Before a weld starts, a check of the material to be weld should be done. The material needs to have a certification showing the alloy content and the mechanical properties.

Before the weld starts a checklist with approximately 30 items is checked – seems to work well. Maybe the list needs to be updated regularly?

The weld is performed in two sequences (compare with POSIVA and TWI – three sequences).

1   Five tack welds are performed that fix the lid to the cylinder. The tack welds are about 120 mm in length and with penetration depths of about 20 mm and uniformly spread around the cylinder. Tack welding is a very reliable and commonly used technique for fixturing of components before the final welding is done and also a technique used by the industry for many years – excellent!

2   Final weld with full penetration. The EBW will re-melt the tack welds and integrate them totally in the final weld.

At the start of the final full penetration weld, the electron beam and the rotation of the cylinder are started simultaneously. The weld is done with an overlap, which is a very good way to avoid problems within the "start-up" region. During the beam current slope-up, whilst establishing the penetration keyhole, probably some defects are created in the weld, but the start-up region will be re-melted completely when the electron beam passes the second time. But it is more likely that weld defects will be found within the

overlap or beam current slope-down region than anywhere else in the weld. The weld in the slope-down region should be controlled and checked extremely well!

One problem could appear during the weld overlap. When the full penetration keyhole should be closed, it must be done smoothly in order to avoid defects. Different parameters/techniques need to be tried in order to find a reliable solution. POSIVA seems to have a fine technique for closing of the keyhole!

5.1.5 Supervision of parameters

Approximately 30 important parameters associated with EBW are supervised and registered in an Excel-file every 2:nd second and stored in a computer memory. *The recording of parameters is started manually – maybe an automatic start would improve the repeatability.* There will be a lot of figures nearly impossible to overview when presented in tables. Therefore some of the parameters are presented as diagrams instead. Some of them have upper and lower limit levels and when one of them is passed an alarm will start. Some of them can also shut off the EB in order to protect the EB equipment. The equipment seems to be well protected.

All the water flow used for cooling of important and sensitive components should be measured, controlled and checked systematically. In some cases the temperature could be measured instead of the water flow, but normally the best is to measure both of them. How to control the primary coolant level? Is it necessary to have the primary coolant level visible?

Quality on-line control systems are so far not used for EBW, but are now under development for laser welding and are expected to be on the market within a year. The idea is quite simple – one sensor or several sensors are set in the vicinity of the weld looking at the weld pool, the keyhole, or the surface of the weld being made in order to find out if anything abnormal happens. The sensors could measure different wavelengths as visible, infrared or ultra light. Also sound could be measured to check for abnormal sounds during weld. Maybe it will be necessary to develop quality on-line system in order to reach the desired quality of the welds?

5.1.6 Work environment

Generally the main risks for EBW are high voltages, X-ray emission, fume and gases and UV and visible light from the melt. In the SKB EBW facility no high risks are expected due to the fact that the EBW is performed automatically without any human person inside the chamber during welding.

If any risk has to be considered maybe the inhalation of copper could be a risk. The fume and gas emissions are relative small but the weld metal vapour condenses as dust in the welding enclosure, rather than being deposited as an adherent layer on the equipment. The airborne dust should be extracted during the enclosure venting cycle before operators enter the chamber. Dust, which has settled on surfaces, can be readily removed by brushing but, again, adequate dust extraction and personal breathing protection equipment must be employed.

A small proportion of the kinetic energy of the electrons is converted into diffuse X-ray radiation impinging on the workpiece, but this represents no problem. The X-rays are

created when the EB impacts on the workpiece. The chamber is constructed in a way that the X-rays can't reach the surroundings (walls of concrete or Pb). Pb-glass can be used as windows in the chamber. Regularly checks of the Pb-glass might be necessary?

The eyes should be shielded against eventually radiation from the melt or the plasma above the melt. Should not be a problem at the SKB facility – automatic welding using closed circuit television.

5.2 EBW Equipment at TWI in Cambridge

TWI still assists SKB with development of both the EBW equipment and the welding process. For the moment the main work at TWI, for the account of SKB, is associated with development of EBW equipment. Still TWI performs EBW on copper bottoms for a Swedish test programme. TWI also occasionally performs EBW for SKB on test blocks.

Fig 7. A 5m long, 1m diameter copper canister assembly, being lowered into TWI's Reduced Pressure Facility at Abington, Cambridge.

The TWI welding procedure

1. 4 * 100 mm long tack welds

2. A weld around the whole periphery of the pipe approximately with 5 mm penetration deep.

3. The final weld with full penetration

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TWI also acts as backup and speaking partner for SKB. The development also brings some opportunities for TWI to gain patents within this technology, which in turn means that some of the knowledge needs to be kept as a secret for a certain period of time. A patent application normally prevents disclosure of commercially sensitive information for 18 months.

One of the main conclusions drawn from EBW experiments performed at TWI during more than 10 years is that the **high vacuum EBW of 60 – 70 mm thick copper will result in root defects**. These defects are very sharp in geometry and could act as corrosion path when the canisters are buried. One way to avoid root defects seems to be EBW with Reduced Pressure that has been introduced at SKB in Sweden.

5.3 EBW Variant Developed by POSIVA in Finland

POSIVA is working together with Outokumpu developing a high vacuum (10^{-3} mbar) EBW process for welding of approximately 50 - 60 mm thick copper. Conventional high vacuum EBW of such a thickness requires only a power of 45 kW or so. There is no EBW machine with this power available in Finland (only up to 30 kW). The nearest developments of the EBW process will probably be done at a company in Germany.

Outokumpu has a lot of experience from high vacuum EBW of 15 mm thick copper used for superconductors.

POSIVA has so far experience from seam welding (not lid welds) with a backing bar simulating the start, overlapping and sloping down sequences, which have been done in Finland and Germany. POSIVA will this year, for the first time, EB weld three copper canisters of thickness 50 mm, diameter 1 m and with a length of ½ m. They will start with the EBW of the bottoms for training and then try to do the EBW of the lids.

Two hours and twenty minutes pumping time will be needed for the evacuation before welding of the bottom and the lid respectively. Of course all sealing need to be of resistant material and needs to be very tight! No measurement of the pressure inside the canister is planned. There could be a difference of pressure inside and outside of the canister without any possibilities to check it. A difference in pressure can affect the result of the EBW, and in this case, it can be discovered afterwards when the result is checked. If necessary then preventative action can be taken. *The pressure is an important parameter and it might need to be measured both inside and outside the canister during the development of the EBW process.*

Before the EBW of the lid is carried out a coil of steel plate with an area of 14 m^2 will be placed inside the cylinder. The coil shall simulate the steel liner that will be holding the spent nuclear rods in a "real" canister.

The full penetration welding will be done with 45 kW and with a focal diameter of a little less than 1 mm and placed on the surface. The EB is moved in a special pattern (beam oscillation technique), which gives a weld width of 4 mm in the bottom and 8 mm at the top. The EB hits the seam coming from above, i.e. the EB is directed vertically down, see Figure 8.
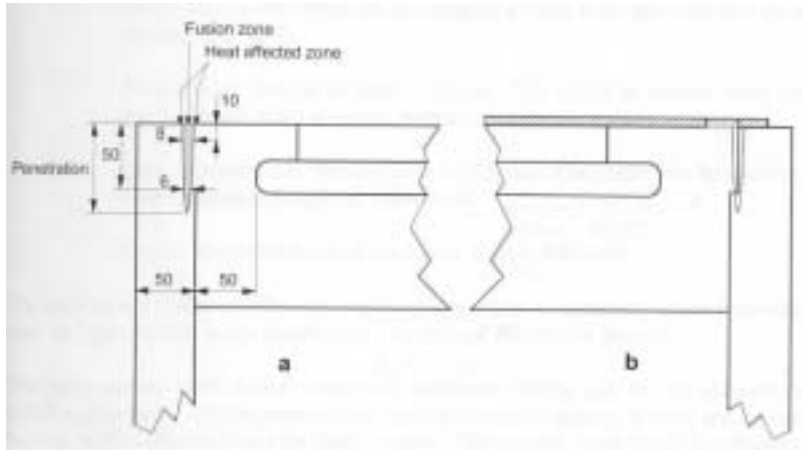
Fig 8. The seam and position of the weld (from Outokumpu).

The closing of the keyhole is done with linear defocusing of the focal spot over a period of 10 seconds whilst decreasing the power at the same time. The focal spot is moved linearly upwards whilst still oscillating the EB.

Figure 9. Closing of the keyhole is done with a linearly defocusing of the focal spot during about 10 seconds and a decrease of the power at the same time (from Outokumpu).

Figure 10. A view of the EB welds after a subsequent surface smoothing run (from Outokumpu).

5.4 Similarities and Differences between the EBW Variants of POSIVA and SKB

Some similarities and differences between the POSIVA and the SKB EBW methods are given here:

Item	*POSIVA*	*SKB*
Beam Orientation	vertical down (*for flat position welding; ASME IX 1G*)	horizontal flat (*horizontal-vertical welding; ASME IX 2G*)
Pressure	high vacuum	reduced pressure
Beam oscillation	Yes	No
Welding sequences	Tack weld Low penetration weld Full penetration weld Surface cosmetic pass	Five tack welds Full penetration weld
Power	45 kW, 150 kV – 0.3 A	65 kW, 190 kV – 0.34 A
Focal spot diameter	<1 mm	~2 mm
Supervision	Video monitoring (*visible light*)	Video monitoring (*visible light*)
Quality control methods	Transverse section Longitudinal section X-ray Ultrasonic testing	Transverse section Longitudinal section X-ray Ultra sound Check of the surface with eddy current

6 Literature Survey with Comments

The purpose with the literature survey was to get an overview of EBW of copper and hopefully also to find important knowledge useful for both SKB and SKI to succeed with the development of the EBW of the copper canisters for spent nuclear fuel.

6.1 Benefits with an RF excited gun

Gun discharging, gun overheating problems, failure of cables and auxiliary supply components and limited control of beam profile particularly at high power levels have all contributed to the need to completely re-think how to generate and control electron beams for welding (2). *A relative new technique generates the EB by using Radio Frequency power (RF), which has been introduced to the SKB equipment. The benefits are according to (2)*

- *Reduction in size and complexity of the EB gun column*

- *The possibility of single core small diameter high voltage cable*

- *Greatly improved beam axial stability and quality over the entire power range*

- *Avoidance of severe component damage by gun discharges*

- *Greatly simplified high voltage power supply*

6.2 Strain measurements as input to an FE-analysis

In (5) a thermo-mechanical FE-analysis of residual stresses for the EBW process of the copper canisters was done and the calculations showed that the maximum plastic strain (plastic + creep) accumulated in the (possibly brittle) heat affected zone should be about 7 % which seems to be well below the reported ductility (30%) for the copper to be used.

In the FE-analysis it was assumed that the heat-input was given at the same time (momentarily) along the whole seam, which is not the case in a real EBW, where the heat-input is more of a line-energy source and a function of the time. *There are substantial movements in the seam during the EBW, probably causing high strains in the weld and in the vicinity of the weld. This will probably not be caught in the FE-analysis without giving a time dependent heat-input. Some strain measurements during EBW of the lids will improve the FE-analysis and provide more reliable results.*

Also the ductility of the weld and the heat affected zone (HAZ) should be measured to check if its toughness is as good as the parent material.

6.3 Non-destructive testing for quality control

In (6) non-destructive examination with an ultrasonic array technique was tested for a copper material block without any welds. The technique seems to be promising for the detection of defects in copper material. *Especially an electronic filter seems to be working quite well, but it still has to be tested on welds*. Welds normally contain more inhomogeneous structures than the parent material, which makes it more difficult to find out what should be the characteristics of "the reference signal". The reference signal should also have some upper and lower levels. When the signal is "out of bounds" it is indicating that the weld might have some defects. A lot of weld trials must be done to find out those limit levels! It will be very difficult to get a reliable method. *Therefore it is of great importance that several different methods (ultrasonic, x-ray, online methods etc) are tested in order to find reliable methods for evaluation of the quality of the welds.*

6.4 The strength of an EBW copper material is good

Some conclusions from (7) from EB welding of copper of thickness 10 – 20 mm are:

- *The strength of the weld joint was similar to that of the parent material*

- *Repeated cosmetic passes did not impair the strength of the welded joints*

This is promising for the copper canister weld development and nothing speaks against the possibility to succeed with it although it has greater thickness than reported in (7).

6.5 EBW of thick material in Japan

The keyhole technique allows deep penetration welding of thick materials and the result is still a relative narrow weld. EBW of 300 mm thick stainless steel has been done in Osaka University in Japan (4) where the width of the weld was approximately 5 – 8 mm. In Japan they seem to have experience from welding of thick material, but as far as known not from EBW of thick copper. *Eventually a study of the EBW equipment in Osaka University at the Joining and Research Welding Centre in Japan could be of interest in order to learn from their experience.*

7 Discussion

In general EBW is considered to have a high investment cost. Other possible methods should therefore not be excluded too early in the development. One main competitor is Friction Stir Welding, but also laser welding will probably be a competitor within 10 years. So far the EBW of copper canisters has been most developed of all the possible methods. EBW seems to have great possibility to be completely ready for an EBW production of copper canisters within a few years.

There are small differences between the methods developed by SKB and POSIVA. The main differences seems to be the orientation of the beam with respect to lid i.e. vertical or horizontal, the pressure used, beam oscillation technique or not, the beam type used. So far, SKB has the most experience regarding the EBW of lids and has so far done 21 lid welds compared with POSIVA´s zero number. One important factor is that SKB/TWI have shelved the high vacuum method and developed the Reduced Pressure method. The Reduced Pressure method seems so far more promising! However, this could be changed when POSIVA has gained more experience from real lid welds. Although this is not certain – there could be a risk that the high vacuum method not will be able to produce welds free of root defects. But even if this will happen it should not be any problem, in principle, for POSIVA to modify the approach and after that reach the same result as SKB. Both methods will succeed with the task within a few years.

The entrance of the beam in vertical or horizontal position seems not to be of any great importance.

The beam oscillation technique used by POSIVA, so far, seems not to be necessary, but could anyway be an advantage – it gives one more possibility to affect the welding quality. The beam oscillation technique can be of importance for closing of the keyhole.

POSIVA use a power of 45 kW compared with the 65 kW used by SKB. If the lid welds can be done with 45 kW it will be an advantage, but it still has to be proved. Normally equipment with lower power is cheaper which of course is an advantage. The mechanical properties of the lid welds need to be checked and there could be a difference in toughness due to different heat input. In that case higher power could be necessary to slow down the cooling rate of the copper material, but with lower power can POSIVA probably compensate with the beam oscillation technique and thereby reach the same result as SKB.

8 Conclusions

8.1 Main conclusions

- Both SKB and POSIVA will within a few years succeed to qualify their respective EBW method for welding of copper canisters. So far SKB has more experience than POSIVA from lid welds.
- The Reduced Pressure technique that SKB use today seems to be very promising in order to avoid root defects. If POSIVA does not succeed to avoid root defects with the high vacuum method and the beam oscillation technique it should be possible in principle for POSIVA to incorporate the Reduced Pressure technique albeit with significant changes to the EB equipment.
- POSIVA has possibly an advantage with the beam oscillation technique, which gives an extra degree of freedom to affect the weld quality. The beam oscillation could be of importance for closing of the keyhole.
- Before EBW of lids it should be checked that the material has a certification showing the alloy content (specifying min and max percentages) and the mechanical properties. The welded material needs also to be tested for mechanical properties. If possible the weld should have the same toughness as the parent material.

8.2 The EBW process developed by SKB

- From EB welding work carried out at TWI it seems that high vacuum EBW of 60 – 70 mm thick copper has a strong tendency to result in root defects. These defects are very sharp in geometry and could act as a corrosion weakness. One way to avoid them seems to be EBW with Reduced Pressure (0.1 – 0.2 mbar).

- When using reduced pressure probably an optimum pressure could be found where the desired shape of the weld is reached and at the same time the welding process will be stable, repeatable and with a minimum of spatter. It will be very important that the optimum pressure is held stable with a minimum variation which in turn means that it must be possible to control all vacuum pumps very precisely and also all seals must be of good quality and leak-tight.

- The pressure is an important parameter and it might need to be measured both inside and outside the canister during the development of the EBW process. After successful test welds it should be enough to measure the pressure on the outside of the canister.

- Before a weld starts a check of the material to be welded is needed. The material needs to have a certification showing the alloy content and the mechanical properties.

- Before the EBW starts a checklist with approx. 30 items are checked – seems to work well. Maybe the list needs to be updated regularly?

- The recording of parameters during EBW of lids is started manually– maybe an automatic start is desirable?

- When all the development work is finished the method of welding and the most important parameters should be described in a Welding Procedure Specification (WPS). The production of EBW of lids must then be performed in the way the WPS describes, without any changes of material, parameters, clamping etc. If anything needs to be changed, a re-qualification of a new WPS must be done.

- Quality on-line control systems are so far not used for EBW, but are now under development for laser welding and are expected to be on the market within a year. Maybe it will be necessary to develop a quality on-line system in order to reach the desired quality of the welds?

- A method giving better accuracy where the EB hits the lid will probably help to improve the repeatability of the EBW. A seam finding or seam tracking system could be useful!

- A long depth of focus seems desirable in order to give a good spatter protection for the gun column and at the same time a weld wide enough to give the gas in the weld pool enough time to escape from the melt before it solidifies. Maybe a continuously flow of helium will help to protect the gun and the nozzle from dust.

- The last alignment coils are used to centre the beam. This trimming is of importance so that the beam penetrates the seam symmetrically along the whole depth. An instrument for measurement of the beam will be useful to both repeat the EBW process, but also for detection of defects in the equipment performance such as harmful erosion of the cathode etc. The instrument should be able to measure the width/diameter and current distribution of the beam. By measuring of the beam at different heights the focal position could be found. The width and the energy distribution will be a function of the power. The beam will increase in size with increasing power due to the fact that a greater number of electrons in the beam will demand more space because of the repulsion of negative charges. Measuring of the beam width/intensity should therefore be measured with high power, if possible the power used for welding.

- It is more likely that weld defects will be found within weld termination region (overlap distance) than anywhere else in the weld. The termination region of the weld should be controlled and checked extremely well!

- Maybe a study of the technique that POSIVA uses for closing of the keyhole could be valuable!

- In (5) a thermo-mechanical FE-analysis of residual stresses for the EBW process of the copper canisters was done and the calculations showed that the maximum plastic strain (plastic + creep) accumulated in the (possibly brittle) heat affected zone should be about 7 % which seems to be well below the reported ductility (30%) for the copper to be used.

- In the FE-analysis it was assumed that the heat-input was given at the same time (momentarily) along the whole seam, which is not the case in a real EBW, where

the heat-input is more of a line-energy source and a function of the time. *There are substantial movements in the seam during the EBW, probably causing high strains in the weld and in the vicinity of the weld. This will probably not be caught in the FE-analysis without giving a time dependent heat-input. Some strain measurements during EBW of the lids will improve the FE-analysis and provide more reliable results.*

- *Also the ductility of the weld and the HAZ should be measured to check if its toughness is as good as the parent material as assumed in the FE-analysis.*

8.3 The EBW process developed by POSIVA

- POSIVA has simulated a very short pumping time for creating of the vacuum compared to what SKB use. It could be of importance to study what the technique used by POSIVA (pumps, sealing, materials used etc).

- POSIVA seems to have a fine technique for closing of the keyhole!

- After the lid closure weld no machining is necessary.

9 References

1   Svetsmetoder – nuläge och utveckling, IVF-report 87601, Lindén G, von Brömssen B, Sweden

2   The development of RF excited guns for high power electron beam welding, IIW Doc. IV-709-98, Sanderson A, UK

3   Three-Dimensional EB deflection and missed joint in welding dissimilar metals, 1997, Wei and Chung, China

4   The high power laser applications in Japan into the millennium 2000, Goldberg F, Svetsen Årg. 57 nr 4, 1998.

5   Thermo-mechanical FE-analysis of residual stresses and stress redistribution in butt welding of a copper canister for spent nuclear fuel, Lindgren, L-E[1,2], Häggblad, H-Å[2], Josefson, B L[3], Karlsson, L[2], [1]Corresponding author, [2] Department of Mechanical Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden, [3] Department of Applied Mechanics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden, Nuclear Engineering and Design 212(2002) 401-408

6   Ultrasonic Array technique for the Inspection of Copper Lined Canisters for Nuclear waste Fuel, T Stepinski, P Wu, M Gustafsson, L Ericsson – Uppsala University, Sweden, 7th European Conference on Non-Destructive testing, Copenhagen 26 – 29 of May 1998.

7   Electron beam welding a model of a sector of an adron absorber, V K Dragunov, V N Lastovirya, A S Khokhlovskii, A V Zaitsev, Welding International 1996 **10** (9) 717-719

8   Charged particle generation with a resonant electric circuit, Sanderson A, TWI, USA Patent No. 5661369, 26 August, 1997, European patent EP-B-0627121.