Disposal of Steam Generators from Decommissioning of PWR Nuclear Power Plants

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ABSTRACT

Amongst other materials remarkable amounts of radioactively contaminated or activated scrap are generated from the dismantling of Nuclear Power Plants. These scrap materials include contaminated pipework, fittings, pumps, the reactor pressure vessel and other large components, most of them are heat exchangers.

Taking into account all commercial and technical aspects an external processing and subsequent recycling of the material might be an advantageous option for many of these components. The disposal of steam generators makes up an especially challenging task because of their measures, their weight, and compared to other heat exchangers high radioactive inventory.

Based on its experiences from many years of disposal of smaller components of NPP still in operation or under decommissioning GNS and Studsvik Nuclear developed a concept for disposal of steam generators, also involving experiences made in Sweden. The concept comprises transport preparations and necessary supporting documents, the complete logistics chain, steam generator treatment and the processing of arising residues and materials not suitable for recycling.

The first components to be prepared, shipped and treated according to this concept were four steam generators from the decommissioning of the German NPP Stade which were removed from the plant and shipped to the processing facility during the third quarter of 2007. Although the plant had undergone a full system decontamination, due to the remaining contamination in a number of plugged tubes the steam generators had to be qualified as industrial packages, type 2 (IP-2 packages), and according to a special requirement of the German Federal Office for Radiation Protection a license for a shipment under special arrangement had to be applied for.

The presentation gives an overview of the calculations and evidences required within the course of the IP-2 qualification, additional requirements of the competent authorities during the licensing procedure as well as the shipment and processing of the steam generators including the processing results. Processing of the steam generators has been performed to a large extent, but is at the time of the IYNC still going on.

1. INTRODUCTION

Back in 2003 the NPP Stade (KKS) was the first PWR type power reactor to be taken out of service in Western Germany. Since the license for the first phase of decommissioning was granted in 2005 dismantling work has been initiated. [1][2]

Dislocation and disposal of the steam generators was scheduled for the second phase of decommissioning commencing in mid 2007. The primary circuit of the power plant was subject to full system decontamination in 2004.

Upon request of KKS different external possibilities to dispose of the steam generators were evaluated by GNS. Two ways were planned in detail and presented to KKS in commercial proposals. After assessment of the proposals KKS decided to choose the way of disposal as described below. The project can be regarded as a pilot project for other steam generators from the dismantling of PWR plants.
2. DESCRIPTION OF THE COMPONENTS

2.1 Design of the Steam Generators

The steam generators from the NPP Stade are of the bent tube type. The outer dimensions are height approx. 16 m, steam dome diameter approx. 3.6 m, diameter at tube bundle 2.9 m and weight 165 metric tons.

The channel head with hot leg and cold leg is separated by a plate. The tube sheet holds approx. 3000 bent tubes.

On the secondary circuit side of the steam generator there is an approx. 16 mm thick inner coat, the so-called wrapper. Above the tube bundle the vessel widens to form the steam dome with its internals that separate moisture from the steam.

2.2 Radiological Description of the Steam Generators

During operation of the Power Plant reactor water flowed through the tubes and the channel head, and their inner surfaces were contaminated by fission and activation products.

Surfaces on the secondary side like the outer surfaces of the tube, the SG shell, the steam dome and its internals only came in touch with secondary coolant. The neutron flux at the steam generators position was negligible. There is no activation of the material itself.

Table 1: Contamination in the tubes prior to full system decontamination

<table>
<thead>
<tr>
<th>Reference Date 03/2004</th>
<th>Cold Leg</th>
<th>Hot Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}\text{Co}$</td>
<td>$1.7\times 10^{12}$ Bq</td>
<td>$1.3\times 10^{12}$ Bq</td>
</tr>
<tr>
<td>$^{60}\text{Co}$ plus 30% safety margin</td>
<td>$1.1\times 10^{05}$ Bq/cm$^2$</td>
<td>$8.6\times 10^{04}$ Bq/cm$^2$</td>
</tr>
<tr>
<td>$^{60}\text{Co}$ plus 30% safety margin</td>
<td>$1.5\times 10^{05}$ Bq/cm$^2$</td>
<td>$1.1 \times 10^{05}$ Bq/cm$^2$</td>
</tr>
</tbody>
</table>

As the tubes were being checked during planned outages and tubes, where a reduction of the wall thickness was detected, were plugged before a leakage from primary circuit to secondary circuit could occur, a contamination of the secondary side could be avoided. This was also proved by measurements.

The complete primary circuit of Stade was cleaned in the course of a full system decontamination. The decontamination factor reached for the steam generator was approx. 160. The remaining
contamination on primary side surfaces was determined by smear tests and scratch samples. The contamination detected in the channel head was less than $2.5 \times 10^4$ Bq/cm². In order to determine the remaining contamination in the tubes the dose rate was measured around the SG in different heights. Additionally the contamination inside plugged tubes had to be determined as well. As a first step it was said that the contamination in the last tubes that had been plugged was maximum as high as the contamination in unplugged tubes before the full system decontamination, but there were different conditions for tubes that had been plugged years ago. From dose rate measurements that had been performed in the channel heads during the planned outages and before decontamination the referring contamination of Co-60 was calculated. By correlation from the results of samples from the primary circuit the contribution of Ni-63 and Fe-55 could be determined. These values could be verified by dose rate measurements for plugged tubes next to the coat. [3]

Table 2: Maximum of contamination inside tubes calculated for 2007, example SG3

<table>
<thead>
<tr>
<th></th>
<th>$a_{\text{Co-60}}$ [Bq/cm²]</th>
<th>$a_{\text{Ni-63}}$ [Bq/cm²]</th>
<th>$a_{\text{Fe-55}}$ [Bq/cm²]</th>
<th>$a_{\text{total}}$ [Bq/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unplugged tubes (decontaminated)</td>
<td>$6.6 \times 10^2$</td>
<td>$7.2 \times 10^2$</td>
<td>$1.7 \times 10^2$</td>
<td>$1.6 \times 10^3$</td>
</tr>
<tr>
<td>Plugged tubes</td>
<td>$9.2 \times 10^4$</td>
<td>$5.5 \times 10^5$</td>
<td>$4.7 \times 10^3$</td>
<td>$6.4 \times 10^5$</td>
</tr>
</tbody>
</table>

3. PROCEDURE FOR THE PROCESSING OF THE STEAM GENERATORS

3.1 Shipping Concept

3.1.1 Transport Regulations

All nozzles and connections of the steam generators were cut, capped and welded leak tight prior to shipment. According to ADR/IMDG-Code the inner surfaces are inaccessible surfaces.

Table 3: Limits according to ADR/IMDG-Code for surface contaminated objects [4]

<table>
<thead>
<tr>
<th>Values in (brackets) $\alpha$-emitters</th>
<th>SCO I</th>
<th>SCO II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed contamination, accessible surfaces [Bq/cm²]</td>
<td>$4 \times 10^4$ ($4 \times 10^3$)</td>
<td>$8 \times 10^5$ ($8 \times 10^4$)</td>
</tr>
<tr>
<td>Non-fixed contamination, accessible surfaces [Bq/cm²]</td>
<td>4 (0.4)</td>
<td>400 (40)</td>
</tr>
<tr>
<td>non-fixed contamination plus fixed contamination, inaccessible surfaces [Bq/cm²]</td>
<td>$4 \times 10^4$ ($4 \times 10^3$)</td>
<td>$8 \times 10^5$ ($8 \times 10^4$)</td>
</tr>
<tr>
<td>qualification of the package</td>
<td>not required</td>
<td>IP-2</td>
</tr>
</tbody>
</table>

If you compare the values of contamination in plugged tubes, which is the highest level of contamination in the SG, with the SCO-II limits you will find that the limit of $8 \times 10^5$ Bq/cm² for $\beta$- and $\gamma$-emitters and low toxic $\alpha$-emitters is not exceeded. This would mean that the SG could be shipped as SCO-II material. But as it cannot be excluded completely that there is an inhomogeneous distribution of contamination, the Federal Office for Radiation Protection could not agree with a classification of the steam generators as SCO-II material and recommended to transport the components under a special arrangement (UN 2919).
### 3.1.2 Qualification of the Steam Generators as an IP-2 package

SCO-II material has to be shipped in IP-2 packages. As there are no IP-2 containers to carry components of the size and weight of the steam generators it had to be proved that the steam generators themselves fulfill the conditions for an IP-2 package which are given by the IAEA recommendations and ADR/IMDG-Code.

For a shipment under a special arrangement this evidence is necessary as well. Compensating measures make sure that the overall level of safety is at least equivalent to that which would be provided if all applicable requirements had been met. [4]

In cooperation with the Federal Office for Materials Research and Testing (BAM) two different drop orientations were chosen for which it was proved, using finite element method, that in case of a drop from 30 cm height a loss or dispersal of the radioactive contents and more than 20 % increase in the maximum radiation level at any external surface of the steam generators can be avoided.

A stacking test was not necessary because of the form of the steam generators.

### 3.1.3 Transport Sequence

The steam generators were taken over by GNS under the gantry crane after the steam generators had been discharged from the reactor building. This was originally planned to be carried out within two consecutive weeks, one steam generator every two or three days. Finally because of other work performed in the reactor building the discharging had to be carried out one week after the other. The steam generators were lowered down from the gantry crane onto a heavy load truck which was already equipped with racks.

![Fig. 2: Route of Transport at NPP Stade Premises][2]  

The steam generators were stored temporarily on a parking space on site of the plant. All transports could be carried out using the same vehicle. After arriving of the floating crane and the transport vessel the steam generators were carried to the pier “Jungbrücke” which belongs to the site.
they were handled with the floating crane and a special lifting traverse, provided by KKS, and loaded onto the transport ship, the Swedish special cargo ship MS SIGYN.

Fig. 3: Loading one SG onto MS Sigyn

After lashing, the ship took the route via River Elbe, Kiel Canal and Baltic Sea to the harbour of the Studsvik Nuclear. There the steam generators were unloaded using RoRo-technique and carried to the workshop.

Fig. 3: Unloading at Studsvik
3.2 Cutting Off of the Steam Dome and Internals

As already mentioned in chapter 2 the secondary side of the steam generators was not contaminated. Therefore as far as the absence of any contamination is proved by measurements the competent Swedish authority gave its approval to release the steam dome coat according to the Swedish regulations without melting (which is otherwise mandatory according to Studsvik’s license).

So the steam domes were being cut off using thermal cutting equipment and a wire saw prior to any other processing or sizing measures. The whole (internal and external) surface of the steam domes is subject to contamination measurements. The steam dome internals were melted because of their geometry in order to reduce time and effort for measurements. Subsequently the material was released directly. The remaining part of each steam generator was capped with a thin plate to avoid contamination dispersal during the following decontamination of the tube bundle.

3.3 Decontamination of the Tube Bundle

In order to open plugged tubes for access during decontamination the steam generators were cut across through the tube sheet using a band saw. Prior to cutting and further treatment of the tube bundle, the inner surfaces of the tubes were decontaminated by blasting. Thus the radiation exposure for the personnel was reduced significantly. Each tube was blasted separately with the injector being positioned by an industrial robot. Based on experiences from the treatment of other heat exchangers a decontamination factor of approx. 70 is expected. Unexpectedly a factor of approx. 350 could be reached.

3.4 Sizing of the Tube Bundle

Assuming that a decontamination factor of approx. 70 was reached, it has been envisaged to perform the sizing of the tube bundle in a shielded cutting cell using an industrial robot that can carry different cutting tools (shear, circular saw, grinder).

The cutting cell should be moved over the steam generator with the gap between the SG shell and the cell being closed by a rubber sealing and the cutting cell being held at low-pressure.
The decontamination factor actually reached allowed to disassemble the tube bundles in a conventional way. That means that is was not necessary to use the aforementioned special shielded cutting cell. All tube bundles could be segmented in a cutting hall without special protection by using mechanical and thermal cutting methods.

3.5 Milling of the Channel Head Cladding

During the treatment of parts of the channel heads and tube sheets it was discovered that the cladding on the surfaces that had been in contact with primary coolant, were very rough and contamination had penetrated the surface into micro cracks. Thus the decontamination by sandblasting was not as successful as expected. In order to reach the aim to release as much as material as possible Studsvik Nuclear made available a CNC milling machine which will now remove the cladding in its entirety.

3.6 Melting

It was envisaged to melt all parts of the steam generators with the exception of the steam dome shells. There are basically three reasons for melting:

1. By melting remaining contamination which could not be removed will be bond within the materials. That means that only compliance with mass specific limits has to be proved during the release procedure. Surface contamination limits are met in any case. Parts of the steam generators especially with higher wall thickness which exceed contamination limits prior to melting can be released after melting.
2. Release measurements are simplified considerably as the release of one furnace batch of approx. 3.5 metric tons can be made by measuring a small sample of less than a pound.
3. Even if there is material that cannot be released, the volume of such material can be reduced substantially, more than with any other processing method.

Hence all material resulting from the tube bundle, tube sheet, coat and the channel head was cut to size for melting. Subsequently all material was compiled to melting batches taking into account as well radiology as metallurgy of the material.

![Fig. 4: Casting of ingots](image)

One melting furnace batch usually consists of approx. 3.5 metric tons of material. After all material of one batch is melted, the melt is overheated and cast into moulds. There are 5 to 6 ingots with a weight of approx. 600 kg resulting from one melting furnace batch.
3.7 Release

In Sweden a release of material is performed in execution of the European guideline RP 89 and its guidance levels. In case of the steam generators from Stade a decay storage of limited amounts of material for up to ten years beginning with the day of receipt of the material was permitted by the authority under certain conditions. Currently no material affording decay storage accrued.

Ingots can be stored in a lightweight construction hall after the measurement results are available until they reach the release limits or until they are shipped back to Germany.

4. BALANCE OF WASTE

Based upon the radiological data described in chapter 2.2 it was assumed that

- the shells of the steam domes will be released without melting,
- the ingots resulting from melting of the coat around the tube bundles, steam dome internals, at least part of the tube sheets, the channel heads and part of the tube bundles will be released,
- solely parts of the tube sheets and tube bundles will have to be taken back as ingots and will be shipped to the interim storage facility LaRA which was erected on site of the NPP Stade packaged in steel sheet containers, so-called KONRAD containers type II,
- in addition to the aforementioned ingots there will be residues from decontamination (blasting residues) and from melting (slag) that have to be taken back as well.

For residues resulting from melting of batches, that are suitable for decay storage or direct release, there is a good chance that these residues will meet the limits according to the German Radiation Protection Ordinance for a release for disposal on conventional waste dump. This would furthermore reduce the amount of material that would have to be disposed of as radioactive waste. The amounts and volumes given below display a very cautious estimate.
The situation for ingots that have to be taken back is quite similar. After some half lives at Co-60 these ingots reach the guiding values according to the German Radiation Protection Ordinance for release for disposal on a conventional waste dump. Two more half lives and the limits for release for recycling are reached.

### Table 4: Expected Waste from Steam Generator Processing

<table>
<thead>
<tr>
<th>SG part</th>
<th>metal processing</th>
<th>waste volume</th>
<th>waste weight</th>
<th>waste processing</th>
<th>final volume</th>
<th>waste packages</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>steam domes</td>
<td>melting (back up)</td>
<td>slag and residues from cutting 4-6 m³</td>
<td>ca. 6 Mg</td>
<td>free release</td>
<td>0 m³</td>
<td>-</td>
<td>Steam domes will be cut off prior to further handling, no risk of contamination dispersal</td>
</tr>
<tr>
<td></td>
<td>release without melting (approval of SSI/SKI provided)</td>
<td>cutting residues 1 m³</td>
<td>ca. 2 Mg</td>
<td>free release</td>
<td>0 m³</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>steam dome internals</td>
<td>melting</td>
<td>slag and residues from cutting 1 m³</td>
<td>ca. 1 Mg</td>
<td>free release</td>
<td>0 m³</td>
<td>-</td>
<td>see above</td>
</tr>
<tr>
<td>coats</td>
<td>blasting</td>
<td>blasting residues 1 m³</td>
<td>ca. 2 Mg</td>
<td>supercompaction</td>
<td>0,5 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>slag and residues from cutting 5-7 m³</td>
<td>ca. 7 Mg</td>
<td>supercompaction</td>
<td>3 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td>tubes</td>
<td>blasting</td>
<td>blasting residues 3-5 m³</td>
<td>ca. 8 Mg</td>
<td>supercompaction</td>
<td>2 m³</td>
<td>concrete container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>ingots 10-12 m³</td>
<td>ca. 88 Mg</td>
<td>packaging</td>
<td>22 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>slag and residues from cutting 1-2 m³</td>
<td>ca. 2 Mg</td>
<td>supercompaction</td>
<td>0,5 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td>tube sheets</td>
<td>blasting</td>
<td>blasting residues 2-4 m³</td>
<td>ca. 6 Mg</td>
<td>supercompaction</td>
<td>2 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>ingots 12-14 m³</td>
<td>ca. 92 Mg</td>
<td>packaging</td>
<td>22 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>slag and residues from cutting 2-3 m³</td>
<td>ca. 3 Mg</td>
<td>supercompaction</td>
<td>1 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td>water chamber</td>
<td>blasting</td>
<td>blasting residues 1 m³</td>
<td>ca. 2 Mg</td>
<td>supercompaction</td>
<td>0,5 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>melting</td>
<td>slag and residues from cutting &lt; 1 m³</td>
<td>ca. 1 Mg</td>
<td>supercompaction</td>
<td>0,5 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td>miscellaneous</td>
<td>mixed waste</td>
<td>foils, protective clothing, masks etc. 10 m³</td>
<td>ca. 2 Mg</td>
<td>incineration</td>
<td>0,1 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>off-gas system</td>
<td>filter dust 1-2 m³</td>
<td>ca. 0.3 Mg</td>
<td>supercompaction</td>
<td>&lt; 0,1 m³</td>
<td>steel sheet container</td>
<td></td>
</tr>
</tbody>
</table>

After processing of the steam generators most of the initial activity was found in the waste from decontamination. These residues shall be supercompacted. They will have to be packed into a shielded (heavy concrete) container.

As far as residues from melting (slag) are not suitable for release they will be supercompacted as well and packed into steel sheet containers, so called KONRAD-Containers.
5. SUMMARY

Based on experience from the processing of steam generators by Studsvik Nuclear, GNS developed a procedure for the external processing and disposal of steam generators from German NPPs. The concept focused on a minimization of the radiation exposure of the personnel, the utilization of most of the material and a minimization of radioactive waste.

The external processing and disposal of steam generators relieved internal disposal capacities and internal logistics to a large extent. This will lead to a reduction of the total decommissioning period in a range of several months. The evidence that the steam generations fulfil the requirements for an IP-2 package was a challenging task. This evidence was successfully produced.

The process resulted in a very small volume of radioactive waste that can even be reduced furthermore if dependent on the decay of the activity all options for a possible release of waste are exercised in the future.

REFERENCES