D&D of the Callisto PWR Loop as part of the Refurbishment of the BR2 Research Reactor – 16168

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ABSTRACT

Research reactor BR2 is undergoing a thorough maintenance and modernisation operation until mid-2016. In order to be able to use the reactor safely and efficiently in the coming period of 10 years, a preventive replacement of the beryllium matrix was required as a major step in the refurbishment. At the same time, a number of preventive maintenance and modernisation activities have been defined, including the dismantling of the CALLISTO[1] PWR experimental facility for in-pile studies installed into BR2 for more than 20 years.

The CALLISTO end of life decommissioning strategy aims for waste, cost and dose uptake minimisation and includes:

- the unloading and removal of the in-pile sections;
- a closed-loop full system decontamination for dose reduction;
- the complete dismantling of the loop;
- the further sorting and segmentation in a dedicated workshop;
- a hard chemical batchwise decontamination for unconditional clearance.

The operation is planned in the period of mid-2015 until mid-2016. The paper will describe in detail these subsequent steps, with a focus on decontamination and dismantling. Lessons learned and potential benefits towards the D&D of commercial PWR will be highlighted.

INTRODUCTION

BR2 is one of the world's principal high-flux materials testing reactors, with a number of unique features in terms of reactor geometry, performance, flexibility and experimental accessibility. Since the start of its operation in 1963, BR2 has undergone already two major refurbishment periods. The ageing of the core material under irradiation has required the replacement of the beryllium blocks composing the reactor core matrix. In combination with the decennial safety reassessment with particular attention to the impact of ageing on safety, it was decided to subject the reactor to a third major refurbishment campaign (2015-2016).

CALLISTO has been one of BR2's principal irradiation experiments since the early 1990s, used for PWR fuel and material studies. Three reactor channels have been used for this purpose, with a common pressurised loop installed principally in the

[1] CALLISTO: Capability for Light Water Irradiation in Steady State and Transient Operation

room directly underneath the lower reactor vessel head. The ageing of the loop required its removal and replacement with new flexible devices for material and fuel testing during the reactor's fourth operational period (2016-2026). Due to difficult access conditions, elevated dose rates caused by deposition of activation products and potentially high waste costs, a dismantling strategy was developed for CALLISTO including decontamination steps aiming dose rate reduction and unconditional clearance.

BR2 REACTOR REFURBISHMENT

BR2 Reactor

BR2 is a light water cooled, water + beryllium moderated tank-in-pool type materials testing reactor. The beryllium reactor core matrix is placed in an aluminium pressure vessel in the shape of a circular hyperboloid, as such creating a unique geometry of a compact core with good top and bottom access to the reactor's 79 channels in which nuclear fuel elements, control rods and various experiments can be placed. [1]

The general lay-out is given in Figure 1, which shows a cross-cut view of the containment building and the machine hall. The reactor vessel is located in the reactor pool, with the room underneath the lower vessel head containing CALLISTO's main circuit. This room is called sub-pile room (SPR), and consists of four narrow work platforms.

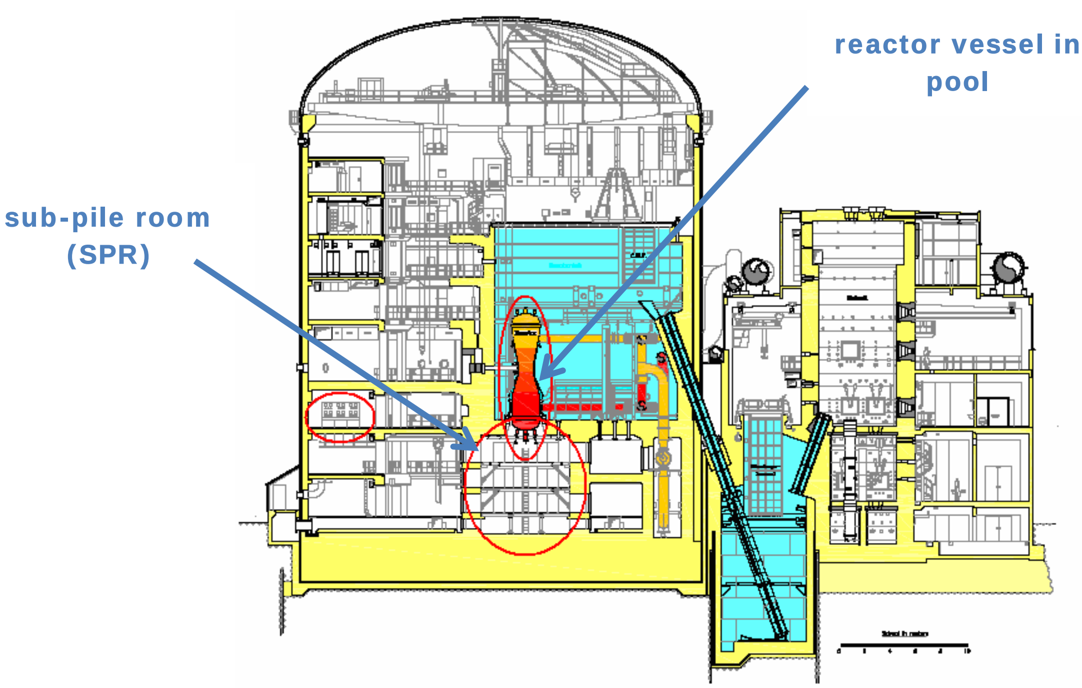

Figure 1: General lay-out of BR2

BR2 has been and – after refurbishment - will be mainly used for:

- Production of Mo-99 by the irradiation of uranium targets;
- Production of isotopes for medical and industrial purposes by neutron irradiation;
- Irradiation of materials, both for nuclear power plants and for fusion projects;
- Irradiation of silicon crystals for semiconductor fabrication;
- Testing of new fuel for research and test reactors in the framework of conversions to low enrichment fuel;
- Testing of new power plant fuels, eventually in transient conditions.

BR2 Reactor Refurbishment

In order to be able to use the reactor safely and efficiently in the coming period of 10 years, a preventive replacement of the beryllium matrix was required. New matrix parts have been ordered abroad and assembled in-house, with a validation of the new matrix assembly in the mock-up vessel. The removal of the existing matrix from the reactor has been performed mid-2015, with the actual installation of the new matrix begin-2016.

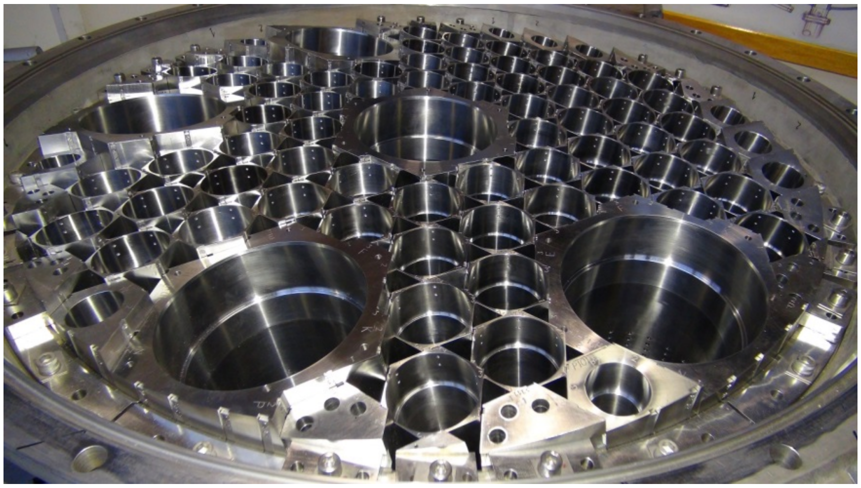

Figure 2: New reactor core, fully assembled in the mock-up vessel

The required fracture toughness for the aluminium reactor vessel is guaranteed until at least 2026, and as such poses no problems for the next operational period. After the removal of the beryllium matrix a thorough inspection of the vessel has been performed for the presence of cracks, as obliged by the operational license. This inspection showed that all of the founded indications are acceptable. As such, the reactor vessel is still fit for operation until at least 2026. An on-going surveillance program will continue to generate data for the period 2026-2036.

Water cooling is one of the vital safety factors in the reactor's operation. Some major maintenance activities have been performed on these water cooling systems. The aged underground piping of the secondary circuit has been replaced, and the cooling towers have been refurbished including the replacement of the fans and the preventive replacement of the towers' inner liner.

The neutron beam tubes were used in the past for research purposes as they are preferential paths for neutrons from the reactor core to escape through the bioshield, and hit the target of interest. These beam tubes had become an obsolete application, and presented a risk of reactor pool leak. A cutting and seal surface machine has been engineered to establish the removal of the tubes and an upgrade of the seals between the pool wall and the beam ports.

The CALLISTO irradiation facility for PWR fuel and material testing has ended its service in 2015 with the unloading from the reactor in preparation of the beryllium matrix replacement. The ageing of the loop called for large investments which could not be justified by large projects. More details on its decommissioning will be highlighted in the following paragraphs.

After the refurbishment BR2 will continue to play a key role in the production of neutron transmutation doped silicon and various radio-isotopes. Thanks to the new reactor core, the production capacity will be higher and more flexible. An increase in availability of the reactor up to 190 days per year is considered. The BR2 reactor will in fact be capable of meeting the global demand for Mo-99 when necessary. In terms of nuclear fuel and material irradiation experiments, SCK•CEN provides a full scope R&D capability on fuel and structure material research, with some new flexible irradiation devices under development for use in the next operational period.

CALLISTO DECOMMISSIONING

CALLISTO PWR Loop

The high pressure and high temperature experimental water loop CALLISTO in the BR2 reactor has been used extensively for various irradiation studies, making use of its three experimental rigs – called in-pile sections (IPS) – which were installed in three of the reactor channels. These IPS were connected to a common pressurised loop, which could deliver a wide range of pressure and temperature regimes.

CALLISTO consisted of a main loop (high pressure and temperature) inside the SPR including following components:

- A pump block with three main circulating pumps in parallel;
- Electrical heater;
- Pressurizer;
- Main cooler (HX111);
- By-pass line between cold and hot legs of the three IPS.

The CALLISTO feed/bleed loop (low pressure and temperature) - both inside and outside the SPR - controlled the system volume/pressure and the water quality. It consisted of:

- Bleed coolers (HX370/HX371);

- Ion exchange column filled with mixed bed resins;
- Make-up tank, surge tank and delay tank;
- Two charging pumps in parallel;
- Two filter units.

The total water volume of the loop in operation was in the order of 1 m^3, with a water chemistry representative of that of a PWR primary circuit and piping diameters in the range of 1/2" up to 3".

CALLISTO Decommissioning Strategy

During the lifetime of CALLISTO, the three IPS have become highly radioactive by neutron activation, while the deposition of (mainly) activated corrosion products on the interior surfaces of the components of the CALLISTO system throughout the years has led to elevated dose rates in the vicinity of the loop, especially inside the narrow SPR. A partial chemical decontamination operation on CALLISTO's main loop highly irradiating components has already been performed in 2011. The evolution of dose rates inside the SPR is illustrated in Figure 3, plotting registered values on a number of fixed measuring points (MP) over time.

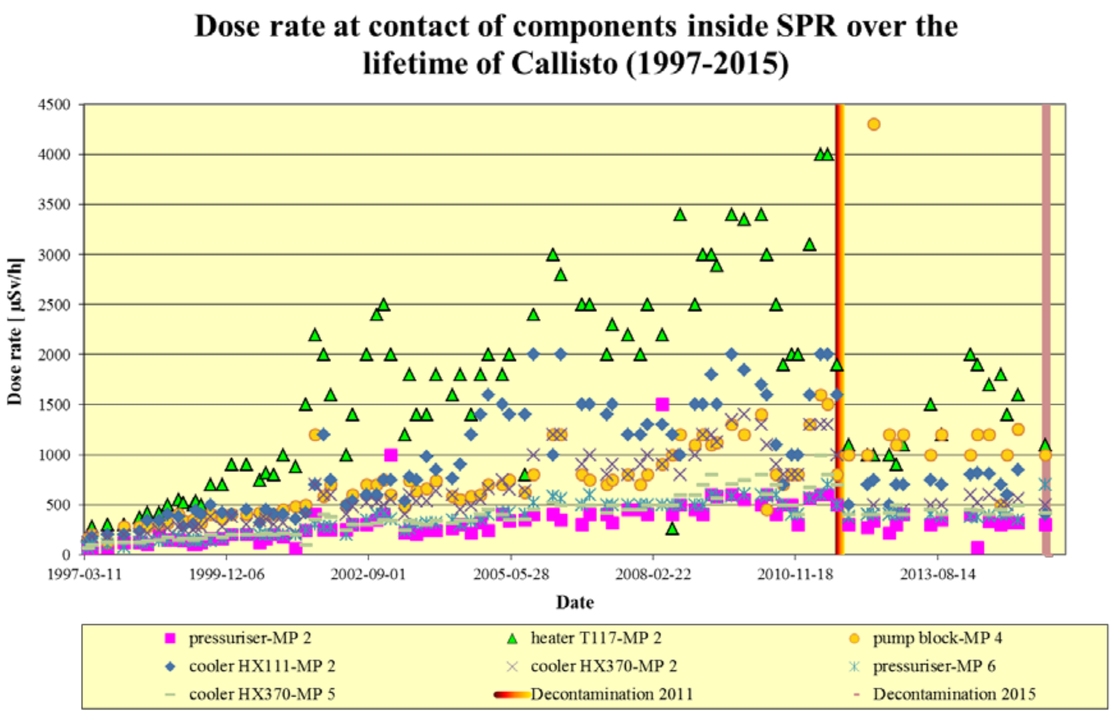

Figure 3: Evolution of dose rates in SPR during CALLISTO exploitation

Figure 3 shows the effect of the partial decontamination operation of 2011, but also reveals that the dose rates remain considerably high for a labour intensive hands-on dismantling in a room (SPR) of limited dimensions which is full of CALLISTO equipment, mainly stainless steel. Ambient dose rates were in the order of 300-400 µSv/h, with contact hotspots well over 1 mSv/h.

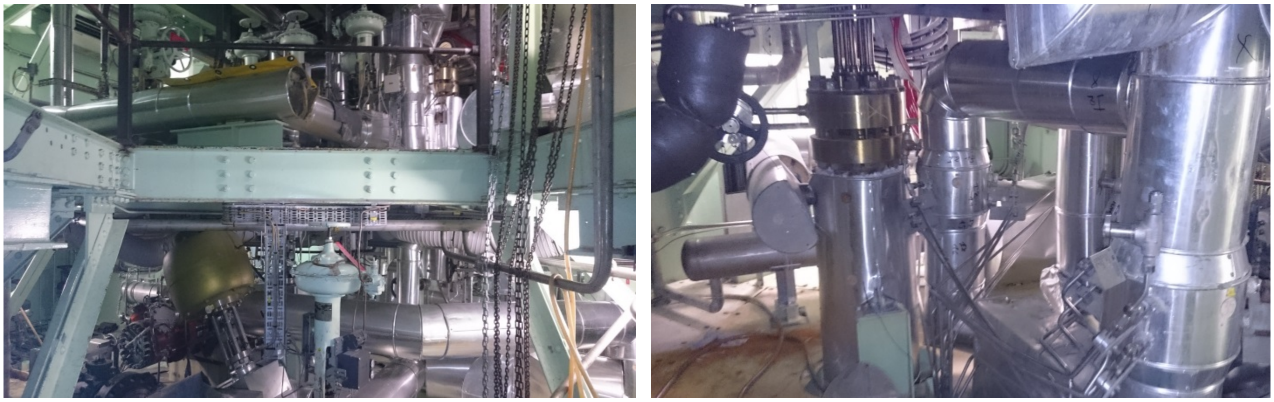

Figure 4: Impressions of CALLISTO main loop over the different levels of the SPR

The decommissioning strategy therefore involves:

- Unloading of the three IPS, transfer to BR2 hotcell for cutting-up and disposal as radioactive waste;
- Chemical decontamination of the water loop, with the focus on the components inside the SPR and the goal of maximal dose rate reduction;
- Conditioning of the operational ion exchange resins for disposal as radioactive waste;
- Transfer of the two filters to BR2 hotcell for cutting-up and disposal as radioactive waste;
- Removal of all non-radioactive equipment for disposal as industrial waste;
- Removal of all radioactive equipment inside and outside the SPR for
  - Disposal as radioactive waste;
  - Further handling in the BR3[2] controlled area
    - Cutting-up;
    - Thorough chemical decontamination of the cut-up pieces, with the goal of unconditional clearance.

IPS Removal

The three IPS have been neutron activated and highly contaminated over the years. Their decommissioning involves the following steps:

- Unloading of the IPS;
- Separation of the IPS from the common pressurised loop in the SPR by cutting of all the connections;
- Removal of the IPS and temporary storage in BR2's storage channel;
- Transfer to BR2 hotcell for cutting-up and disposal;
- Reclosing of the pressurised loop by welding of pipe bends on the created openings (for future loop decontamination);

[2] BR3: Reactor at SCK•CEN in dismantling, equipped with facilities for radioactive waste treatment and conditioning

- Testing of the new connections on leaktightness and pressure resistance (for future loop decontamination).

Chemical decontamination

The performance of a closed-loop chemical decontamination operation demands the connection of a specific installation for decontamination to the loop. The performed partial decontamination operation in 2011 allowed us to:

- Reuse the installations for decontamination and resin transfer;
- Follow the same proven decontamination protocol in terms of chemicals and follow-up;
- Use the then executed procedures as a starting point;
- Use the same type and quantities of resin for purification.

The decontamination installation was mounted on three skids for ease of manipulation and flexibility on the skids' mutual distance with the goal of limiting personnel exposure during execution.

Figure 5: Installation for decontamination in the BR2 containment building

The connections between the installation for decontamination and the CALLISTO loop were made outside the SPR for ease of access. The entire CALLISTO system inside the SPR was included in the decontamination loop, with the three main circulating pumps in use for high flow rates. To increase the flow rate over the pressuriser an extra temporary connection was established inside the SPR. Once connected to the loop, control of the decontamination was done simultaneously from both the CALLISTO and decontamination operation panel.

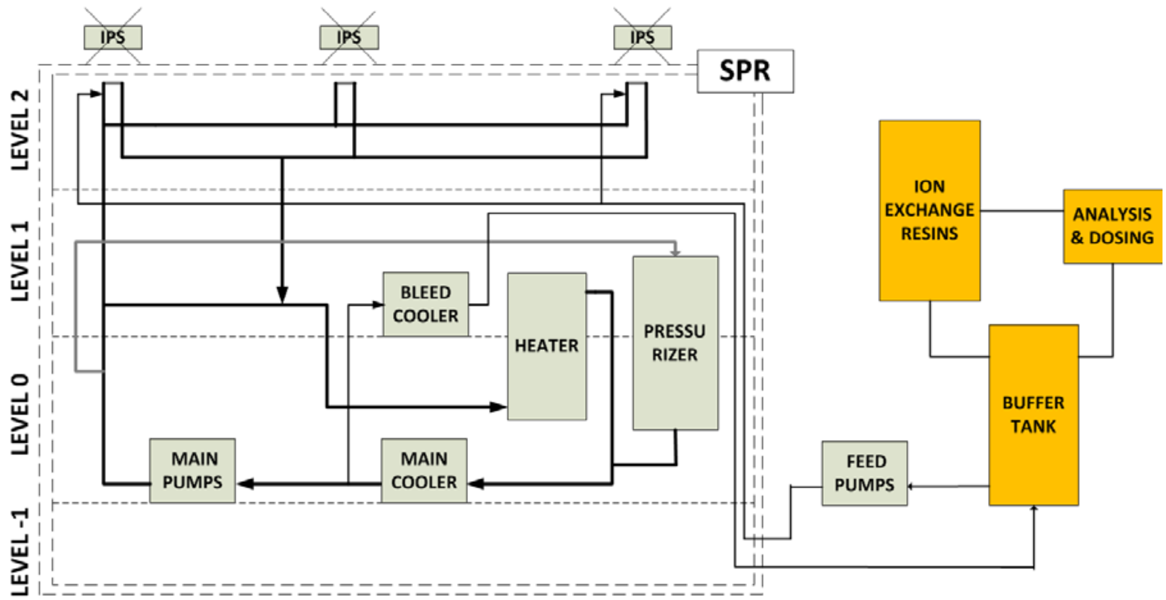

Figure 6: Decontamination flow diagram

The installation was cold tested for leaktightness check of the flexible hoses and for review of the working procedures, so that improvements could be implemented and risks eliminated. Special attention in the test program was paid to the evacuation of the resins from their columns into specific waste containers. A training program for the operators was set up. A list of working procedures was written, covering all parts of the decontamination project, starting from the preparation activities on the loop and utilities over the actual decontamination to the secondary waste conditioning. Each procedure contained in detail the different steps for execution, together with the necessary safety precautions. ALARA estimations using the Visiplan[3] dose assessment program were used for evaluation of radiological safety measurements to be taken in terms of zoning, shielding and monitoring.

The decontamination protocol involved a number of repetitive cycles, each containing the following steps:

- Oxidation with $HNO_3/KMnO_4$ for chromium dissolution;
- Decontamination with $H_2C_2O_4$ for activity removal;
- Purification with ion exchange resins for solution clean-up.

The heating of the decontamination solution was delivered from the CALLISTO heater, with an adapted control in the nominal temperature range of the decontamination loop. The purification loop with the ion exchange resins was limited to a lower temperature of 40°C. All excess decontamination chemicals and dissolved corrosion products were to be captured by the cationic and anionic exchange resins, together with the dissolved activity.

[3] The VISIPLAN 3D ALARA planning tool is developed by SCK•CEN to assist the person responsible for ALARA on a nuclear site. The tool provides the possibility to plan the work in a 3D environment taking into account the geometry, material and radioactive source specifications. It allows assessing the individual and collective dose uptake for a defined work scenario and enables through comparison of work scenario's the optimization needed for efficient ALARA planning.

Three types of specific measurements were performed to follow and control the decontamination process:

- On-line measurements of temperature, pressure, flow rate, level, pH, redox potential, conductivity and SPR's ambient dose rates;
- Liquid sampling at regular intervals for immediate radiochemical (gamma spectroscopy using ISOCS[4]) and chemical (titration) analysis for short-term intervention on the process. A temporary, mobile lab was installed in the vicinity of the work area for these direct measurements;
- Liquid sampling at regular intervals for radiochemical (gammaspectroscopy) and chemical (ICP-MS[5]) analysis for global evaluation.

A large number of measurement points inside the SPR were fixed for evaluating the decontamination efficiency by dose mapping before and after each decontamination cycle.

The decontamination operation was done with teams of three persons in a 24h working regime. A total of six decontamination cycles have been executed, with a hold point and slight change in decontamination flow path after cycle 4.

The decontamination targets were to minimise the total activity inventory and lower ambient dose rates to values under 50 µSv/h to limit futur personnel doses during decommissioning. TABLE I summarises the main results.

TABLE I: Main decontamination parameters

Process Parameters	
Decontamination Time	7 days
Main Loop Temperature	95°C
Main Loop Pressure	6 bar
Main Loop Flow Rate	8-10 kg/s
Corrosion Products (Fe, Cr, Ni)	600 g
Total Activity Removed (Co-60)	16E+09 Bq
Radiation	
Dose Reduction Factor Overall	10
Collective Radiation Exposure	4 man.mSv
Waste	
Ion Exchange Resins	250 kg
Filters (<2 mSv/h)	10

[4] ISOCS™: In Situ Object Counting Systems, Canberra
[5] ICP-MS: Inductively Coupled Plasma Mass Spectrometry

Ambient dose rates over the different levels of the SPR have been reduced on average by a factor 10 to values in the magnitude of 30 µSv/h. Contact dose rates have also been significantly reduced, with over 95% of the measurement points lower than 100 µSv/h. Figure 7 clearly highlights the effect of the decontamination operation on some representative measuring points (MP) in the SPR. The only remaining hotspots are situated at the bottom part of the pressuriser and the water chamber of the bleed cooler, caused by local low flow rates. Estimated gain on collective dose uptake for the cutting and removal of the loop from the SPR lies in the order of 100 man.mSv.

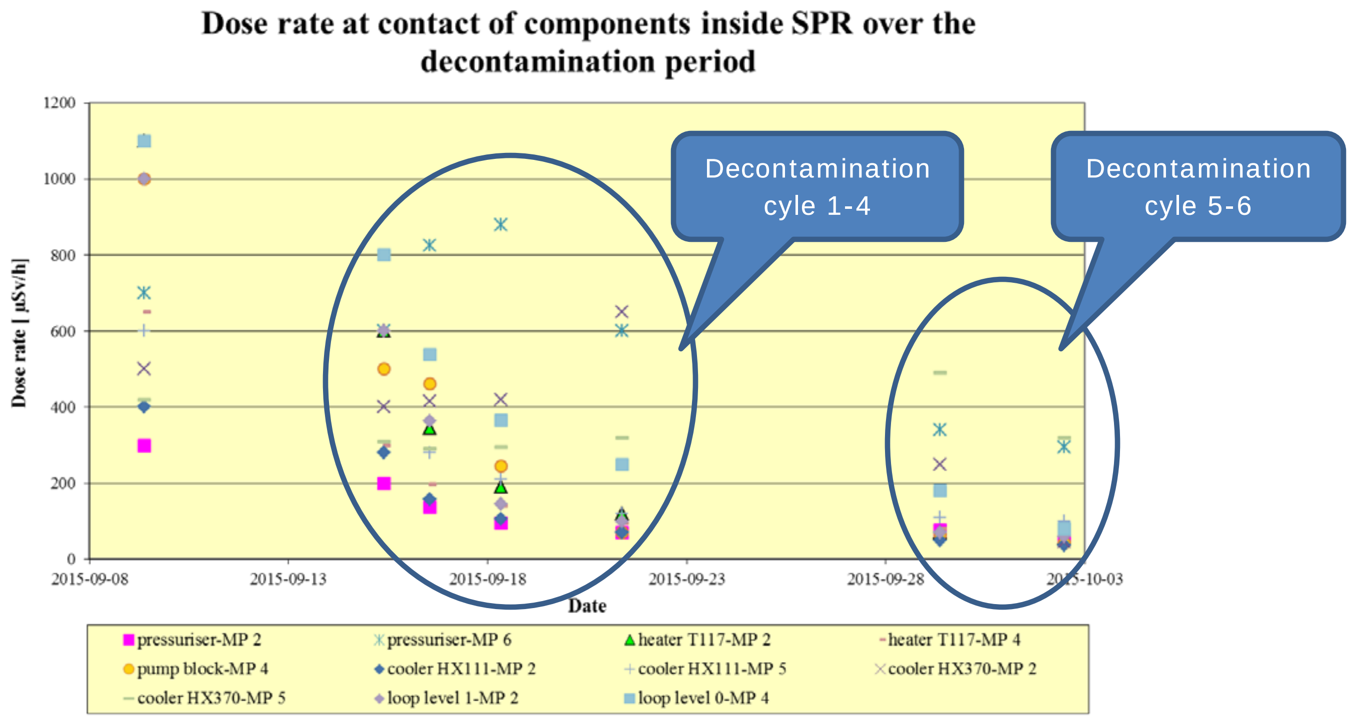

Figure 7: Evolution of dose rates in SPR among period of decontamination

After discharge of the decontamination solution as low active waste water, the highly irradiating spent ion exchange resins have been transferred to waste drums for transfer, conditioning and storage at the national waste repository.

Operational Waste Evacuation

The ion exchange resins used for purification of the CALLISTO water during operation (~ 30 liters) have been removed from their column to a waste drum in the same manner as the ion exchange resins used for decontamination. Figure 8 shows the sytem configuration during this remotely operated transfer operation. These resins will be evacuated as medium active waste.

Figure 8: Resin transfer set-up with shielded containers

The two filter units used for purification of the CALLISTO water during operation are composed of a stainless steel filter (housing) surrounded by a lead castle. They contain high levels of deposited activity. They will be separated from the rest of the loop and transferred to BR2's hotcell for further handling and conditioning for evacuation as medium/high active waste.

Equipment Dismantling

The CALLISTO system consists of a number of circuits with different levels of contamination, situated both inside and outside the SPR, such as:

- CALLISTO water loops (main loop, feed/bleed loop, make-up circuit, analysis circuits, waste circuit);
- Cooling water circuits;
- Gas circuits;
- Ventilation circuits;
- Electrical systems.

The construction of CALLISTO is such that a considerable amount of equipment will be cut up or dismantled in situ using hands-on methods. As a result of the performed chemical decontamination, radiation levels around this equipment are low enough to make such work possible in a justified manner. The larger items (tanks, pressuriser, heater, coolers, pump block) will be transported as a whole to a confined workshop at BR3 for hands-on cutting in a controlled environment.

The dismantling will start outside the SPR, with non-radioactive components such as electrical cabinets, gas lines, cooling water piping, … All connections with the SPR will be separated and shut off. The smaller radioactive equipment outside the SPR will be cut and assembled in drums for evacuation (Ø < 1/2") or further decontamination. Before cutting operations start inside the SPR, all loose parts and thermal insulation have to be removed for accessibility to the actual CALLISTO loop(s).

A systematic approach is maintained inside the SPR, starting with the cutting of the piping, valves, instrumentation between the large components using industrial equipment as grinders and reciprocating/band saws, always taking into account the origin and further destination of the material. The larger components will then hereafter be removed from the SPR one at a time.

Further Treatment

Contaminated pipework (Ø ≥ 1/2") and all larger components are transferred from BR2 to BR3 for further treatment. This material will eventually be offered to the in-house hard chemical decontamination workshop, and therefore has to be cut and conditioned accordingly. The cutting and size reduction workshop at BR3 allows for a safe and controlled handling of contaminated material, both for the operators doing the hands-on cutting as for the environment to be kept free from contamination.

Figure 9: In- and outside view of the cutting and size reduction workshop at BR3

Aiming unconditional clearance of contaminated material originating from a PWR loop requires the thorough decontamination of the interior surfaces of the dismantled material. The dismantling of BR3 has led to the construction of an in-house decontamination workshop based on the MEDOC® process, which is appropriate for the treatment of stainless steel CALLISTO material. The MEDOC® (Metal Decontamination by Oxidation with Cerium) hard decontamination process is based on the use of cerium IV as a strong oxidant in sulphuric acid with continuous regeneration using ozone. [2] Single step dissolution of both the oxide layer (if present) and the base metal at high corrosion rates allows for the unconditional clearance of the treated material as schematically depicted in Figure 10.

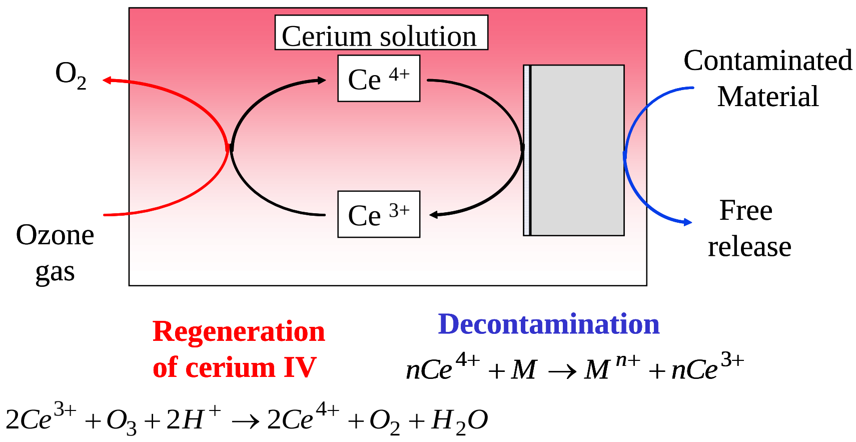

Figure 10: MEDOC® single step treatment with continuous regeneration of cerium

The batch treatment of dismantled contaminated pieces consists of the following steps [3]:

- Loading and sorting of the pieces via the basket into the decontamination reactor;
- Circulation of the decontamination solution;
- Rinsing of the decontaminated pieces in the rinsing reactor;
- Drying and characterisation of the rinsed pieces.

Figure 11: MEDOC® chemical decontamination workshop

The high corrosion rates necessary for efficient metal attack are established by heating the strongly oxidising solution to 80°C and promoting the decontamination even more with ultrasonic resonators. The applied strategy aiming waste minimisation as described allows an estimated 20 tons of material to be unconditionally cleared instead of deposited as radioactive waste.

CONCLUSIONS

CALLISTO has not only proven to be useful in simulating PWR conditions in exploitation, but can also be seen as representative for the coming major dismantling activities with regard to commercial power plants. The strategy applied at NPP's is of course country and site specific, but some of the experience from the decommissioning of CALLISTO can certainly be taken into account:

- The succesful chemical decontamination prior to dismantling has proven to be indispensable for a justified hands-on dismantling of the loop;
- A thorough sorting, conditioning and labeling of all dismantled material at the source is needed for a safe and traceable management;
- Temporary storage facilities for dismantled material in attendance of evacuation or further treatment are often limited and can as such be(come) a major factor in planning and logistics;
- An evacuation route for all material coming from the decommissioning of contaminated water loops should ideally already be defined before the start of the actual dismantling;
- Waste minimisation by thorough decontamination can be an independent, economical and viable strategy for decommissioning of PWR's.

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