Materials harvesting and SMILE materials library

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Abstract

The overall objective of the Studsvik Materials Integrity Life Extension (SMILE) project is to provide LWR plant operators and national nuclear safety regulators with an improved understanding of materials ageing mechanisms in support of plant ageing management, life extension programs and operating license renewals [1].

The SMILE project leverages a unique opportunity to extract and test actual plant aged materials and components, with the aim of improving and validating the knowledge of materials ageing phenomena and their kinetics. This paper describes in detail the strategy for materials selection, techniques and challenges in harvesting and storing irradiated components as well as current and planned content of the SMILE materials library.

Introduction

The world's light water reactor (LWR) fleet is aging with many reactors passing the original design life of typically 40 years. Many operators plan for life extension programs, often beyond 60 years, which combined with high availability requirements drives the focus on aging and life extension programs as well as plant life management in general. The overall objective of the SMILE project is to provide LWR plant operators and national nuclear safety regulators with an improved understanding of materials ageing mechanisms in support of plant ageing management, life extension programs and operating license renewals.

The SMILE project started in January 2021 and is organized as a 5-year Studsvik/OECD/NEA project that connects experts from all over the world. SMILE creates a forum for knowledge transfer between organizations and age generations based on experimental examinations and testing of aged materials harvested from LWRs decommissioned after up to 40+ years of operation. The project has 16 member organizations from 8 countries.

Aging management relies on models of the kinetics of the various mechanisms of degradation as well as use of validated replacement materials/components where necessary. The SMILE project aims to improve knowledge of materials ageing phenomena and their kinetics by leveraging a near-unique opportunity to harvest various components from two Swedish BWRs of ASEA-ATOM design [e.g. 2, 3] at Oskarshamn and one Swedish PWR of Westinghouse design at Ringhals, all of which have been recently withdrawn from service.

Several studies conducted over the last decade were designed to identify where future ageing related challenges to LWR Nuclear Steam Supply Systems (NSSS) structural integrity might arise [4-6]. The conclusions and recommendations of these studies provided an objective basis for SMILE research proposal [1]. These proposals were then scrutinized, discussed, and prioritized among by the SMILE members, which resulted in the final scope of work divided into four tasks, see Figure 1.

Task 1, Materials library, is a prerequisite and basis for the experimental tasks (Task 2- 4). This task described in this paper includes acquiring materials and any necessary background information on fabrication and operating history. The task is divided into three subtasks; Subtask 1.1 Acquisition of materials includes the preparations for and extraction of components, transport of active components from the plants to Studsvik and storing of components at Studsvik; Subtask 1.2 Documentation of all harvested materials compiles all necessary manufacturing and operating data of the harvested components; Subtask 1.3. Calculations comprises the modelling of neutron dose and temperature due to gamma heating of any extracted components.

Task 2 investigates reactor pressure vessel (RPV) irradiation embrittlement, comparing mechanical / microstructural evolution of real RPV material to surveillance material from the same plants. Task 3 covers irradiation embrittlement and irradiation assisted stress corrosion cracking of reactor internals and is summarized in Jenssen et al. [7] at this conference. Task 4 covers aging and stress corrosion cracking of Nickel base dissimilar metal welds, Alloy 690 and mechanical stress improvement of a SS weld.

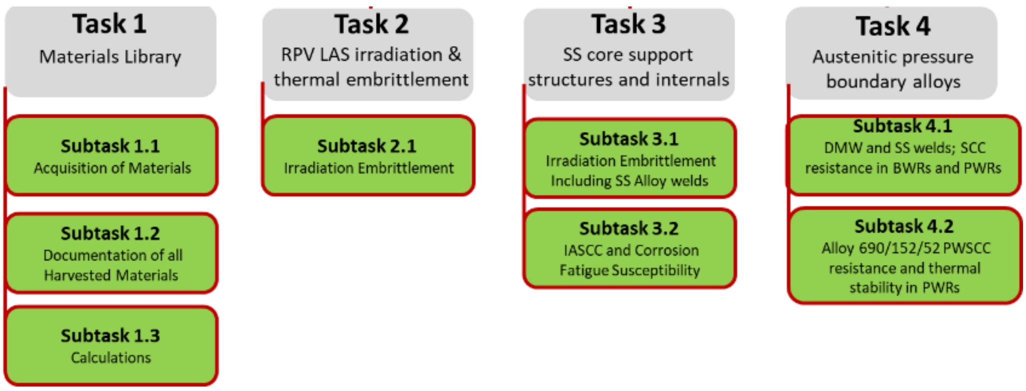

Figure 1: Overview of the SMILE project organized into tasks and subtasks.

Harvesting, logistics, storing and testing of aged and activated components from a NSSS is complex task and requires significant planning and organization. For this to be of value, it requires extensive information on manufacturing and operational histories, including in-service and post-service non-destructive inspections.

Key data for the three Swedish LWRs used for harvesting

SMILE relies on the availability of harvested components from two Swedish BWRs, Oskarshamn 1 and 2, plus one retired PWR, Ringhals 2. Summaries of some key design and operational parameters of these three LWRs are shown in Table 1 and a list of the main structural materials grades of interest is shown in Table 2.

	Oskarshamn 1 (BWR)	Oskarshamn 2 (BWR)	Ringhals 2 (PWR)
NSSS vendor	ASEA-ATOM	ASEA-ATOM	Westinghouse
Reactor type	BWR with 4 external recirculation loops	BWR with 4 external recirculation loops	PWR 3-loop plant
Commercial operation dates	1972-2017	1974-2013	1975-2019
Net electrical output	440 to 473 Mwe[1]	570 to 638 Mwe[1]	800 to 875 Mwe[1]
Effective Full Power Years operation	~28.2 EFPY	~31.7 EFPY	~29.7 EFPY
RPV inlet/outlet temperatures	270/286 °C	270/286 °C	289/323 °C
PWR Pressurizer temperature	-	-	343 °C
Primary coolant chemistry	NWC to date with Zn addition for the last ~15 years	NWC to 1992 then HWC with Zn addition for the last ~15 years	Standard PWR primary water chemistry
Major component replacements or modifications	Top guide replaced in 1986 Core shroud[2] replaced in 1998	Top guide replaced in 1986 MSIP applied to Recirculation loop welds in 1988	Steam generators replaced in 1989 RPV Upper Head and CRDM Penetrations replaced in 1995

1) Design output and after uprates respectively

2) The core shroud is also known as the 'moderator tank' in Scandinavia

EFPY – Effective Full Power Years

NWC – Normal Water Chemistry and HWC – Hydrogen Water Chemistry (BWRs)

MSIP – Mechanical Stress Improvement Process

CRDM – Control Rod Drive Mechanism

Table 1: **Summary of key design and operating parameters for Oskarshamn 1 & 2 and Ringhals 2**.

	Oskarshamn 1	Oskarshamn 2	Ringhals 2
RPV upper head	ASTM A 302B [a]	A 533 Gr B Class 1 [a]	Replacement in 1995 SA 533 Gr B Class 1 [a] Alloy 690 CRDM penetrations
RPV cylindrical section	ASTM A 302B [a]	A 533 Gr B Class 1 [a]	SA 508 Class 2 [b]
RPV lower head	ASTM A 302B [a]	A 533 Gr B Class 1 [a]	SA 533 Gr B Class 1 [a]
RPV Internals	Type 304, C<0.05% Type 308/309 welds CASS lower core support plate Replacement top guide from 1986 Type 316L Replacement core shroud from 1996/7 Type 316L	Type 304, C<0.05% Type 308/309 welds CASS lower core support plate Replacement top guide from 1986 Type 316L	Type 304, C<0.05% Type 316 baffle bolts CASS lower core support castings
PWR Pressurizer Vessel	NA	NA	SA 533 Gr B Class 1 [a]
DMWs	Alloy 182	Alloy 182	Stainless steel
Recirculation Pipework (BWR) or Primary Circuit Pipework (PWR)	Carbon steel internally lined with overlay welded stainless steel	Type 304, C<0.05% Type 308/309 welds	Type 304, C<0.05% Type 308/309 welds
Valve bodies & elbows	CASS	CASS	CASS
PWR Steam Generators	NA	NA	Replacement SGs with Alloy 690 TT tubes (1989)

[a] Product form: Plate.

[b] Product form: Forging.

Table 2 Main structural material grades used at Oskarshamn 1 & 2 and Ringhals 2.

Strategy for selecting and harvesting materials

The preparations for harvesting consist of several interconnected steps, selecting materials, choosing the correct extraction positions, sizes and technique for extraction and whether to do specific extractions or include extraction in the scheduled dismantling work, all having impact on the quality of extracted sections as well as cost and time schedule for both SMILE and the dismantling projects. It is important to recognise that in order to gain acceptance for harvesting from plant owners, risks for affecting the dismantling time schedule need to be small. Also, extraction and dismantling projects have distinctly different objectives, needs and time schedules. Further limitations on mainly size, weight and dose rates of extracted irradiated and/or contaminated components are imposed by the subsequent transport, handling and fine sectioning before testing.

The strategy for selecting materials is an iterative process starting with the previously mentioned analysis of possible aging issues, combined with prior knowledge of the specific reactors design and operating histories. Together with Swedish plant owners' analyses of their specific needs and additional component specific information lists of potentially interesting materials were created. These lists were then reworked several times based on SMILE member input, additional retrieved materials information, dose and temperature calculations etc. to create short-lists of the most important components and positions for extraction.

For each component the most conservative position was chosen, based on e.g., dose, temperature, weld strain or combinations thereof. Where possible, the full range of relevant aging states is retrieved. The lowest possible aging state is also extracted in cases where archive materials are not available, Component sizes were chosen based on; the above-mentioned logistical limitations; the amount required by planned testing needs; extraction of sufficient sizes to retain any local weld residual stress state.

Many of the components have been or will be extracted as part of the dismantling work. These include the RPV and nearby components from both Oskarshamn 1, 2 and Ringhals 2. The main benefits of this strategy are generally:

- Limited effects on dismantling time schedule and extraction costs
- Tools and handling equipment for extraction are designed, tested and available

while typical limitations are:

- Additional cutting needed on site prior to transport.
  - Limited precision in positioning of cuts and extracted pieces are potentially unnecessarily large, often several tons per piece
  - Cutting techniques inducing deformation or excessive heating by, e.g., thermal cutting processes with large heat affected zones (HAZs) limiting the amount of unaffected material.
- Need to be included at an early stage in the request for quotation (RFQ) for dismantling and often with limited flexibility if changes to the extraction plans are necessary
- Long lead times in decommissioning projects leading to late material availability
- Specific equipment, e.g. pools for post extraction cutting or loading of transport flasks that may already have been decommissioned.

Specific extraction procedures for components are being followed for the Ringhals 2 internals, Ringhals 2 RPV head penetrations and the Oskarshamn 2 MSIP-treated stainless steel weld. The main benefits of this strategy are:

- Materials available for early testing, potentially years prior to scheduled segmentations
- High precision in positioning extracted pieces is possible and adjustable to specific needs
- Possible to choose cutting techniques that minimize the zone affected by cutting
- Potentially more flexible with modifications to extraction locations
- Possibility to extract materials with intact system oxides prior to primary system decontamination
- Possibility to measure the global stresses acting on the component during extraction

Limitations are typically

- Higher cost and time-consuming cutting processes where a cut in some cases can take one week
- Only possible prior to the start of segmentation so as not to affect the decommissioning time schedule
- Limited access to specific components and positions before decontamination and disassembly
- Removal of pressure boundary segments may require subsequent resealing

Oskarshamn 1 and 2 RPV internals were segmented under water by a mechanical cutting technique using a remote-controlled rotating blade. Segments of varying sizes of core shroud pieces from 25 ×

150 × 300-2000 mm^3 to lower core plate pieces with Control Rod Guide Tube (CRGT) of 300 × 300 × 800 mm^3 were extracted.

The Ringhals 2 RPV-internals, e.g. baffle plates and core barrel segments are being extracted mechanically under water using hole sawing equipment. Some difficult to reach components, e.g. guide tube support pins are being extracted using Electric Discharge Machining (EDM). The Ringhals 2 RPV-head CRDM-penetrations of Alloy 690 are being extracted by hole sawing, see Figure 6. All these items are extracted prior to the final chemical decontamination to allow testing next year, which requires the additional temporary resealing of pressure boundary by welding in stainless plates.

RPV and main pressure boundary sections are extracted as a part of the final decommissioning by dry segmentation using thermal processes at both Ringhals and Oskarshamn. These segments will be cropped prior to storage in the SMILE materials library at either the NPP or Studsvik depending on equipment and logistics.

Transportation, storing and handling of components

The SMILE materials library contains large quantities of irradiated and contaminated test materials which requires both infrastructure and special procedures for handling and processing. Several different options are utilized for transporting materials from the plants depending on specific activity, size and weight as well as total amount to be transported. Further considerations on site concern interim storage possibilities, transport flask compatibility and limited transport time windows available during decommissioning.

For high specific activity objects, Studsvik's so called 29 ton cask is preferred since several of these items can be transported simultaneously, thus minimizing time on site, costs and any risks associated with transportation. Figure 2 shows the 29 ton transport cask and a small type A cask allowing a total activity up to class A2[1]. In Figure 3, the 29 ton cask with Ringhals 2 components and inserts is shown. These component specific inserts allow for easier handling and storage of components on site and at Studsvik as well as fixing components in the transport cask during transport.

Low dose or contaminated objects are transported using containers of various sizes up to type IP2 (<1/1000 A2) or LP55 (<1 A2), allowing up to 27 and 1.5 tons of payload respectively.

Figure 2: Transport casks Type A – 29 tons, Ø450 mm × 4 m (left), Ø300 mm × 450 mm (right).

[1] A2 is the maximum activity of normal form radioactive material permitted in a Type A transport package.

Figure 3: Transport cask 29 tons with components and their specific inserts and from Ringhals 2

Once at Studsvik, the flasks are transported to the pool facility (FA), which consists of three high purity water pools for receiving and handling transport flasks, irradiated material and irradiated fuel elements. All SMILE materials are received and stored in pool 1: Figure 4. Large components are stored in containers on the pool floor while smaller objects are stored in dedicated racks along the pool edges. In the smaller pool-in-pool seen to the left in Figure 4, non-destructive testing and rough cutting are performed before transporting the extracted pieces to the active metals laboratory for specimen preparation and testing, seen here in the right picture in Figure 4.

Low dose and contaminated materials and sections of the RPV beltline are dry stored in container depending on size and dose rates.

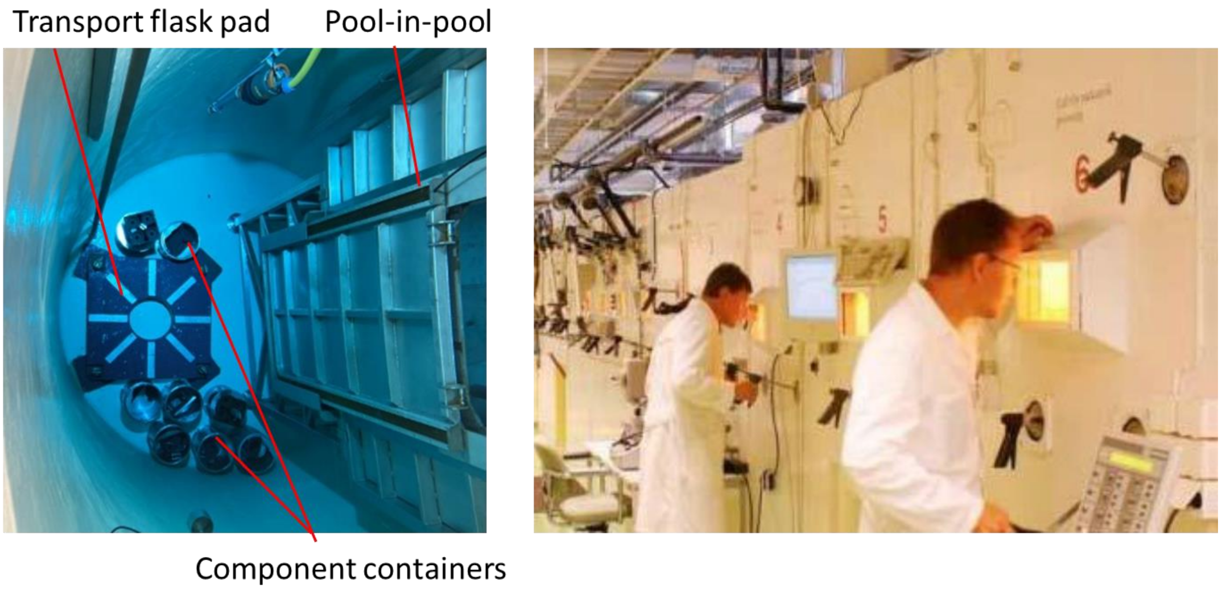

Figure 4. Storage pool and pool-in-pool (left) and the linked hot cells at the Active Metals Laboratory (AML)

To keep track of each component or specimen through the process of handling, naming and labeling, procedures including a database are in place to keep track of each piece and its history e.g., from which component/specimen including the cutting drawings, dose, performed tests etc. as well as current location.

Materials library

Material harvesting for SMILE started in 2019 and will continue until 2025. As of June 2022, the library contains irradiated BWR internals from Oskarshamn 1 and 2, e.g. type 304 core shroud pieces including welds, type 316 core spray piping, cast stainless steels and high strength brackets and bolts (X-750/XM19). Both BWR and PWR RPV surveillance specimens are also available, as are archive materials. Harvesting during the coming half year will include a BWR pipe weld that was treated in service by the Mechanical Stress Improvement Process (MSIP), PWR reactor vessel internals and Alloy 690 steam generator tubes.

Tables 3 to 6 summarize the components that are or will be included in the library as well as some components extracted beyond the scope of the SMILE project. RPV internals are excluded here since these are extensively described in [1].

The RPV 300-500 mm × 500-1000 mm sections shown in Tables 3 and 4 are full thickness and include cladding and are currently scheduled to be extracted. Nozzles will include ≥2x pipe diameter lengths of low alloy steel. The core shroud support from Oskarshamn 2, where indications have been found, include a connection weld, buttering and a full thickness section of RPV. The BWR pipe weld was MSIP-treated in 1988 and subsequently, no further growth of the shallow crack (detected in 1986) was observed by subsequent ultrasonic testing conducted up to plant closure. The reference weld is an untreated nearby weld with the same orientation and manufacturing history.

Penetrations of various types and materials are also included in the materials library, see Tables 3 and 4. The designs of Oskarshamn 2 level measurement penetrations and bottom nozzles are shown in Figure 5. Figure 6 shows the replacement Ringhals 2 upper head with Alloy 690 penetrations in operation from 1995. Central positions with a low setup angle and peripheral positions with the highest set-up angles are included. An additional compilation of several available welds is shown in Table 6.

System	Component	Material grades	Fluence n/cm^2 E>1 MeV
RPV	Belt line-max dose [a]	A533 Grade B Cl. 1, incl. HAZ & weld	~3×10^{18}
	Belt line-low dose	A533 Grade B Cl. 1, incl. HAZ & weld	~1×10^{17}
	Belt line-intermediate dose	ASTM A533 Grade B Cl. 1	1-3×10^{18}
	Not belt line-minimum dose	ASTM A533 Grade B Cl. 1	<<1×10^{17}
	Surveillance capsule C	ASTM A533 Grade B Cl. 1	~10^{18}
	Bottom nozzle, 1st set up circle	1.4301/(SS-weld Fox 21/10Nb)/Clad LAS	~0
	Bottom nozzle, outer set up circle	1.4301/(SS-weld Fox 21/10Nb)/Clad LAS	~0
	Archive materials	A533 Grade B Cl. 1, incl. HAZ & weld	0
Other	Core shroud support	600/182 & 82/A533 Grade B Cl. 1	~0
Penetrations	Water level meas. penetration	LAS/182/600 to SS pipe	<<1×10^{17}
	Recirculation nozzle	A508 Cl. 2/SS clad CS pipe	<<1×10^{17}
	Feedwater nozzle	A533 Grade B Cl. 1/Alloy 82	~0
Piping	MSIP treated weld w. defect	Type 304 base + weld	0
	Reference to MSIP treated weld	Type 304 base + weld	0

a) Extensive surveillance results and one un-tested chain at similar dose available

Table 3: Library of aged BWR components available or in planning.

System[a]	Component[a]	Material grades	Fluence n/cm^2 E>1 MeV
RPV	Beltline-max dose [b]	SA-508 Class 2, incl. HAZ and weld	~4×10^{19}-4×10^{18}
	Beltline-intermediate dose	SA-508 Class 2, incl. HAZ and weld	~7×10^{18}-7×10^{17}
	Beltline-low dose	SA-508 Class 2	~1×10^{18}-1×10^{17}
	Beltline forging-low dose	SA-508 Class 2, incl. HAZ and weld	<1×10^{17}
	Surveillance capsules	SA-508 Class 2, incl. HAZ and weld	up to 4.2×10^{19}
	RPV archive materials	SA-508 Class 2, incl. HAZ and weld	0
	Nozzle shell course	SA-508 Class 2	<<1×10^{17}
Penetrations	BMI, 1st and outer set up circles	A533 Grade B Cl. 1/Alloy 600/Alloy 182	~0
	CRDM , 1st and outer set up circles [d]	A533 Grade B Cl. 1/Alloy 690/Alloy 52	~0
	CRDM , 1st and outer set up circles	A533 Grade B Cl. 1/Alloy 600/Alloy 182 [c]	~0
	BMI, 1st and outer set up circles	A533 Grade B Cl. 1/Alloy 600/Alloy 182	0
	CRDM , 1st and outer set up circles [d]	A533 Grade B Cl. 1/Alloy 690/Alloy 52	0
	CRDM , 1st and outer set up circles	A533 Grade B Cl. 1/Alloy 600/Alloy 182*	0
SG	tubes, hot and cold sides [d]	Alloy 690	0
	tube support plate, hot & cold	Alloy 690/Type 304	0

a) BMI=bottom mounted instrument nozzle, CRDM=control rod drive mechanism, SG=steam generator
b) Surveillance data and material available
c) Material from Ringhals 3
d) Archive materials are available

Table 4: Library of aged PWR components available or in planning.

Cast stainless steel (CASS) components of both irradiated type CF8 and unirradiated type CF8M are listed in Table 5. The lower core supports are shown to the left in Figure 7. Core support castings with different compositions are being extracted, each exhibiting the complete available dose range of <0.01-3.5 dpa. The lower dose Ringhals 2 flow mixing device including a portion of upper core plate is shown centrally in Figure 7. An Oskarshamn 2 lower core plate welded to the control rod guide tube (CRGT) is shown in the right Figure 7.

Reactor Type	Component	Material grades	Dose dpa
BWR	CRGT + lower core plate, central pos.	CASS/Weld/Type 304 (CF8)[a]	0.1-0.5
	CRGT + lower core plate, peripheral pos.	CASS/Weld/Type 304 (CF8)[b]	0.1-0.5
PWR	Flow mixing device	CASS/CF8[c]	<0.01
	Lower core support	CASS/CF8 [c]	<0.01-3.5
	Pipe elbows, hot leg (325 °C) – 91 khrs	CF8M [c]	0
	Pipe elbows, cold leg (289 °C) – 91 khrs	CF8M [c]	0
	Pressurizer spray cooler (345 °C), 30 yrs	CF8M [c]	0

a) Oskarshamn 2
b) Oskarshamn 1
c) Ringhals 2

Table 5: Materials library cast stainless steel components available or in planning.

Reactor Type	Component[f)]	Material grades	Dose dpa
	Core barrel [a]	Type 304 + weld	<0.1 to ~2
PWR	Core barrel [b]	Type 304 + weld	<<0.1 to >5
	Core shroud [c]	Type 304, + horizontal & vertical welds	0.02-0.35
	Core shroud [d]	Type 304, + horizontal & vertical welds	0.025-0.5
	CRGT, core plate [e]	Weld between CASS & 304	~0.1
BWR	CRGT, core plate [d]	Weld between CASS & 304	~0.1
	Riser pipe [e]	Weld metal (316L)	~0.1
	ECCS bracket [e]	Alloy 82 welds joining 316L & XM-19	<0.1
	ECCS bracket [e]	316L weld joining 316L	<0.1

a) Zorita
b) Ringhals 2
c) Barsebäck 2
d) Oskarshamn 2
e) Oskarshamn 1
f) ECCS=emergency core cooling system

Table 6: Materials library welds available or in planning.

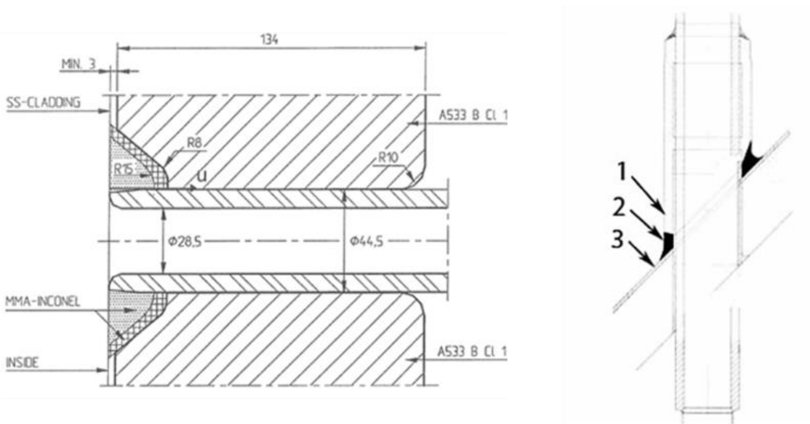

Figure 5: Schematics of Oskarshamn 2 level measurement penetration (left) and RPV bottom nozzle (right).

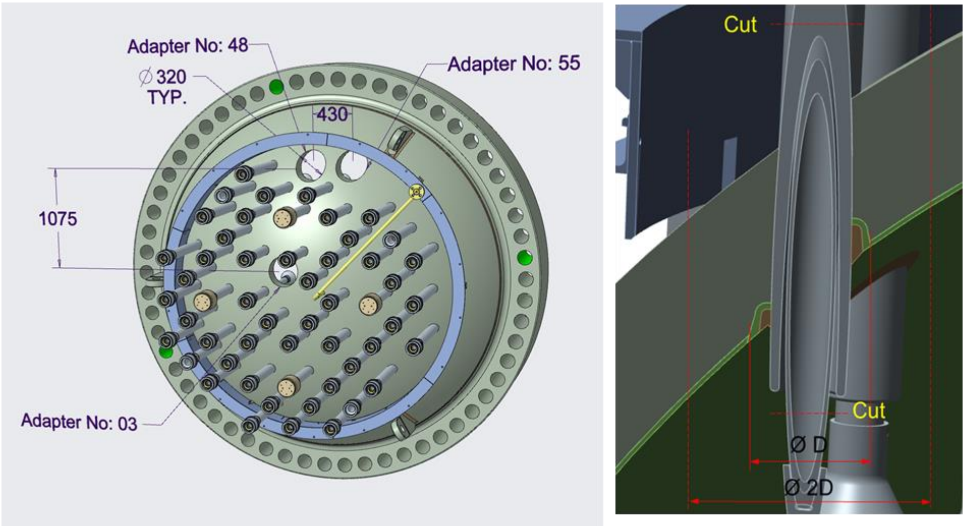

Figure 6: Schematics of Ringhals 2 RPV head with penetrations extracted (left) and the penetration in crossection (right).

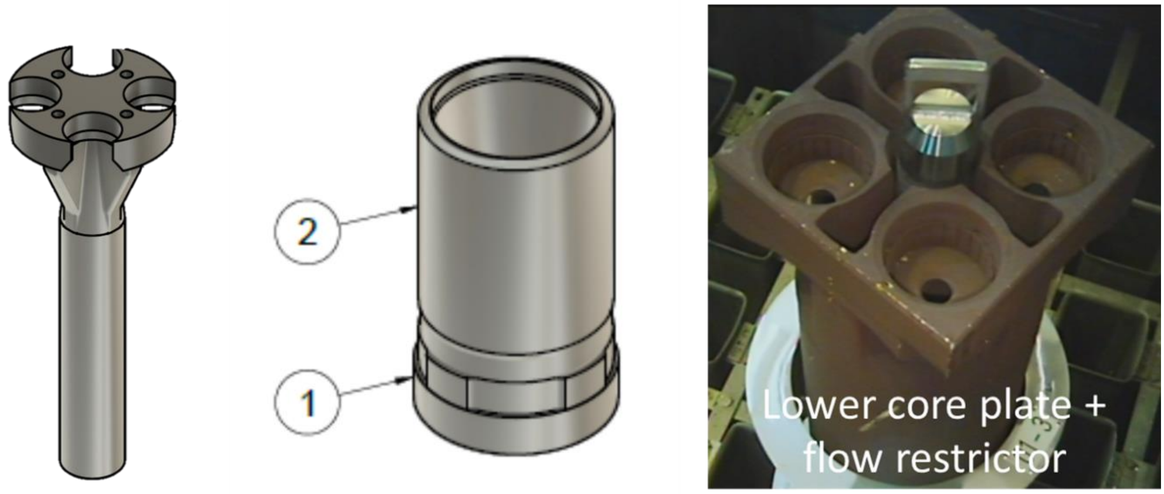

Figure 7: Schematics of CASS components: Ringhals 2 RPV lower core support including core plate on top (left), flow mixing device (2) incl. upper core plate (1) (center) and Oskarshamn 2 rectangular piece of lower core plate incl. flow restrictor welded to the control rod guide tube (right).

The SMILE library includes for each component a report covering all available background information, which is compiled within SMILE subtask 1.2. It includes:

- Procurement specifications and acceptance certificates detailing chemical compositions and mechanical properties
- Archive samples where available
- Pressure, thermal and irradiation history in service including significant transients
- Water chemistry history and any significant transients
- Neutron doses for the RPVs and core support internals as well as gamma heating and temperature calculations for the core internals where available
- Fatigue loading calculations prior to service and actual fatigue loading history where relevant and available

While extensive data are available, collecting all documentation is a laborious task that includes searching the plant operators archives and, in some cases, Studsvik, vendor or subcontractor archives. Since the 70s when these plants were built, some of the archives have also been restructured, digitized and/or copied to microfilm.

In Subtask 1.3, calculations of neutron flux have been conducted to guide the choice of components and extraction positioning. Detailed calculations of neutron flux and dose gradients are being performed with the objective of optimizing subsequent machining of test specimens and fully characterizing the history of each tested specimen. Further, gamma heating temperature calculations including their sensitivity to the calculation method and input uncertainties will be assessed. For each case, are at least beginning of the study, mid and end of cycle results will be calculated.

Summary

The SMILE project leverages a unique opportunity to extract and test real plant aged materials and components with the aim of improving and validating the knowledge of materials ageing phenomena and their kinetics.

This paper describes in detail the strategy for materials selection, extraction techniques and challenges in harvesting and storing irradiated components as well as current and planned content of the SMILE materials library.

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