Studsvik

okg

NEA Nuclear Energy Agency

VATTENFALL

Strål säkerhets myndigheten Swedish Radiation Safety Authority

SMILE – Technical Project Description

Peter Scott, Anders Jenssen, Martin Bjurman,
Lotta Nystrand, Joakim Lundström, Sofia Björnsson

January 23, 2020

SMILE PROJECT OVERVIEW

- SMILE (Studsvik Material Integrity Life Extension) will support LWR operators and authorities worldwide in plant ageing management.
- It will leverage a near-unique opportunity to harvest NSSS components from 3 Swedish BWRs (Oskarshamn 1 and 2, Ringhals 1) and one Swedish PWR (Ringhals 2) that have recently shut down or will soon be withdrawn from service.
- Its objective is to provide critical data and mechanistic understanding of NSSS materials ageing mechanisms in support of plant ageing management, life extension programmes and operating licence renewals.
- SMILE content and priorities to be discussed at this meeting and to be defined in the final technical description.

SMILE TASKS & SUB-TASKS

Task 1
Materials Library

- **Subtask 1.1** Acquisition of materials
- **Subtask 1.2** Documentation of harvested materials
- **Subtask 1.3** Fatigue & irradiation calculations
- **Subtask 1.4** Create database

Task 2
RPV C&LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Task 3
SS core support structures and internals

- **Subtask 3.1** Irradiation embrittlement including SS welds
- **Subtask 3.2** IASCC and corrosion fatigue susceptibility
- **Subtask 3.3** CASS and weld thermal ageing with irradiation effects

Task 4
Austenitic pressure boundary alloys

- **Subtask 4.1** DMW and SS welds; SCC resistance in BWRs and PWRs
- **Subtask 4.2** Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs
- **Subtask 4.3** Fatigue in BWR and PWR reactor coolants

SMILE content and priorities to be discussed at the OECD NEA workshop and to be defined in the final technical description.

Task 1
Materials Library

- **Subtask 1.1** Acquisition of materials
- **Subtask 1.2** Documentation of harvested materials
- **Subtask 1.3** Fatigue & irradiation calculations
- **Subtask 1.4** Create database

Subtask 1.2 – Documentation of harvested materials

- Objective:
  - Procurement specifications, copies of acceptance certificates and archive samples
  - Mechanical properties tests on archive samples
  - Pressure, thermal, water chemistry and irradiation history in service including significant transients
  - Neutron doses for the RPVs and core support internals plus gamma heating calculations for the core internals, where available

Task 1
Materials Library

- **Subtask 1.1** Acquisition of materials
- **Subtask 1.2** Documentation of harvested materials
- **Subtask 1.3** Fatigue & Irradiation Calculations
- **Subtask 1.4** Create Database

- **Subtask 1.3 – Irradiation and fatigue calculations**
- Objective:
  - Calculate neutron flux and dose gradients in thick section materials in order to optimize machining of test specimens
  - Gamma heating calculations and their sensitivity to the calculation method and input uncertainties to be assessed
  - Fatigue loading calculations prior to service and actual fatigue loading history where relevant and available

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.1 – Irradiation Embrittlement

- Objective:
  - Study mechanical properties, particularly fracture toughness, of harvested BWR and PWR RPV steels (Beltline and Nozzle Course Shell)
  - Study the metallurgical reasons for irradiation embrittlement in order to contribute to the development/validation of predictive models

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off			O2 RPV Beltline weld & HAZ; O1 RPV Beltline weld & HAZ	R2 RPV Beltline weld & HAZ	

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.1 – Irradiation Embrittlement

- Approach to meet subtask objective:
  - Gamma spectroscopy characterization of irradiated samples to compare actual neutron doses to estimated doses from plant surveillance calculations
  - Tensile tests, Charpy V impact and fracture toughness tests
  - Comparison of fracture toughness results to existing plant evaluations using current extrapolation models
  - Detailed characterization (ATEM and APT) to determine the causes of embrittlement
  - Results of fracture toughness testing in air to be compared later to results obtained in LWR environments at the end of SCC testing

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off		O2 RPV Beltline weld & HAZ	O1 RPV Beltline weld & HAZ	R2 RPV Beltline weld & HAZ	

Studsvik

Task 2
RPV C&LAS irradiation & thermal embrittlement

Subtask 2.1
Irradiation embrittlement

Subtask 2.2
Thermal ageing embrittlement

Subtask 2.3
Stability in service of casting and forging anomalies

Subtask 2.4
SCC tests in simulated reactor coolants

Subtask 2.2 – Thermal ageing embrittlement

- Objective:
  - Study unirradiated samples of RPV steels and welds harvested from a retired PWR pressurizer for evidence of hardening and loss of fracture toughness due to thermal ageing compared to archive samples
  - In-depth physical metallurgical characterization (ATEM, APT and Auger) of the causes of degradation in the event of any significant effects on hardness and toughness being observed

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R4 RPV Pressurizer Plate & Forging		R2 RPV Pressurizer Plate & Forging		

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.2 – Thermal Ageing Embrittlement

- Approach to meet subtask objective:
  - Hardness tests across welds of PWR pressurizer vessel samples
  - If any measurable and repeatable increases in hardness, physical metallurgical characterizations (ATEM, APT and Auger)
  - Tensile tests
  - Charpy V impact and fracture toughness tests

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R4 RPV Pressurizer Plate & Forging		R2 RPV Pressurizer Plate & Forging		

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.3 – Stability in service of casting and forging anomalies

- Objective:
  - Study samples of LAS forgings and welds for evidence of metallurgical inhomogeneity, associated degradation of fracture toughness, and potential mechanisms of propagation of sub-surface flaws

Q4 2020 → 2021 → 2022 → 2023 → 2024 → 2025

- Q4 2020: SMILE kick-off
- 2023: O2 RPV Beltline weld; R2 Pressuriser forging
- 2023–2024: O1 RPV Beltline weld
- 2024: R2 RPV Beltline weld

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

• Subtask 2.3 – Stability in service of casting and forging anomalies

- Approach to meet subtask objective:
  - Metallography, SEM and hardness characterizations of samples of BWR and PWR RPV forgings and welds
  - Charpy V impact tests and fracture toughness tests if any significant C and/or P segregation, hardness variations or defects observed
  - Measure dynamic strain ageing susceptibility as a function of temperature
  - Determine H_2 solubility and diffusivity to quantify any contribution from radiation damage
  - Determine the effect of realistic H_2 contents from exposure to PWR primary water and BWR HWC on effective fracture toughness of RPV forging base metals, weld metals and HAZs

Q4 2020 | 2021 | 2022 | 2023 | 2024 | 2025

SMILE kick-off (Q4 2020)

O2 RPV Beltline weld (2023)

R2 Pressuriser forging (2023)

O1 RPV Beltline weld (2023/2024)

R2 RPV Beltline weld (2024)

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.4 – SCC and corrosion fatigue tests in simulated reactor coolants

- Objective:
  - Study the effect of neutron irradiation dose and thermal embrittlement of RPV steels on the rate of corrosion fatigue and SCC crack propagation in simulated LWR coolants.
  - Study the effect of LWR environments on effective fracture toughness at the end of each SCC/corrosion fatigue test

Q4 2020 | 2021 | 2022 | 2023 | 2024 | 2025

SMILE kick-off

O2 RPV Beltline weld & HAZ

O1 RPV Beltline weld & HAZ

R2 RPV Beltline weld & HAZ

Studsvik

Task 2
RPV LAS irradiation & thermal embrittlement

- **Subtask 2.1** Irradiation embrittlement
- **Subtask 2.2** Thermal ageing embrittlement
- **Subtask 2.3** Stability in service of casting and forging anomalies
- **Subtask 2.4** SCC tests in simulated reactor coolants

Subtask 2.4 – SCC & corrosion fatigue tests in simulated reactor coolants

- Approach to meet subtask objective:
  - Corrosion fatigue and SCC crack propagation rate measurements on high and low dose RPV steels in simulated BWR NWC, BWR HWC (with and without maximum acceptable Cl^- or SO_4^-) and PWR primary water
  - Terminate each crack growth test with a fracture toughness test in the simulated reactor coolant
  - If any significantly higher crack growth rates are observed relative to the known database for unirradiated LAS, carry out detailed physical metallurgical examinations (metallography, SEM, ATEM APT) to identify the causes

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off			O2 RPV Beltline weld & HAZ; O1 RPV Beltline weld & HAZ	R2 RPV Beltline weld & HAZ	

Task 3
SS core support structures and internals

Subtask 3.1
Irradiation embrittlement including SS welds

Subtask 3.2
IASCC and corrosion fatigue susceptibility

Subtask 3.3
CASS and weld thermal ageing with irradiation effects

- **Subtask 3.1 – Irradiation embrittlement including stainless steel welds**
  - Objective:
    - Study the metallurgical and mechanical properties, including fracture toughness, of irradiated stainless steels, Alloy 182 welds, and some higher strength alloys (Alloy X-750 in both BWRs and PWRs, Alloy 718 in PWRs, and XM-19 in BWRs) with particular emphasis on maximum irradiation doses attained in the harvested materials available

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O1 SS Brackets O2 Core Shroud R2 Fuel Nozzle O2, R2 X-750 R2 718	R2 baffles, bolts, core barrel, alignment pins			

Task 3
SS core support structures and internals

- **Subtask 3.1** Irradiation embrittlement including SS welds
- **Subtask 3.2** IASCC and corrosion fatigue susceptibility
- **Subtask 3.3** CASS and weld thermal ageing with irradiation effects

- **Subtask 3.1 – Irradiation embrittlement including stainless steel welds**
  - Approach to meet subtask objective:
    - Gamma spectroscopy characterizations to compare actual neutron doses to those estimated from plant calculations
    - Detailed physical metallurgical characterizations by TEM ar APT (dislocations, elemental segregation, void swelling, hydrogen and helium gas content measurements) and hardness surveys as a function of neutron dose and irradiation temperature
    - Tensile, fatigue endurance, Charpy V and fracture toughnes tests as a function of neutron dose, irradiation temperatur hydrogen content and reactor type, BWR or PWR

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O1 SS Brackets O2 Core Shroud R2 Fuel Nozzle O2, R2 X-750 R2 718	R2 baffles, bolts, core barrel, alignment pins			

Studsvik

Task 3
SS core support structures and internals

Subtask 3.1
Irradiation embrittlement including SS welds

Subtask 3.2
IASCC and corrosion fatigue susceptibility

Subtask 3.3
CASS and weld thermal ageing with irradiation effects

Subtask 3.2 – IASCC & corrosion fatigue susceptibility

- Objective:
  - Determine IASCC and corrosion fatigue susceptibility and crack growth rates in wrought, cold worked and welded austenitic stainless steels, Alloy 182 weld metal, and some higher strength alloys (Alloy X-750, Alloy 718 and XM-19) from retired BWRs and PWRs
  - Establish the combinations of metallurgical factors and residual stresses induced by high irradiation doses that giv rise to IASCC
  - Determine effective fracture toughness in simulated LWR environments at the end of crack growth tests

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O1 SS Brackets O2 Core Shroud R2 Fuel Nozzle O2, R2 X-750 R2 718	R2 baffles, bolts, core barrel, alignment pins			

Task 3
SS core support structures and internals

Subtask 3.1
Irradiation embrittlement including SS welds

Subtask 3.2
IASCC and corrosion fatigue susceptibility

Subtask 3.3
CASS and weld thermal ageing with irradiation effects

Subtask 3.2 – IASCC & corrosion fatigue susceptibility

- Approach to meet subtask objective:
  - Additional gamma spectroscopy characterizations, as required for addition samples
  - Dye penetrant, polymer replica and macroscopic metallurgical examinatior to detect any IASCC, if present, in all highly irradiated BWR and PWR austenitic stainless steel samples
  - Detailed physical metallurgical characterizations (SEM, TEM APT) plus heliu and hydrogen gas content measurements of any cracked irradiated stainles steels samples
  - IASCC susceptibility and crack propagation rate measurements testing as a function of neutron dose in simulated BWR NWC and HWC water and in simulated PWR primary water
  - Terminate each SCC propagation test with a fracture toughness test in the simulated reactor coolant

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O1 SS Brackets O2 Core Shroud R2 Fuel Nozzle O2, R2 X-750 R2 718	R2 baffles, bolts, core barrel, alignment pins			

Task 3
SS core support structures and internals

- **Subtask 3.1** Irradiation embrittlement including SS welds
- **Subtask 3.2** IASCC and corrosion fatigue susceptibility
- **Subtask 3.3** CASS and weld thermal ageing with irradiation effects

Subtask 3.3 – CASS thermal ageing with irradiation effects

- Objective:
  - Investigate possible interactions between thermal and irradiation embrittlement on the fracture toughness and IASCC susceptibility of CASS components and duplex stainless steel weld metals in both BWRs and PWRs

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O2 CRGT CASS	R2 Core Supports CASS			

Task 3
SS core support structures and internals

Subtask 3.1
Irradiation embrittlement including SS welds

Subtask 3.2
IASCC and corrosion fatigue susceptibility

Subtask 3.3
CASS and weld thermal ageing with irradiation effects

Subtask 3.3 – CASS thermal ageing with irradiation effects

- Approach to meet subtask objective:
  - Gamma spectroscopy characterizations of irradiated CASS and stainless steel weld metal samples in order to compare actual neutron doses to those estimated from plant calculations
  - Dye penetrant, polymer replica and macroscopic metallurgical examinations to detect any cracks if present in all highly irradiated BWR and PWR CASS and stainless steel weld metal samples
  - Detailed physical metallurgical characterizations (ATEM and APT) plus helium and hydrogen gas content measurements of any cracked samples
  - IASCC susceptibility and crack propagation rate measurements testing as a function of neutron dose in simulated BWR NWC and HWC water and in simulated PWR primary water
  - Terminate each SCC propagation test with a fracture toughness test in the simulated reactor coolant

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	O2 CRGT CASS	R2 Core Supports CASS			

Studsvik

Task 4
Austenitic pressure boundary alloys

- **Subtask 4.1**
  DMW and SS welds; SCC resistance in BWRs and PWRs
- **Subtask 4.2**
  Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs
- **Subtask 4.3**
  Fatigue in BWR and PWR reactor coolants

Subtask 4.1 – Dissimilar Metal Welds and stainless steel welds; SCC resistance in BWRs and PWRs

- Objective:
  - Study selected unirradiated stainless steel and Alloy 182 weldments including DMWs to identify metallurgical features associated with cracking or its absence, including those welds that have been treated with inlays/overlays of more resistant alloys or have been subjected to residual stress modification treatments.
  - SCC crack growth tests on the susceptible weld metal to check whether plant thermal ageing has affected susceptibility compared to the unaged database

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 Coolant Pump O2 T-joints & pipes (MSIP)	O2 DMWs R2 Pressurizer Heater Weld	O1 DMW T-joint		

Task 4
Austenitic pressure boundary alloys

Subtask 4.1
DMW and SS welds; SCC resistance in BWRs and PWRs

Subtask 4.2
Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

Subtask 4.3
Fatigue in BWR and PWR reactor coolants

Subtask 4.1 – Dissimilar Metal Welds and stainless steel welds; SCC resistance in BWRs and PWRs

- Approach to meet subtask objective:
  - Dye penetrant, polymer replica and metallurgical examinations of harvested unirradiated welds to determine the presence or not of any SCC.
  - Detailed physical metallurgical characterizations (SEM, TEM, APT) of any cracked weld metal and HAZ samples
  - Determine through-thickness residual stress profiles of butt welds, particularly those subjected to MSIP, and measure shrinkage strains in HAZs adjacent to fusion lines – compare to archive specimens
  - SCC propagation rate measurements in simulated BWR NWC and HWC and in simulated PWR primary water
  - Terminate each SCC crack growth test with a fracture toughness test in the simulated reactor coolant

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 Coolant Pump O2 T-joints & pipes (MSIP)	O2 DMWs R2 Pressurizer Heater Weld	O1 DMW T-joint		

Studsvik

Task 4
Austenitic pressure boundary alloys

- **Subtask 4.1** DMW and SS welds; SCC resistance in BWRs and PWRs
- **Subtask 4.2** Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs
- **Subtask 4.3** Fatigue in BWR and PWR reactor coolants

Subtask 4.2 – Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

- Objective:
  - Examine selected Alloy 690 steam generator tubes and also selected Alloy 152/52 butt welds and J-groove weldments from the replacement Ringhals 2 steam generators and upper head for any evidence of PWSCC initiation and LRO with particular attention on determining the effect of weld shrinkage strain on cold work levels in Alloy 690 HAZs adjacent to the fusion lines of all weld geometries

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 SG tubes Alloy 690	R2 CRDM tube Alloy 690?			R2 CRDM tube Alloy 690 J-Weld 182?

Studsvik

Task 4
Austenitic pressure boundary alloys

Subtask 4.1
DMW and SS welds; SCC resistance in BWRs and PWRs

Subtask 4.2
Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

Subtask 4.3
Fatigue in BWR and PWR reactor coolants

Subtask 4.2 – Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

- Approach to meet subtask objective:
  - Dye penetrant, polymer replica and metallurgical examinations of harvested unirradiated welds to determine the presence or not of any SCC
  - Measure residual stresses in J-groove welds as a function of CRDM penetration set-up angle in the upper head
  - Detailed physical metallurgical characterizations (SEM, TEM, APT) of any cracked weld metal and HAZ samples
  - X-ray diffraction examinations for intermetallic phases associated with Long Range Ordering (LRO) during thermal ageing
  - If evidence of PWSCC or LRO is found then conduct mechanical properties, fracture toughness tests and PWSCC crack propagation rates in simulated PWR primary water
  - Terminate each PWSCC crack growth test with a fracture toughness test in the simulated primary water environment and compare to fracture toughness test results in air

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 SG tubes Alloy 690	R2 CRDM tube Alloy 690?			R2 CRDM tube Alloy 690 J-Weld 182?

Task 4
Austenitic pressure boundary alloys

Subtask 4.1
DMW and SS welds; SCC resistance in BWRs and PWRs

Subtask 4.2
Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

Subtask 4.3
Fatigue in BWR and PWR reactor coolants

- **Subtask 4.3 – Fatigue in BWR and PWR reactor coolants**
  - Objective:
    - Examine low cycle fatigue sensitive components for any evidence of corrosion fatigue cracking
    - Examine any high cycle fatigue sensitive components for any evidence of cracking and wear
    - Compare observations to fatigue life predictions

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 Spray Nozzle CASS O1 T-joints O2 Steam Drier	R2 Flow Mixer CASS O2 T-joints			

Task 4
Austenitic pressure boundary alloys

Subtask 4.1
DMW and SS welds; SCC resistance in BWRs and PWRs

Subtask 4.2
Alloy 690/152/52 PWSCC resistance and thermal stability in PWRs

Subtask 4.3
Fatigue in BWR and PWR reactor coolants

- **Subtask 4.3 – Fatigue in BWR and PWR reactor coolants**
  - Approach to meet subtask objective:
    - Dye penetrant, polymer replica and macroscopic metallurgical examinations to determine the presence or not of any cracks and/or wear damage
    - Fatigue life calculations for the harvested components using the original design transients and, where available, using known plant transient histories, together with environmental corrections like F_{en} where applicable, and compare with the original plant design calculations

Q4 2020	2021	2022	2023	2024	2025
SMILE kick-off	R2 Spray Nozzle CASS O1 T-joints O2 Steam Drier	R2 Flow Mixer CASS O2 T-joints			