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CHALLENGES FOR LTO BEYOND 60 YEARS IN CLASS 1 PIPING SYSTEMS

Martin Bjurman, Anders Jenssen, February, 2024

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OUTLINE

- Introduction to Class 1 piping
- Swedish status with respect to LTO beyond 60 years
- Identified gaps
- SMILE perspective
  - Specifics of the relevant subtasks
- Conclusions

INTRODUCTION

- This presentation covers gaps identified where further work would be beneficial to Class 1 piping for aging plants in LTO
  - Most of the areas are important to, but not explicit to aging beyond 60 years
  - Applicability also to lower class piping as well as peripheral internals and penetrations where radiation effects are negligible
  - Highly relevant from the perspectives of plant availability and defense in depth perspectives

SAFETY CLASS 1 PIPING SYSTEMS

- Primary piping that cannot be closed off by double safety valves and where pipe rupture causes a significant leak (equivalent to >10 mm pipe rupture)
- Components of concern are:
  - **Piping including elbows, tees, etc.**
  - *Valves including internals as e.g. valve stems and seats*
  - *Penetrations and safe-ends, etc.*
- Many material qualities and components are covered, e.g.
  - Stainless steels, e.g., types 304, 304L and 316L, as well as cast grades CF3(M) or CF8(M) including weldments – historically mainly type 308
  - Low alloy steels, often clad with stainless steel or Ni-base alloys
  - Nickel base materials e.g. Alloy 600, 690
  - *High strength components e.g., X-750, XM19, 17-4PH etc.*

INTRODUCTION TO THE CASE OF SWEDISH NPPS

- 12 LWRs were built during the 70s and 80s
  - 6 reactors remain in service
    - Ringhals 3 and 4 - Westinghouse 3-loop PWRs
    - Forsmark 1-3 and Oskarshamn 3 - ASEA-Atom BWRs

- Owners publicly expressed aims for life extension of Swedish NPPs to 80 years

- Components from the shut down BWRs Oskarshamn 1 and 2, and the PWR Ringhals 2 have been and will be harvested for aging research

BACKGROUND TO STUDSVIK AGING WORK AND THE SMILE PROJECT

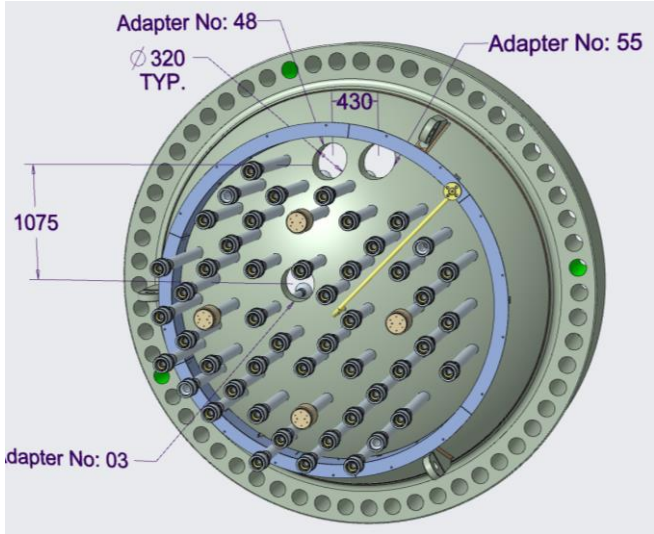
- Ageing degradation of structural materials in LWRs is a significant challenge for their continued safe and reliable operation
  - In particular for plant life extension beyond the original 30 to 40-year design life
- Several international studies have identified, categorized, and prioritized the main causes of materials degradation due to metal fatigue, corrosion-related mechanisms, thermal ageing, and neutron irradiation damage
  - Methodologies and guidelines for the development of Ageing Management Plans (AMPs)
- Aging management relies on models of the kinetics of the degradation mechanisms as well as validated replacement materials/components where necessary
  - Quantifying ageing to justify extended operation requires acceleration of laboratory tests and a soundly based method of extrapolation in time
  - For most ageing processes, good mechanistic understanding and verification against plant operating experience as well as laboratory data are required

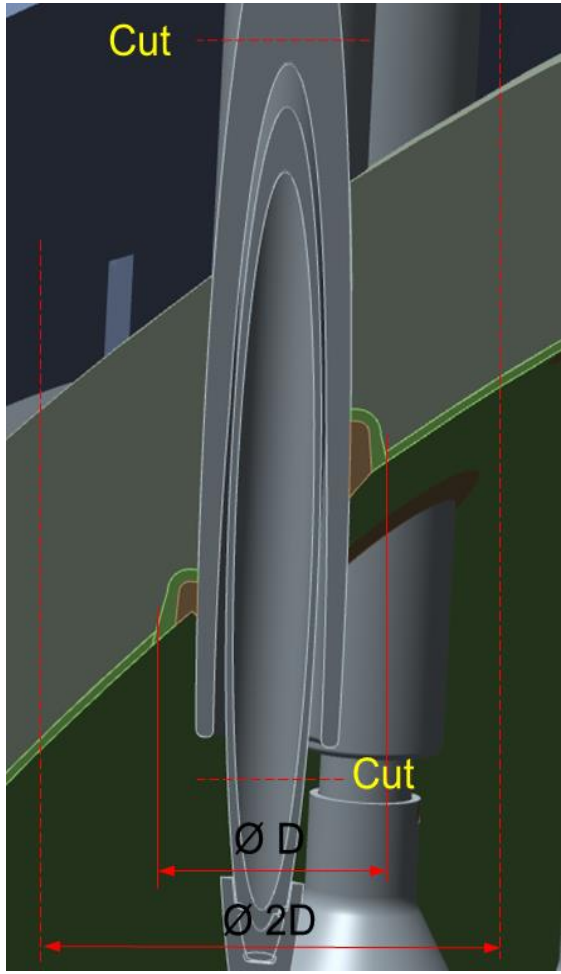
PWR & BWR DEGRADATION MOST RELEVANT TO LTO BEYOND 60 YEARS

- Fatigue – Significant conservatism/uncertainty when applied at component level
  - Low cycle fatigue (LCF) in LWR environments
  - Effects of aging on LCF behavior
- Thermal aging
  - Possible degradation of Alloy 690 causing hardening and possibly increased SCC sensitivity by various contributing factors, e.g., LRO, precipitate and GB void formation
  - CASS and stainless steel welds - reduction of fracture toughness
    - Aging studies of CASS at operating temperatures (well below 400°C) and very long aging times to verify level of conservatism
    - Weld and HAZ regions of CASS
  - Embrittlement of precipitation hardened high strength stainless steel – e.g., valve stems
  - LAS piping incl. weld with particularly susceptible compositions
  - Non-destructive techniques to quantify degradation

PWR – DEGRADATION MOST RELEVANT TO 60+

- PWSCC - Primary Water Stress Corrosion Cracking
  - SS with increased strain or high residual stress states – most recently the French experience of cracking in 316L ECCS
  - Long-term effectiveness of mitigation techniques, e.g., overlay/inlay welding or introduction of surface compressive stresses by peening, MSIP* etc.
  - Alloy 600 and weldments - cracking of penetrations/nozzles and safe-ends
  - Alloy 690 and weldments - crack growth rates and possible increased SCC susceptibility linked to long term aging degradation processes

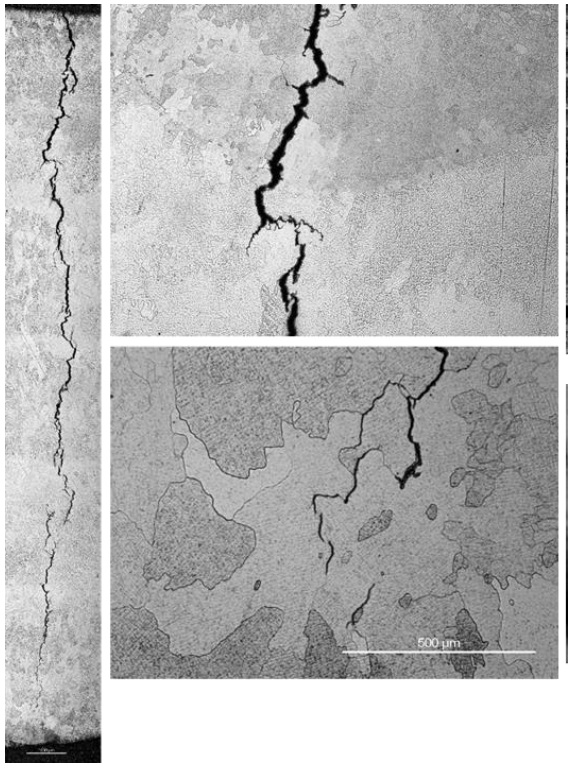




* Mechanical Stress Improvement Process

BWR - DEGRADATION MOST RELEVANT TO 60+

- SCC
  - SS with increased strain/stress or high residual stress states – Intergranular cracking of 316L after relatively short times in service were seen in BWRs - some similarities to the recent events in French PWRs
  - Long term effectiveness of mitigation and repair techniques, e.g., overlay/inlay welding or introduction of surface compressive stresses by peening, MSIP* etc.
  - Alloy 600 and weldments - cracking of penetrations/nozzles and safe-ends
- Oxide stability of Nickel base alloys
  - Alloy 82 exhibits increased dissolution rates in NWC with high flow rate

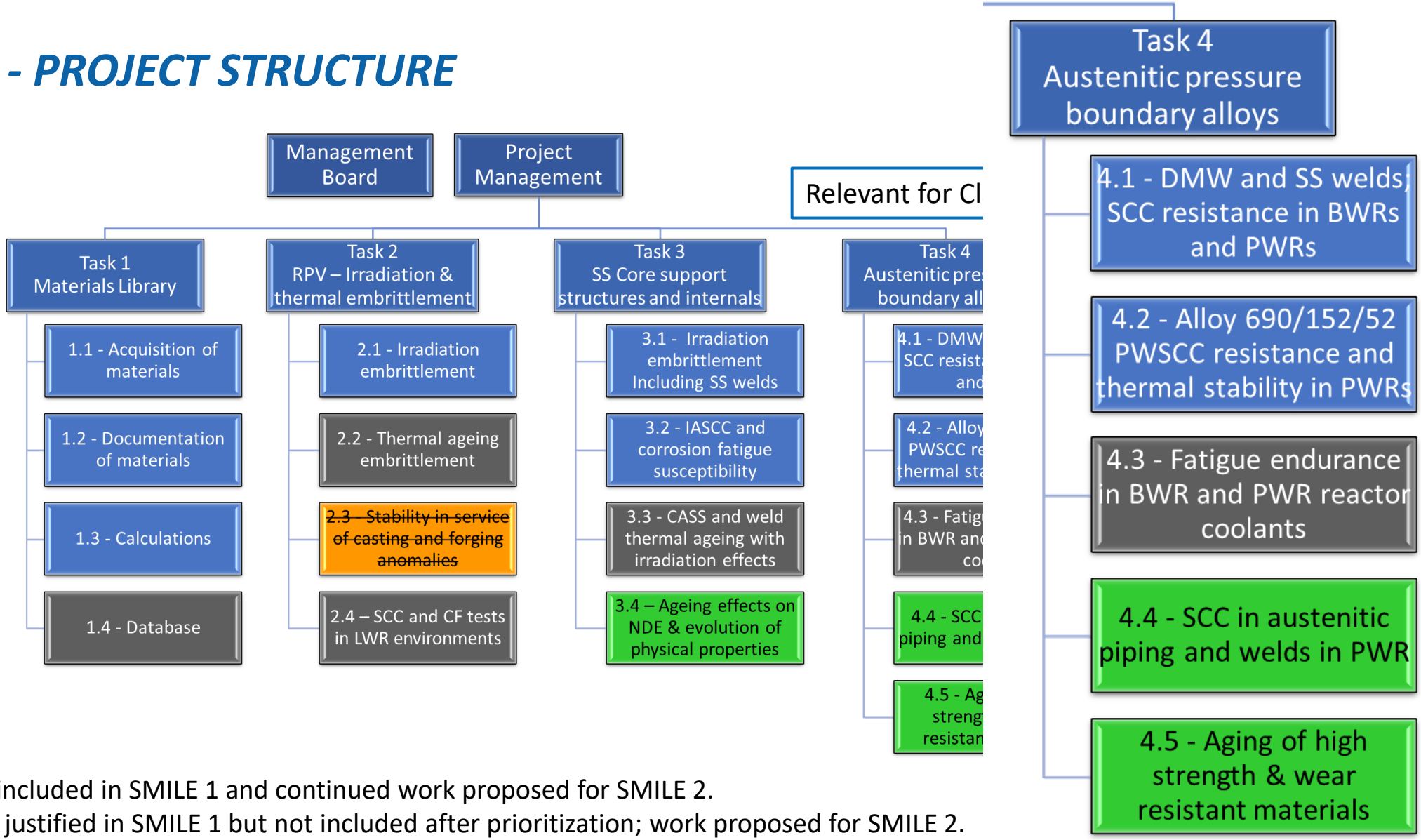


* Mechanical Stress Improvement Process

SMILE PHASES 1 AND 2

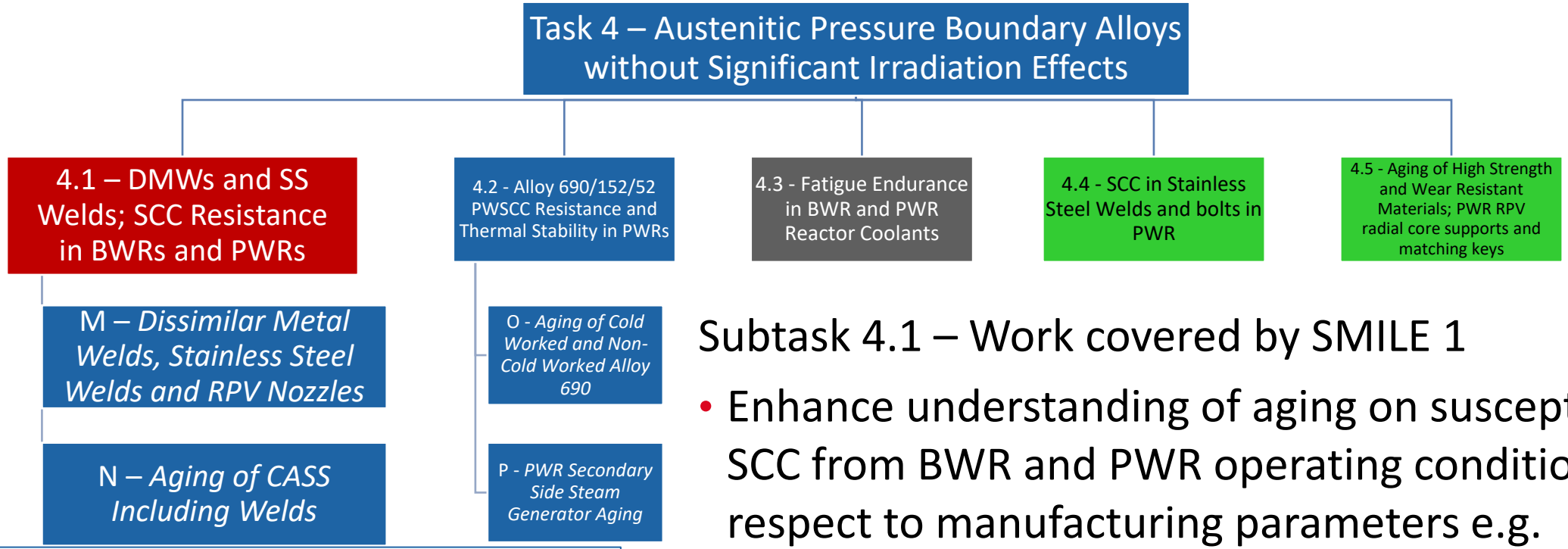
- Studsvik has launched SMILE (Studsvik Materials Integrity Life Extension), a project that supports LWR operators and authorities worldwide in plant ageing management
- The main objective is to provide critical data and mechanistic understanding of materials ageing mechanisms in support of plant ageing management, life extension programs and operating license renewals
- The experimental approach leverages a unique opportunity to harvest materials from Swedish LWRs that have recently shut down after 40+ years of operation
  - Examination and testing of fully aged materials directly relevant to LWRs will provide information that can be used to improve and develop models for the prediction of ageing
- SMILE is a 5-year project that started in January 2021
  - Currently SMILE has 15 member organizations from 8 countries
- A second phase of SMILE is under preparation with planned start January 2026
  - Extended assessment of aging degradation issues

SMILE - PROJECT STRUCTURE



Blue boxes –included in SMILE 1 and continued work proposed for SMILE 2.
Grey boxes – justified in SMILE 1 but not included after prioritization; work proposed for SMILE 2.
Green boxes – not justified in SMILE 1 but work in these areas has been identified for SMILE 2.
Orange box - justified in SMILE 1 but not included after prioritization; work not proposed for SMILE 2.

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (1)



- Alloy 600/182
  - Penetrations - BWR and PWR
  - Core support leg - BWR
- MSIP treated SS pipe with crack (treated 1988) - BWR

Subtask 4.1 – Work covered by SMILE 1

- Enhance understanding of aging on susceptibility to SCC from BWR and PWR operating conditions and with respect to manufacturing parameters e.g.
- Weld parameters and setup angle, geometry
  - Residual stress and residual strains
  - Defects and microstructure
- Aging influence with respect to
  - Microstructural stability
  - Mechanical properties
  - SCC growth rates

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (2)

Task 4 – Austenitic Pressure Boundary Alloys without Significant Irradiation Effects

- 4.1 – DMWs and SS Welds; SCC Resistance in BWRs and PWRs
  - M – *Dissimilar Metal Welds, Stainless Steel Welds and RPV Nozzles*
  - N – *Aging of CASS Including Welds*
- 4.2 - Alloy 690/152/52 PWSCC Resistance and Thermal Stability in PWRs
  - O - *Aging of Cold Worked and Non-Cold Worked Alloy 690*
  - P - *PWR Secondary Side Steam Generator Aging*
- 4.3 - Fatigue Endurance in BWR and PWR Reactor Coolants
- 4.4 - SCC in Stainless Steel Welds and bolts in PWR
- 4.5 - Aging of High Strength and Wear Resistant Materials; PWR RPV radial core supports and matching keys

- Alloy 600/182
  - **Penetrations - BWR and PWR**
  - Core support leg – BWR
  - **Weld inlay/repair weld BWR and PWR**
- MSIP treated SS pipe with crack (treated 1988) - BWR

Subtask 4.1, RT M – Work proposed for SMILE 2

- Continued work from SMILE 1 with the addition of:
  - BWR – RPV nozzles with Alloy 82 inlays and A600/182 RPV penetration at low set-up angle
  - PWR – A600/182 RPV head penetration at low set-up angle, BMI nozzles, and RPV inlet nozzle
- Increased attention to:
  - Mechanical properties - Tensile and FT testing
  - Susceptibility to SCC-initiation

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (3)

Task 4 – Austenitic Pressure Boundary Alloys without Significant Irradiation Effects

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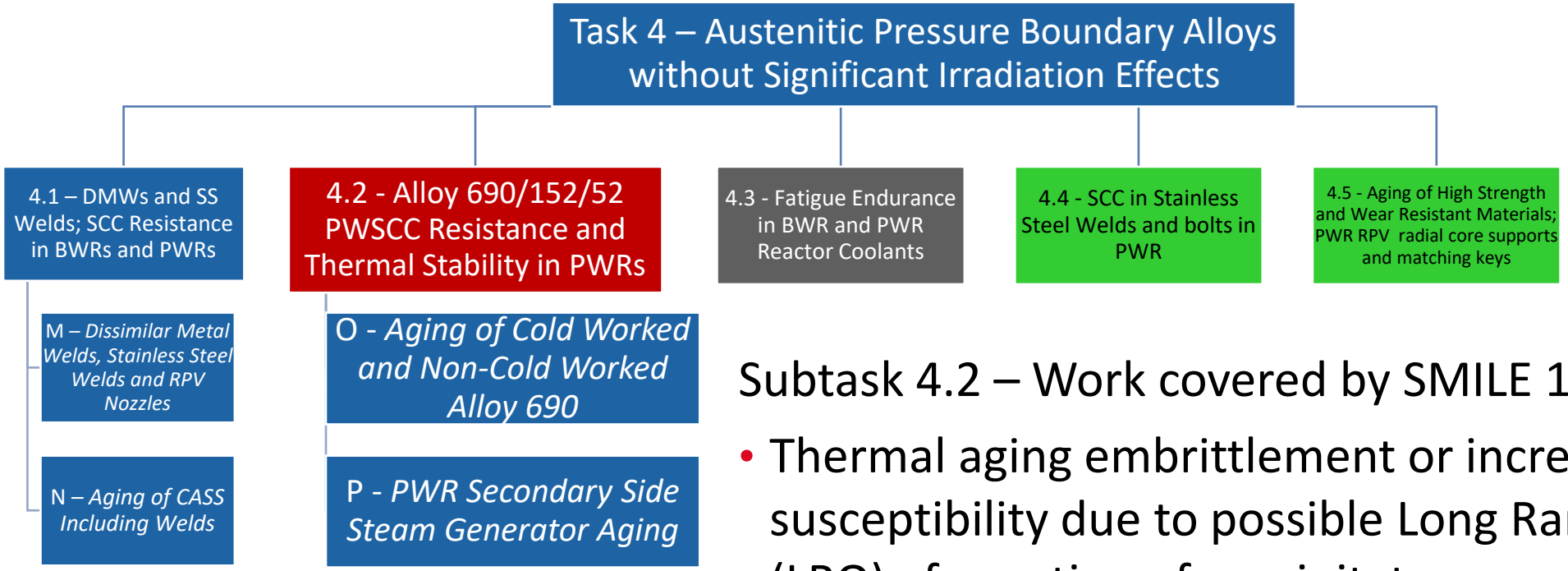
- CASS - CF3M and CF8M incl. welds e.g. Ringhals reactor coolant pump (RCP)
- Austentic welds Type 308 (and 316(L))

- Subtask 4.1, RT N – Work covered by SMILE 1?
  - Not addressed in SMILE 1
- Subtask 4.1, RT N – Work proposed for SMILE 2
  - Understanding of aging degradation of welded CASS at operating conditions is incomplete
  - Study metallic inter-mixing zone of Type 308 welds, HAZ and regions with high residual stress near the weld, and CASS far away from the weld where there are no effects of stress or microstructure
  - Characterization includes; LOM/SEM, hardness, ferrite measurements, and FT and tensile testing
  - Quantification of phase evolution and decomposition by TEM & APT

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (4)

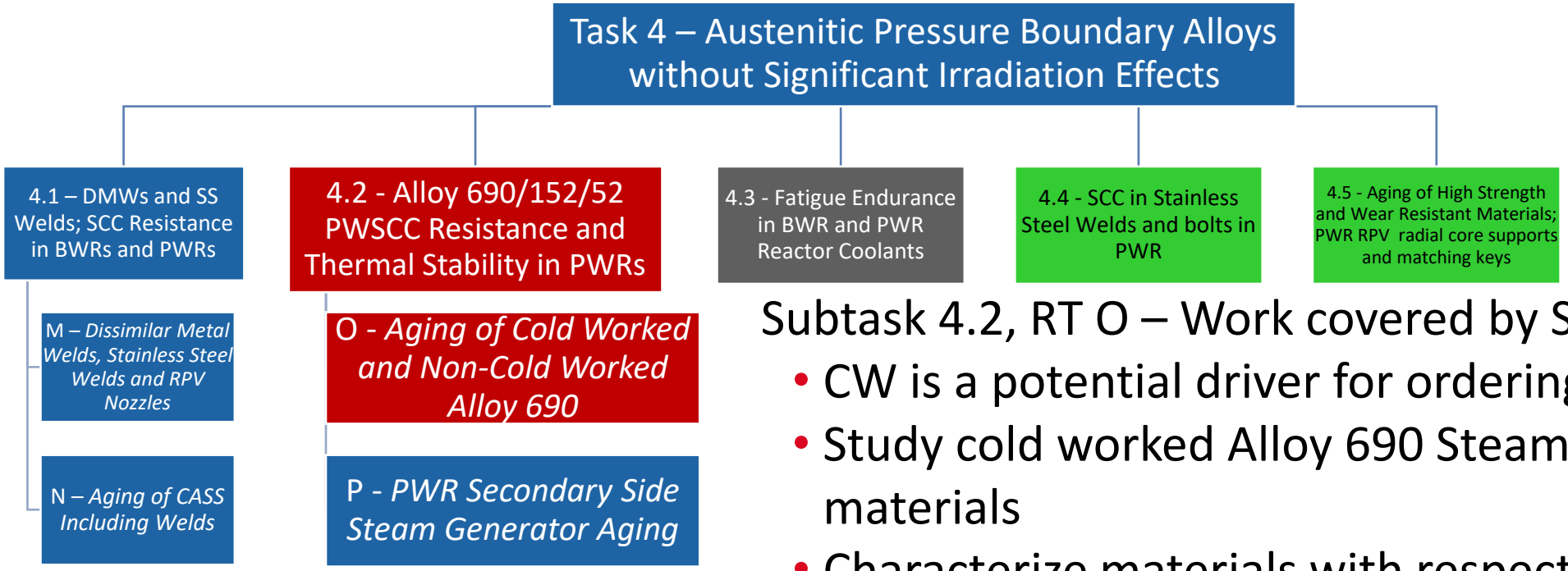


- A690/152/52 RPV head penetrations
- A690 SG tube (>9% Fe)

Subtask 4.2 – Work covered by SMILE 1

- Thermal aging embrittlement or increased PWSCC susceptibility due to possible Long Range Ordering (LRO), formation of precipitates, or voids at GBs
- Understanding of weld shrinkage strain on CW levels in Alloy 690 HAZs adjacent to the weld fusion lines is incomplete and could be aggravating for LRO and SCC
- Find signs of precursors to PWSCC or any effect of aging on microstructure, mechanical properties or SCCGRs

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (5)

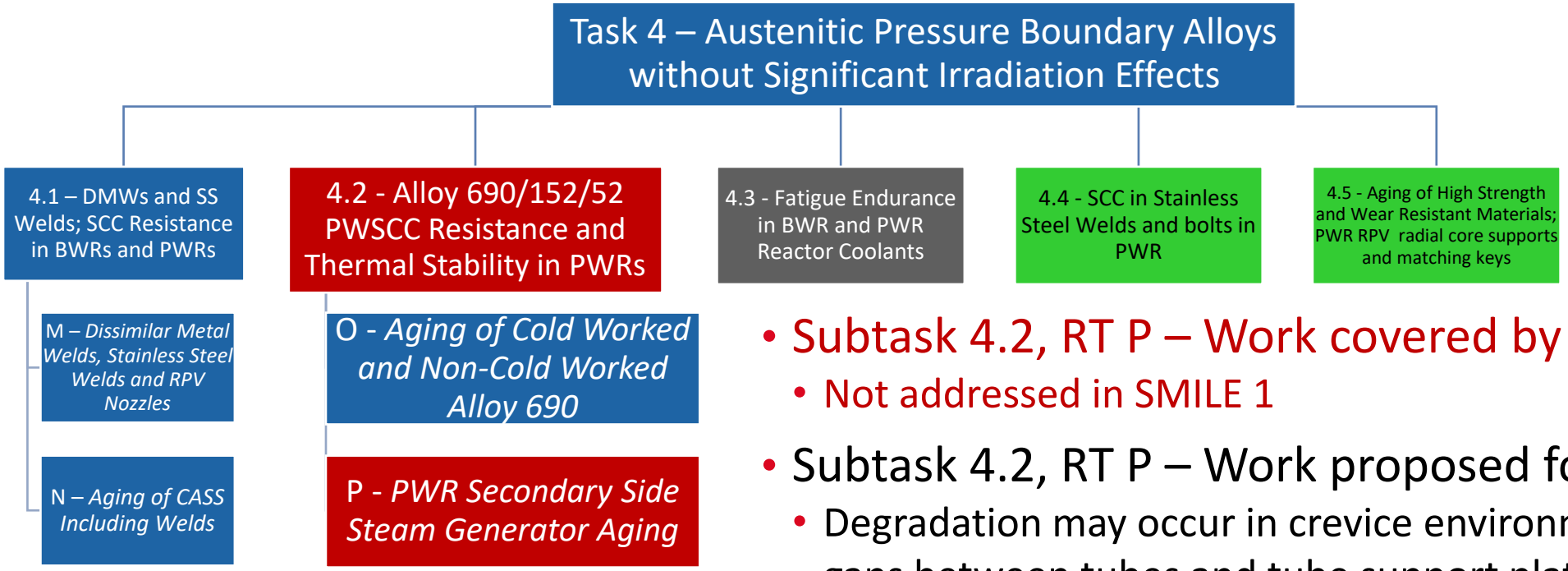


- A690/152/52 RPV head penetrations
- A690 tubes (<9% Fe), from tube plate region, inner radius tubes from upper part of SG, tube plugs

Subtask 4.2, RT O – Work covered by SMILE 2

- CW is a potential driver for ordering, SCC, etc.
- Study cold worked Alloy 690 Steam generator materials
- Characterize materials with respect to
  - Microstructure, mechanical properties, hardness and tensile testing, residual stress state in tube-to-tube plate weld and tube expansion transition
- Quantify effects on SCC initiation and propagation
- Furnace age materials at times and temperatures corresponding to additional 20 to 40 years

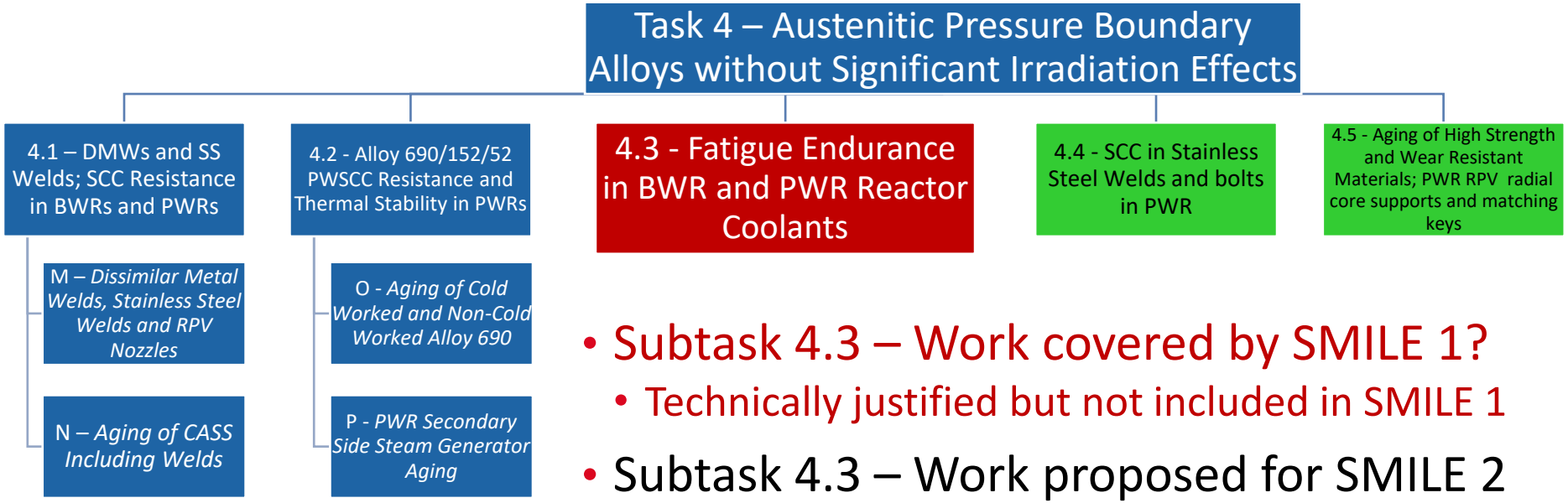
TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (6)



- A690 tubes (<9% Fe), tubes at tube support regions and tube plate region

- Subtask 4.2, RT P – Work covered by SMILE 1?
  - Not addressed in SMILE 1
- Subtask 4.2, RT P – Work proposed for SMILE 2
  - Degradation may occur in crevice environments formed in the gaps between tubes and tube support plates, and locations where sludge piles have formed
    - Examination of oxides and precipitates in these regions
    - Examine full thickness of tube-to-tube plate regions and tubes with known indications at support plate positions
    - Visual inspections, LOM/SEM, deposit analysis, and detailed oxide characterization using XRD and TEM

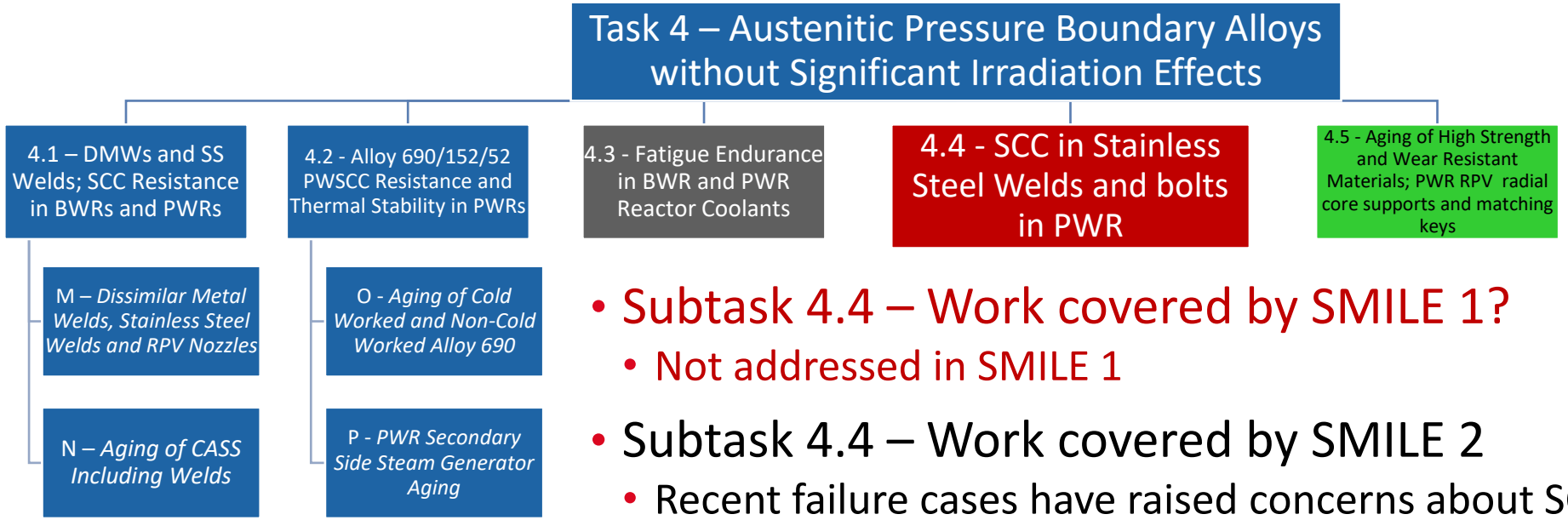
TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (7)



- Subtask 4.3 – Work covered by SMILE 1?
  - Technically justified but not included in SMILE 1
- Subtask 4.3 – Work proposed for SMILE 2
  - Cracking at positions mixing hot and cold water is a relatively common cause of failures with large uncertainty (conservatism) in predictions. Case validation of the complete system from flow modelling to quantifying thermal fatigue in BWR and PWR environments is therefore beneficial
  - Characterization of cracking and mechanical properties
  - Fatigue endurance testing in BWR and PWR environments

- Stainless steel Mixing-T with known cracking
- BWR FW nozzle and cracked bracket from a thermal shield
- PWR pressurizer surge line

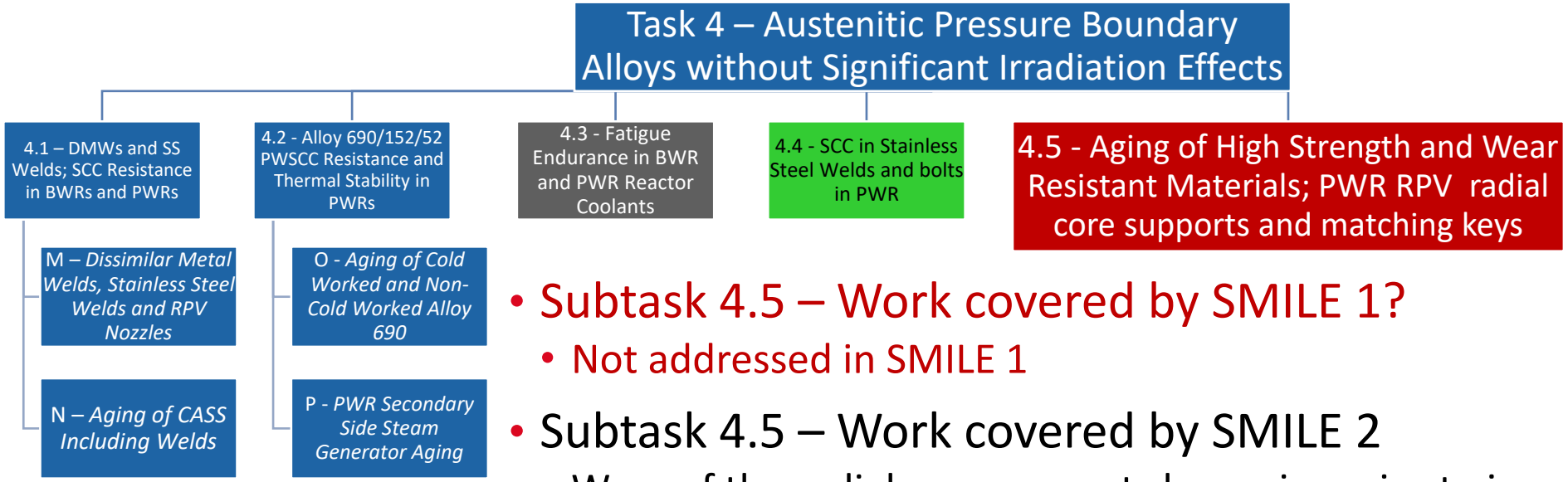
TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (8)



- SS welds, including cast elbows, turning vane bolts and pressurizer heaters

- Subtask 4.4 – Work covered by SMILE 1?
  - Not addressed in SMILE 1
- Subtask 4.4 – Work covered by SMILE 2
  - Recent failure cases have raised concerns about SCC of SS weldments in PWR primary water. Influence of strain/stress, microstructure and environment can be enhanced by studying harvested components
  - Study SS welds, including cast elbows, turning vane bolts and prz heaters
    - NDT, RSM, and surface oxide characterizations and microscopy by LOM/SEM, including hardness, to investigate for signs of cracking or its precursors
    - If there are signs of SCC - Perform crack initiation, and CGR testing in PWR environments representing flowing and stagnant conditions

TASK 4 – AUSTENITIC ALLOYS WITHOUT IRRADIATION EFFECTS (9)



- Core support key and clevise
- Possible addition of further high strength components

- Subtask 4.5 – Work covered by SMILE 1?
  - Not addressed in SMILE 1
- Subtask 4.5 – Work covered by SMILE 2
  - Wear of the radial core supports have given rise to increased rotational vibration of the core
  - Not relevant for class 1 piping, but:
- Thermal aging embrittlement of other high strength steels such as 17-4PH in e.g., valve spindles etc. may need reconsideration for 60+ years

CONCLUSIONS

- The presentation summarizes needs for additional research for Class 1 piping when operating plants beyond 60 years - No areas of critical importance and general nature have been identified.
- Some areas where further work would be beneficial from both safety and operational perspectives were identified.

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THANKS
FOR LISTENING!