**AMP163 DISSIMILAR METAL WELDS (Version 2021)**

**Programme Description**

This ageing management programme (AMP) refers to dissimilar metal welds (DMWs), sometimes called bi-metallic or tri-metallic welds. A DMW is a weld between: 1) carbon or low alloy steels and high alloy austenitic stainless steels, 2) carbon or low alloys steels to nickel base alloys, or 3) high alloy austenitic stainless steels to nickel base alloys. DMWs are employed to account for and to accommodate differences in materials chemistries and thermo-mechanical and thermo-physical incompatibilities of the materials to be joined. Because materials of different chemistries are often employed to fabricate DMWs, e.g. nickel base alloys are used for DMWs between carbon or low alloy steels and high alloy austenitic stainless steels, the constraints imposed on DMWs and the concerns for ageing management can be significantly different to those for welds between similar metals [1].

The type of DMW depends on the design of the reactor, the materials used and the welding method. However, the design and the welding techniques for DMWs of BWR, PWR and WWER NPPs are similar, because ferritic steel (carbon or low-alloy steel) or stainless steel (high-alloy steel) is used as a base material. In all cases however the role of the filler metal is to provide a thermo-mechanical and chemical buffer layer between the two materials, for instance direct welding of low alloys ferritic steels to high alloy austenitic stainless steels can result in diffusion of chemical elements from one phase to the other which can result in degradation of properties of either steel. Moreover, the direct contact of ferritic and austenitic materials can, due to their differences in thermal expansion, result in undesirable welding residual stresses and, accordingly, increased stresses from the operational load. Various types of alloys are used as filler and buttering layer material (high-alloy steel or high-nickel alloy). A buttering layer is using more specialized chemical compositions and more restrictive welding parameters is often used on one side of the DMW to prepare the weld joint to be less sensitive to the effects of higher heat input welding as the weld joint gap is filled with the filler metal selected for the major portion of the DMW. Note that while DMWs can occur as butt welds between piping components they are also used to attach penetrations to pressure boundary components, e.g. joining reactor vessel head penetrations into the reactor vessel head. Because of the differences in materials across the weld gap and the differences in chemical composition that can occur in the filled metal across the weld gaps, DMWs can be susceptible to degradation modes that do not occur in similar metal welds. In particular, DMWs in western type PWRs and BWRs which include nickel base alloy filler metals have been found to be prone to a form of stress corrosion cracking (SCC), known as intergranular stress corrosion cracking (IGSCC) (often referred to as primary water stress corrosion cracking (PWSCC) for PWRs). Both J-groove and butt welds have been found to be affected in plants. Cracking can be affected not only by the differences in mechanical constraints across the weld joints but also by the microstructures of the weld.

A power plant application of DMWs is given in ASME Boiler and Pressure Vessel Code [2]. It should be noted that DMWs in western type PWRs and BWRs generally employ nickel base alloys (308/309, 52/152 (Inconel 690) and 82/182 (Inconel 600)) between low alloy steels and austenitic stainless steels, WWERs use medium alloyed steel filler metals for low alloy steel to stainless steel DMWs.

This AMP includes activities for inspecting, detecting, preventing, monitoring, mitigating and evaluating of the ageing degradation effects of DMWs of the primary piping system and their connections to the vessels nozzles and sleeves, and head penetrations of BWR, PWR and WWER reactors [3]. For BWRs the ageing management of DMWs can be also covered by AMP107 and AMP108 and for PWR by AMP111.

### Evaluation and Technical Basis

1. ***Scope of the ageing management programme based on understanding ageing:***

The scope of the programme includes the following DMWs:

* + Reactor pressure vessel (RPV) nozzles to safe ends (SE) welds: inlet, outlet (PWR, WWER-440), safety injection (PWR);
  + RPV recirculation outlet and inlet nozzles to SE welds (BWR);
  + RPV jet pump instrumentation nozzles welds (BWR);
  + RPV core spray nozzles to SE welds) and SE to safe end extension welds (BWR);
  + RPV control rod drive (CRD) return line nozzle to SE welds (BWR);
  + RPV instrument penetrations welds (BWR, PWR);
  + RPV standby liquid control (SLC) nozzles/Core ΔP nozzles weldments (BWR);
  + RPV feedwater nozzles to SE welds (BWR, PWR);
  + RPV bottom mounted instrumentation (BMI) nozzles welds (PWR);
  + RPV control rod drive mechanism (CRDM) penetration welds (BWR, PWR) and in-core monitoring (ICM) penetration welds;
  + SG inlet and outlet primary side nozzles to pressure boundary welds (PWR);
  + SG channel head drains welds (PWR);
  + SG inlet and outlet primary side collectors to vessel nozzles welds (WWER-440);
  + Reactor coolant pump suction and discharge nozzles welds (PWR);
  + Pressurizer spray and surge nozzles welds (PWR);
  + Pressurizer safety and relief valve nozzles welds (PWR);
  + Main coolant pipeline (MCP) hot leg nozzle SE weld to surge pipeline (PWR, WWER-1000);
  + MCP hot leg nozzles SE welds to shutdown cooling and drain pipelines (PWR);
  + Main coolant pipeline (MCP) cold leg nozzle SE welds spray pipeline (PWR, WWER-1000);
  + MCP cold leg nozzles SE welds to charging, safety injection and letdown/drain pipelines (PWR);
  + Emergency core cooling system pipelines and pressurizer surge pipeline welds (WWER-1000).

The following ageing degradation mechanisms are considered in this AMP:

* + Stress corrosion cracking (BWR, PWR);
  + Fatigue /low-cycle and environmentally assisted fatigue/ (PWR);
  + Thermal ageing (PWR);
  + Thermal fatigue (PWR);
  + Boric acid corrosion (PWR).

Stress corrosion cracking

Stress corrosion cracking (SCC) is a complex phenomenon driven by the synergetic interaction of a corrosive environment, a tensile stress and a specific and to some extent susceptible material. SCC typically shows branched cracks.

The cracking morphology of SCC can manifest itself in three forms [4]:

* + Intergranular stress corrosion cracking (IGSCC). The crack predominantly propagates along grain boundaries in materials of wrought forms or the heat affected zone of a weld. Austenitic stainless steel with sensitized grain structure is susceptible to IGSCC. The chromium–depleted grain boundaries offer less resistance to corrosion.
  + Transgranular stress corrosion cracking (TGSCC). The crack predominantly propagates through grains without a preferential crack path. Chloride–induced SCC in austenitic stainless steel has such form of cracking morphology.
  + Interdendritic stress corrosion cracking (IDSCC). This form of SCC can be found in weld deposit consisting of dendritic solidification structure. The crack path tends to follow the interdendritic areas where undesirable microstructural constituents and carbides tend to agglomerate. The interdendritic area can also be chromium depleted. With dissimilar metal flaws, the cracking is interdendritic rather than intergranular.

Primary water stress corrosion cracking (PWSCC) is defined as the intergranular cracking of nickel-base alloys that requires the presence of high applied or residual stress, susceptible microstructures (few intergranular carbides) a primary water environment and high temperatures. Note that the term PWSCC is not used as a term for SCC occurring under BWR conditions [5].

AMP 111is focused on managing the effects of cracking due to SCC of all susceptible nickel alloy-based components of the reactor coolant pressure boundary, including nickel-alloy butt welds (600/82/182). AMP 107 covers the SCC ageing management of reactor coolant pressure boundary piping and piping welds made of austenitic SS and nickel-based alloys in BWRs.

Crack initiation and crack growth in DMWs could be affected by the several parameters. In particular, research indicates that:

a) The possibility of crack initiation due to the SCC is a function of operating time and operating temperature.

b) Several parameters are involved in the crack growth rate of the SCC. In addition, actual tests, which were conducted to measure SCC crack growth rates, show that crack growth rates are highly scattered. Hence, the quantification of crack growth rate due to SCC would be challenging.

Low cycle fatigue

Low cycle fatigue is caused by cyclic loading of system, structures and components (SSC) during operation. The critical locations for low-cycle fatigue are RPV, SG, Pressurizer, MCP nozzles to SE connections and RPV penetrations welds (AMP101).

Thermal ageing

Thermal ageing of materials is a time and temperature-dependent degradation mechanism that reduces material toughness. During reactor operation, the reactor coolant pressure boundary components are exposed to temperatures above 250 °C, which may lead to thermal ageing and change the level of the mechanical properties and service characteristics of the material. The effect of thermal ageing embrittlement of austenitic stainless steel welds is manifested in cleavage fracture in the ferrite phase or separation of the ferrite/austenite phase boundary [6].

Thermal fatigue

Thermal fatigue is the major ageing mechanism for surge and spray pipelines and nozzles (ECCS pipelines, charging and safety injection pipelines, etc.) that are subject to thermal transients during plant startup/shutdown, thermal stratification, thermal shock, turbulent penetration and thermal cycling. The DMW safe ends connections of MCP (manufactured from austenitic stainless steel) to RPV nozzles are also susceptible to thermal fatigue [7].

The heat–up and cooldown cycles impose thermal strains on DMWs having stainless steel as filler metal, because the thermal expansion coefficient of stainless steel is about 30% higher than that for ferritic steel [4].

Boric acid corrosion

Boric acid corrosion of carbon or low alloy steel can be a consequence of SCC failure of a DMW. Breach of the pressure boundary by DMW SCC cracking can expose carbon steel or low-alloy steel to heated borated water. The impingement of escaping borated water onto piping or structural sections of reactor vessel heads can result in significant loss of material due to boric acid corrosion. However, it is noted that advantage may be taken of the visible formation of white boric acid deposits from small, early-stage leaks as part of the ageing management program.

1. ***Preventive actions to minimize and control ageing degradation:***

The programme identifies the preventive actions defined as those that are necessary to prevent or minimize initiation of degradation during normal operation.

Prevention/mitigation of SCC has often involved repair and replacement actions using more resistant materials like Alloy 690TT and its compatible weld metals Alloys 152 and 52 [1]. An overview of the repair and mitigation methods applicable for light water reactors is given in [8].

Increased attention is also being paid to mitigation measures involving: weld build-up at the pipe inside surface (inlay); weld build-up of the pipe outside surface (overlay); surface treatment (e.g., water-jet and shot peening for generating compressive stress on the outer surface of the pipe to arrest a crack growth and prevent initiation of new cracks); Mechanical Stress Improvement (MSIP); water chemistry optimization (e.g., adjustment of hydrogen concentration levels and/or addition of potentially inhibiting species such as zinc) [1]. For BWRs, the use of hydrogen-water chemistry (HWC) is used for mitigation of SCC. The programme description, evaluation and technical basis for monitoring and maintaining of reactor coolant chemistry are addressed in AMP103.

The preventive actions to reduce boric acid corrosion are addressed in AMP110. On-line diagnostic systems for leakage monitoring of the primary system pressure boundaries are also used.

1. ***Detection of ageing effects:***

For each ageing effect of a DMW, the state parameters that have an impact on the ageing and thus need to be controlled are determined, as well as adequate control techniques to ensure the ageing management of the elements under consideration.

The programme manages the following age-related degradation effects and mechanisms:

a) Cracking induced by stress corrosion cracking (PWSCC, IGSCC, TGSCC and IDSCC), thermal fatigue, fatigue/cyclical loading.

In-service inspections (ISI; see AMP102 and [2-4, 9]) are intended to detect degradation (i.e., ageing effects). As example for BWRs information on inspection schedules are given in [10]; for PWR information on inspection schedules can be found in e.g. ASME Code Case N-770 [11].

The following non-destructive examination (NDE) methods may be used: visual testing (VT), surface examinations such as dye penetrant testing (PT) and eddy current testing (ECT), and volumetric ultrasonic testing (UT). ECT examinations of the inside surface, where PWSCC cracks initiate, are only practical on the reactor vessel inlet and outlet nozzle butt welds since the inside surfaces of most butt welds are not accessible. For example, NDE requirements and methodology for performing examination of DMW locations are provided in MRP-139 [12]. Inspection methods, schedules, and ISI frequency of the DMW are implemented in accordance with applicable regulatory requirements and industry guidelines.

Detailed information on corresponding national inspection programmes is also given in IAEA Technical Report No. NP-T-3.13 [8]. Accordingly, the inspections mainly rely on the following requirements as modified by the applicable guidance, e.g.:

* + US NRC GL 88-01 [13];
  + Section XI of the ASME Code [2]
  + KTA 3201.4 [14] (e.g. Germany);
  + JSME S NA1-2016 [15] and NRA-1408063 [16];
  + SKIFS 2005:2 (Sweden; risk-based approach) [17];
  + BWRVIP-75-A [10].

b) Loss of fracture toughness induced by thermal ageing

The development of thermal ageing is monitored by hardness measurements. For example, in accordance with Russian regulations [18] the mechanical properties of pipelines by destructive and/or non-destructive techniques shall be carried out at least every 100 000 hours of operation for NPPs with WWER. The management of thermal ageing is carried out by NPPs plant specific programmes.

c) Boric acid corrosion

The impact of boric acid leakage on components made from carbon steel or low-alloy steel materials is addressed in AMP 110 and IAEA-TECDOC-1361 [7].

1. ***Monitoring and trending of ageing effects:***

The methods for monitoring, recording, evaluating, and trending the data that result from the programme’s inspections shall provide identification of adverse ageing trends so that corrective actions can be performed in a timely manner if needed.

ISI results from monitoring and trending

A comparison of the current NDE results with previous ones is performed in order to determine the indications (flaws) growth rate. To facilitate monitoring and trending of DMWs the data from inspection results are collected, compared and assessed to make future predictions.

Reduction of fracture toughness monitoring

The activities for mechanical properties monitoring of the DMW are indicated in section 3.

The actual number of cycles monitoring and cumulative effect of fatigue

Monitoring and trending of the low-cycle fatigue effects are addressed in AMP101.

Leakage monitoring

Implementation of the boric acid corrosion programme is to monitor the leakage from the pressure boundary in the primary system. Leak detection systems are key element to detect a leakage from a through wall crack in a DMW.

Water chemistry parameters monitoring and trending

In addition, trending of the monitored electrochemical corrosion potential (ECP) is an effective method for BWRs if HWC is applied, as well as monitoring and trending of other water chemistry parameters for all types of reactors in scope.

1. ***Mitigating ageing effects:***

The activities referred to section 2 are implemented to mitigate degradation of ageing effects.

The approaches for mitigating SCC (specific methods to modify the material, environment, or stress condition of susceptible locations) and thermal fatigue ageing mitigation are described in MRP-139 [12] and IAEA-TECDOC-1852 [4] respectively.

1. ***Acceptance criteria:***

Acceptance criteria are provided by pertinent governing requirements or guidance documents for the NPP.

1. Acceptance criteria for NDE (VT, PT and UT) are derived from applicable national regulations, codes & standards and guidelines (e.g. [2, 9, 14]).

For example MRP-139 [12] and MRP-287 [19] provide important considerations when performing ASME Section XI [2] flaw evaluations of ISI indications in Alloy 600/82/182 DMWs in PWR primary coolant system piping and components.

For BWRs information on crack growth rates in Alloy 82/182 to use in evaluating cracking can be found in [20]. When HWC is used to mitigate SCC, information on whether this mitigation method is effective for the component in scope can be obtained from a plant-specific assessment.

The reliability of flaw detection and sizing is confirmed by the ISI system qualification of the DMWs in accordance with national or international requirements (e.g. [2, 21–24]), since the detection of fatigue cracking is challenging.

The following two analyses may be required when a crack like defect in a DMW is detected by UT to ensure the structural integrity up to the next planned outage:

* + Deterministic leak before break (LBB) assessment (e.g. advance finite element analysis, similar to the finite element approach [25]);
  + Probabilistic LBB assessment to demonstrate the low probability of failure using Probabilistic Fracture Mechanics code.

Deterministic and probabilistic LBB assessment account for uncertainties of several parameters that could affect possible crack growth in DMWs.

Strength calculations (cyclical crack growth due to fatigue mechanism, resistance to brittle fracture for postulated or fixed discontinuities) are applied to estimate the critical size of crack-like defects (e.g. [25, 26]).

Evaluation of PWSCC initiation and growth in Alloy 82/182 butt welds and the role of residual stresses including the effect of weld repairs are reported in MRP-106 [27], MRP-113NP [28] and MRP-114 [29].

1. Acceptance criteria for mechanical properties are their compliance (conformity) with manufacturer data or Technical Specifications (for conservative assessment) for a given grade of material (e.g. Russian regulations for base metal [30] and welding materials [31]).

There are currently no specific rules or standards regarding DMW. They are treated in the same way as similar welded joints and their mechanical properties are assumed to be equivalent to the material with the guaranteed (normative) mechanical properties of the materials used in welding. This approach leads to the use of very conservative assumptions. The main methods for evaluating DMWs have been developed or are under development within different programmes (e.g., MRP-106 [27], MRP-112 [32], MRP-113NP [28], MRP-114 [29], MRP-115 [33], MRP-116 [34]), in order to determine the type and rate of development of degradation mechanisms and to assess the condition.

1. The estimated number of loading cycles is defined in the list of operation modes of the reactor installation taking into account extended lifetime period.
2. Acceptance criteria of the fatigue cumulative usage factor ‘CUF’ with and without taking into account the environment influence ‘CUFen’ are addressed by AMP101.
3. ***Corrective actions:***

Corrective measures shall be carried out in accordance with the instructions, design rules, codes and standards applicable to NPPs. Corrective actions include material changes, corrosion resistant cladding, weld material changes, design changes, weld overlays, stress improvements, environmental improve­ment, mechanical repair, and component replacement. Detailed information on these corrective actions can be found in guidelines such as IAEA Technical Report No. NP-T-3.13 [8], NUREG-0313, Rev. 2 [35], ASME Section XI Code and Code Cases [11] and the pertinent governing requirements or guidance documents for the plant.

In order to satisfy the safety requirements, further evaluation to demonstrate fitness-for-service of the component until the end of the next periodic inspection interval may be required. Examination results and flaws that exceed the acceptance criteria given in the governing requirements or guidance documents may require analytical evaluation (for example, new strength calculations [26, 30]) for continued service until the next inspection, as well as supplementary examinations to further characterize the detected condition.

Acceptable corrective actions may include repair or replacement of components, design modifications, revision of operating procedures, and more rigorous analysis to demonstrate that the design code limit will not be exceeded during the plant operating periods. For example fracture mechanics analyses of Alloy 182 butt welds to assess the potential for crack initiation and growth to evaluate the impact of weld repairs are referred to in MRP-114 [29].

1. ***Operating experience feedback and feedback of research and development results:***

This AMP addresses the industry-wide generic experience. Relevant plant-specific operating experience is considered in the development of the plant AMP to ensure the AMP is adequate for the plant. The plant implements a feedback process to periodically evaluate the plant and operating experience and research and development (R&D) results [36, 37], and, as necessary, either modifies the plant AMP or takes additional actions (e.g. develop a new plant-specific AMP) to ensure the continued effectiveness of the ageing management.

Appropriate sources of external operating experience are WANO Operating Experience Programme, IAEA IGALL Programme, etc. Effective experience exchange is an important element for implementing continuous improvement in this programme and in defining adequate corrective actions.

Operating experience has shown that nickel alloys used in the manufacturing of DMWs in PWR and BWR plants may be susceptible to SCC. Weld repairs of the inner diameter during fabrication are known to increase the susceptibility to SCC by increasing the residual stress profiles from the inner surface to a certain depth of the wall thickness, e.g. about half of the wall thickness. Ageing degradation mechanisms effects detected in this type of DMW are presented in IAEA-TECDOC-1361 [7]. Reference [8] provides some additional information on operating experience for all types of light water reactors. For BWRs some information on operating experience can be found in [38].

Summary of lessons learned and recommendations that may be obtained from several international studies on DMWs with different NDE techniques and procedures are presented in the IAEA-TECDOC-1852 [4]. But some of the U.S history of cracking in DMWs in U.S. plants is not covered by IAEA-TECDOC-1852 [4]. Prior to 2006, PWSCC experience in DMWs in U.S. plants involved primarily axially oriented cracking/leakage, and it was observed that their length was limited by adjacent non-susceptible materials. However, in Autumn 2006, several circumferential indications, which could lead to guillotine type of double-ended pipe break if growing further, were detected by UT in the DMWs of the pressurized nozzle at Wolf Creek NPP in the U.S. Advanced finite element analysis (AFEA) was used to evaluate the pressurized nozzle for the purpose of demonstrating LBB up to the Spring 2008 inspection. In addition, a complex crack was detected in the DMWs in the Duane Arnold BWR operating in the U.S. This crack consisted of a 360-degree internal surface crack with a small portion of through wall penetration resulting in a short through wall crack (MRP-216 [25]).

Research activities are aimed at better justifying degradation mechanisms, developing qualified degradation assessment methods, and verifying models and analyses. There were 6 European projects that are directly related to the assessment of DMW degradation and integrity:

* + DISWEC - Evaluation of Techniques for Assessing Corrosion Cracking in Dissimilar Metal Welds [39];
  + BIMET - Structural Integrity of Bi-Metallic Components [40];
  + ADIMEW - Assessment of Aged Piping Dissimilar Metal Weld integrity [41];
  + NESC-III Project [42] was organised by the Network for Evaluating Structural Components (NESC [43]) to extend the results obtained in the BIMET and ADIMEW projects;
  + STYLE – Structural integrity for lifetime management of non RPV components [44];
  + MULTIMETAL – Structural performance of multimetallic components [45].

By the time of the 2021 revision of this AMP another Euratom funded project on pipe integrity assessment, including DMW integrity, called ATLASplus (Advanced Structural Integrity Assessment Tools for Safe Long Term Operation) was ongoing.

The following PHARE programs [46] have been implemented to enhance the reliability of NDE at WWER NPPs and to improve UT of DWMs:

* + PHARE 4.1.2/93, WWER 440-213 In-Service Inspection (in part of "RPV safe-end weld"), completed July 1997;
  + PHARE 1.02/94, Technical justification for the 5 inspection areas of PH 1.02/94, (in part of "WWER 440 steam generator collector dissimilar weld"), completed February 1998;
  + PHARE 1.07/97A, In-Service Inspection of Primary Components (in part of "WWER 440 pressurizer dissimilar weld", completed May 2002.

1. ***Quality management:***

The AMP is carried out in agreement with site QA procedures, review and approval processes, and administrative controls, which are implemented in accordance with the different national or international regulatory requirements and standards (see [47-50] as examples).

The inspections and monitoring are performed by qualified personnel using qualified techniques in accordance with approved licensee procedures. The personnel performing these inspections are certified by the international or national legal organizations, e.g. [51, 52].

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