ASSESSMENT OF THE REPAIR STRATEGY AND THE EFFECTS OF THE REPAIR ON THE REACTOR POOL LINER

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EXECUTIVE SUMMARY

Based on analysis of documents provided by ARPANSA, a technical review was carried out for the repair proposed by INVAP for the misplaced penetrations in the Reactor Pool Liner (RPL). The repair arises from the need to correct the errors that occurred in positioning of the penetrations during the construction of the pool. Some of these penetrations were repaired without due authorisation and were not subjected to non-destructive examination. The consequences of the repair were analysed from a metallurgical point of view and the requirements of ASME Section III and ASME Section IX. Possibility for the formation of hot cracks in circular welds joining the repair patches was evaluated with the use of a Circular Patch Test (CPT), covering the range of heat inputs matching those specified in the relevant welding procedures qualified for the manufacture of the Research Pool Liner. Microstructures of the heat affected zones of the CPT welds, made at various heat inputs, were also evaluated following recommendations of ASTM A 262 – 02a. It was recommended not to re-repair the unauthorised repair RP-1 provided that evidence of the quality of the welds could be presented.

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1 Introduction

CSIRO Manufacturing and Infrastructure Technology (MIT) was approached by ARPANSA to evaluate the weld repair of the Reactor Pool Liner (RPL) proposed by INVAP and its effect on the pool shell material, particularly heat affected zones, corrosion properties, safety margins, etc. The repair was aimed at correction of the errors made in the locations of a number of penetrations to the pool shell that occurred during the pool shell manufacture. Positions of the misplaced penetrations were indicated in the corresponding drawings, and some of these penetrations were repaired without due authorization.

2 Analysed Documentation

The following documents and drawing were analysed:

Documents:

1. Review of RFA001
2. Welding Procedure Specification C1/309 Rev 1
3. Welding Procedure Specification C1/309 Rev 2
4. Welding Procedure Specification C1/328 Rev 2
5. Welding Procedure Specification C1/328
6. Welding Procedure Specification C1/309 Rev 1
7. Welding Procedure Specification C1/331R
8. RRRP-0610-3BEIA-001A, Revision: A, Preliminary Directives for Repair Works on the Reactor Pool Shell
9. RRRP-0610-BEIN-075-C, Revision: C, Reactor Pool Shell – Misplaced Holes: Design Code Compliance
10. RRRP-0610-3BEDM-801-A, Revision: A, Reactor Pool Penetration Technical Report
11. Assessment of the Repair Strategy and the Effects of the Repair on the Reactor Pool, D Vassalo, 4 June 2003.
12. Metallurgical Aspects of the Proposed RRR Pool Liner Repairs, Memo, 12 June 2003-08-07
13. RRRP-0610-3BEWT-001-A, Welding Review for the Reactor Pool Shell Repair, WTIA Confidential Report, 16 June 2003-08-07
14. ANSTO/INVAP Comments and Commitments with Respect to the Conclusions, 1 July 2003.
15. Statement on the RPO Shell Stress Analysis, INVAP - 6 June 2003,
16. Acceptance No: 0610-006-AC-001, Acceptance of Project Deliverables, 13 June 2003.
17. RRRP-0610-3BEIN-079-A, Review Transmittal Sheet 0494, 13 June 2003.
18. RRRP-0610-3BEIN-145-A, Review Transmittal Sheet 0495, 26/05/03.
19. SITP template No. RRRP-7033-EGEDM-803-A
20. RRRP-0610-3BEDM-005,Revision: A, Reactor Vessel 0610 –Repair Procedure for misaligned Holes in RPO Repair 1 (Mock up)
21. ANSTO letter msx/Reg54/ARPANSA/0778 of 29 July 2003, Plus Table 1,
22. Attachment A-1 and A-2 and accompanying documents listed in A-2.

Drawings:

1. No. RRRP-0610-3AEIM-008-E, Reactor Pool Shell
2. No. RRRP-0610-3AEAM-001-A, Reactor Pool Shell "As rolled Feb. 03"
3. No. RRRP- 0610-3AEAN-002-A, Reactor Pool Shell Unauthorised Repair
4. No. RRRP-0610-3AE-DM-009-C, Reactor Pool Shell Proposed Authorised Repairs

3 Scope of Work

CSIRO MIT was engaged to:

- Review relevant documentation of the repair strategies and their effectiveness with regard to the potential effect of the repairs on any of the outcomes of the stress analysis, particularly in relation to material properties, heat effected zones, corrosion properties, safety margins etc.

- Write a short report to the CEO of ARPANSA regarding the efficacy of the proposed repair strategy, and the effect of the repairs on safety margins for the repaired Reactor Pool Liner in comparison to the original design.
- In addition to this it was accepted by ARPANSA for CSIRO MIT to carry out appropriate testing to evaluate the tendency for formation of hot cracks in circular welds.

4 Limits of Review

The review is based on analysis of the supplied documents, a visit to construction place of the Reactor Pool Liner, discussions with ARPANSA, the Fabricator of the vessel, and ANSTO carried out during the meetings held on 4 July 2003, and results of the weldability test carried out by CSIRO MIT.

The 22 penetrations requiring repair were considered, of which 10 have been repaired without the authorisation of the designers and therefore were recommended for re-repair. The extent of the re-repairs and patch locations are detailed in the drawing No. RRRP- 0610-3AEAN-002-A. From the latest, re-repair of the weld RP-1 (penetrations P20, P21 and P22) required special consideration due to difficult location.

The approved repairs carried out on the vertical seams in strake 2 and strake 8 were not considered.

5 Material Response to Welding

The Research Pool Liner was constructed using ASTM A240 304L stainless steel plates 6 mm thick for the shell and 12 mm thick for the floor plate. Carbon content in this material is limited to maximum 0.03%. According to the batch certificates of the plates the carbon content was below this limit.

Main problems related to weldability of stainless steel are:

- formation of hot cracks in the weld and heat affected zone (HAZ),
- carbide precipitation in the areas of HAZ heated to between 450-950°C,
- high stresses generated in the weld joints due to low heat conductivity and high thermal expansion of the steel,
- embrittlement of welds containing delta ferrite due to formation of sigma phase.

Chemical compositions of the steel plates, as indicated in the batch certificates, were used to predict delta ferrite content (FN – Ferrite Number) in the autogenous welds made on these materials. A relatively high delta ferrite content of about 7.5 FN and 9.2 FN can be expected in the welds made on 6 mm thick plates and 12 mm thick plates respectively. Even higher delta ferrite content, of 11.7FN and 13.7FN, can be expected in the welds made with ER308L and ER308LSi filer materials respectively. This indicates that possibility of formation of hot cracks (solidification cracks) in the welds comprising combinations of these materials is low. This was confirmed by the results of the Circular Patch Test (CPT) shown in Appendix A.

Carbide precipitation at grain boundaries in austenitic stainless steel is responsible for sensitisation of the steel to intergranular corrosion. The degree of the sensitization, and amount of carbides formed at grain boundaries, depends on the carbon content in the steel, temperature and time at temperature. Presence of stresses is an additional factor which may accelerate carbide precipitation if the other factors remain constant. With the materials used for the Research Pool Liner construction, carbon content is very low, which shifts the range of the highest rate of sensitization to lower temperatures of 500°C to 650°C and longer time ranging from 3[1] to 8 hours[2,3,].

However, in the case of welding thermal cycles the minimum time required for sensitization of 0.03% carbon containing stainless steel could be shorter due to presence of stresses developed during welding, but still long enough compared to the duration of the welding thermal cycles (usually from two to several minutes). These create a safe margin for the welding process to be completed without the material being sensitized even with multiple run welding procedures.

Welding of stainless steel materials produces much steeper thermal cycles in the weld HAZ due to lower thermal conductivity of the material, which combined with higher thermal expansion, contributes to the generation of higher stresses in the weld area. The stress level depends on the amount of heat and restraint imposed on the material during welding. Therefore, it can be expected that stresses will be higher in the joints welded with high heat input and they also increase as the thickness of the joints and the size of the weld deposit is increased. In the case of welding circular patches it is expected that the stresses in the welds would decrease as the radius of the patches is increased. The presence of high residual tensile stresses may contribute to stress corrosion development during service of the joints. This however, requires access of corrosive media, containing chloride or fluoride ions, to the welded area. The service conditions of the Research Pool Liner, as defined in the relevant documents, indicate that development of such corrosion is less probable from inside of the pool liner as the pool was designed to contain high purity demineralised water. Therefore, more probable is development of corrosion from outside of the pool liner if the water contaminated with atmospheric pollutants condenses and stays for a long time on the wall surface. Probability of corrosion from the bottom of the vessel is low, however, due to high alkalinity of the concrete base supporting the Research Pool Liner[4]. It should be taken into account also that the liner is embedded in concrete, and that there is a leak detection system for water and design provisions to prevent spillage of water into any concrete gaps that may be associated with the embedded method. It is therefore assumed that the water drainage areas provided will ensure a dry area for the bottom of the pool.

The degree of the embrittlement of stainless steel welds due to sigma phase formation at the temperature range of 550°C to 950°C is controlled by its chemical composition, residence time at this temperature range, and the presence of stress. Therefore, it is

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[1] Brooks J. A and Lippold J.C.; Selection of Wrought Austenitic Stainless Steels, Fig. 14, p. 467 in ASTM handbook Vol.6, 1993.

[2] Davison R. M. et al: Metals Handbook, Vol. 13, Corrosion, 9th ed., ASM, Metals Park, OH, p.551, Fig. 1, 1987.

[3] Lundin C. D., et al: Sensitization of Austenitic Stainless Steels; Effect of Welding Variables on HAZ Sensitization of AISI 304 and HAZ Behaviour of BWR Alternative Alloys 316 and 347, WRC Bulletin 319, November 1986.

[4] Fint G. N., Cox N. R.; The resistance of stainless steel partly embedded in concrete to corrosion by seawater, Magazine of Concrete Research, vol. 40. No. 142, March 1988.

expected that thicker and high heat input multiple run welds would be more prone to sigma phase embrittlement than the welds made on thin plates.

6 Analysis of Repair Strategy

The repair strategy submitted by INVAP S.E, (Doc. No. RRRP-0610-3BEIA-001-A, Revision A) takes into account 22 penetrations to be repaired, their locations in the RPL, and position of the repair welds in relation to the existing welds. It also proposes to increase the size of smaller penetrations to minimum 100 mm diameter, and cover close distance small-diameter penetrations, with one bigger penetration to avoid overlapping of HAZ's from nearby welds.

All unauthorised repairs were proposed for cutting out and re-repairing with qualified welding procedures. Re-repair of the unauthorised repair RP-1 was reconsidered due to its difficult location. This was reflected in a letter directed to Dr Loy on 29 July 2003 from Mr Whitbourn of ANSTO containing all supporting documents, to prove that the repair in the first place was carried out under controlled conditions according to qualified welding procedures (WP C1/328), and met all codes requirements (Shown in Attachment A-1 and A-2 to the letter). Quality of the RP-1 repair was assured by adequate non-destructive testing including 100% radiography, ultrasonic and dye penetrant tests. It is important to mention that welding of the RP-1 patch to the shell of the RPL was completed prior to the welding of the strake to the pool base. This allowed the Fabricator to assure a consistent quality for the weld joining the bottom plate with the liner shell.

7 Welding Procedures

There are some discrepancies between the welding procedures utilised for manufacture of the RPL especially in the permitted heat inputs and interpass temperature.

For example; the welding procedure WPS C1/309 Rev 1 allows heat input ranging from 1.0-2.4 kJ/mm for first run, and 0.94 to 2.43 kJ/mm for subsequent runs, with interpass temperature of 150°C. The welding procedure WPS C1/309 Rev 2 gives a range of welding parameters producing the heat input ranging from 0.80 to 2.97 kJ/mm with the same interpass temperature of 150°C.

The welding procedure WPS C1/328 Rev 2, prepared for the thickness ranging from 1.6 to 7 mm, gives a range of welding parameters producing heat inputs ranging from 0.9 to 1.76 kJ/mm for the root run, and 0.6 to1.12 kJ/mm for the subsequent runs. Because both of these runs are made simultaneously, from both sides of the plate, calculated total heat input is in the range of 1.5 to 2.88 kJ/mm. This procedure was used for welding longitudinal and circumferential welds of the shell.

The welding procedure WPS C1/328 specifies the same welding parameters as WPS C1/328 Rev 2 and the maximum interpass temperature of 300°C. This welding procedure was utilised for unauthorised weld repairs; RP-1 (P-20, P-21 P-22), P-64, P-16, P-66, P-29, P-30, P-31 and P-19, according to the attachment RP-1.2 and RP-1.5, page 1 of 1, (see msx/reg54/ARPANSA/0778 and attachments of 29 July 2003).

The welding procedure WPS C1/331R was proposed for welding the mock-up of RP-1, to simulate the re-repair welding the shell to the bottom of the RPL, specifies the heat input

for first run in the range of 0.5 to 1.44 kJ/mm and for subsequent runs in the range of 0.7 to 1.48 kJ/mm, with interpass temperature not higher than 150°C.
In addition to this, Notes 3 and 4 on the drawing RRRP-610-3AEDM-009C require maximum interpass temperature of 150°C and maximum heat input of 1.5 kJ/mm for all the re-repair welds.

These very high heat inputs imposed onto the base material and welds during manufacture of the RPL have the potential for metallurgical consequences (possible sensitization of welds) and generation of increased residual stresses in the welds. This is especially relevant for the welds made according to the welding procedures; WPS C1/309 Rev 1, WPS C1/309 Rev 2, WPS C1/328 Rev 2 and WPS C1/328, which were originally used for welding all welds within the RPL.

8 Inspection requirements

The inspection requirements imposed on the Licence holder calls for 100% radiographic and dye-penetrant inspection of all factory and on-site butt welds for the Reactor Pool Tank categorised as Safety category 1 or 2. This applies also to the repair welds of the misplaced holes (see RRRP-0610-3BEIN-075-C, Revision: C). It would also be advisable to require 100% ultrasonic testing of the weld joining the bottom plate to the shell of the vessel carried out from the bottom side of the vessel.

8.1 Preparation for welding

These include such operations as cutting out the unauthorised repair patches, increasing the size of the penetrations and preparation of patches for repairs. Potentially these operations should not produce any differences in the behaviour of the material. There are no metallurgical problems associated with them as long as qualified procedures are used.

8.2 Repair Welding

It was proposed (see RRRP-0610-3BEIA-001-A, Revision: A) that all 22 misplaced penetrations should be repaired including re-repair of 10 unauthorised repairs. Proposed strategy for the repairs included increasing the diameter of small penetrations to 100 mm and covering close distance penetrations with a single repair patch as specified in the drawing No. RRRP-0610-3AEDM-009-C, Reactor Pool Shell Proposed Authorised Repairs. The welding procedure WPS C1/328 Rev 2 proposed for the repair and re-repair is in conflict with the requirements set in the above mentioned drawing (RRRP-0610-3AE-DM-009-C, see Note 2 and 3), which requires the heat input and interpass temperature to be limited to 1.5 kJ/mm and 150°C, respectively, and a double Vee bevel for welding. Similar requirements were imposed on welding the mock up simulating the re-repair of the RP-1 (see Doc. RRRP-0610-3BEDM-005, Revision: A).

It would be advisable to follow these recommendations to limit the effect of the repairs on the material properties in the weld area. These repair welds are highly restrained and more careful control of heat input during the repair welding is recommend for minimising the combined effect of the thermal cycles and stresses on the material properties in the HAZ.

One exception from this recommendation is the repair weld RP-1. After careful consideration, taking into account all the possible consequences of the unauthorised repair and the proposed re-repair, it is suggested to accept this repair weld. The reasons supporting this advice are that the re-repair could contribute to possible deterioration of the properties of the bottom plate affected by the weld completed prior to the re-repair, as this section of the bottom plate was not proposed for replacement, and acceptable quality of the welds contained in the RP-1 was proved by supportive documentation supplied by ANSTO and the Fabricator (see letter msx/reg54/ARPANSA/0778 to Dr Jon Loy and attached documents). An additional fact supporting this recommendation is that the RP-1 was welded to the first stake of the vessel prior to welding of the shell wall to the bottom plate. Therefore, only the quality of the butt weld joining the RP-1 to the bottom strake was questionable but this was clarified by the testing carried out after the completion of the weld.

Testing was carried out at CSIRO MIT to evaluate material response to the repair welds comprising mostly circular welds of 100 mm diameter. The testing employed a Circular Patch Test in which the weld was highly restrained during welding. The diameter of the test weld was limited to 50 mm to provide higher stresses induced by the welding thermal conditions compared to those stresses induced during completion of 100 mm diameter weld.

Susceptibility to Intergranular corrosion was evaluated according to ASTM A 262 – 02a, Practice A with the Oxalic Acid Etch Test and reported in the APPENDIX A in this report. This test is used for acceptance test of material but not for rejection of material, and it is to screen specimens intended for testing in the other Practices recommended by the standard (Practice B, C, E and F in the standard). Each practice contains a table showing which classifications of the etch structures on a given stainless steel grade are equivalent to acceptable or unacceptable performance in that particular test.

The presence of some overlapping pits at grain boundaries was observed in the microstructure of the welds (refer to APPENDIX A). These pits could originate from dislocations present in these areas which were preferentially attacked by the oxalic acid during etching or were caused by higher concentrations of chromium in these areas which may create suspicion that chromium carbides were present in these areas. The later, however, is less probable because the carbon content in the steel is below 0.03%. It was found that mainly step and dual structure (according to classification proposed by the standard) was present in the certain areas of the HAZ of the weld made with heat input ranging from 1.6 to 3.3 kJ/mm. This indicates that these areas had acceptable structure and, according to the standard recommendations, did not qualify these welds for further corrosion testing in the specified hot acid solutions.

It was observed that the amount of dual structure increased with the increased heat input and concluded that the observed pits at grain boundaries are related to dislocations being more sensitive due to higher stresses generated during welding. Therefore, it can be concluded that sensitisation of the HAZ of the circular, highly restrained, repair welds is least probable.

9 Conclusions

1. The proposed repair strategy for misplaced penetrations appears to be adequate.
2. The repairs carried out according to the approved procedures are expected to have similar effects on the material behaviour to the other construction welds

completed on the RPL, provided that the heat input and residual stress level are minimised.

3. The RP-1 unauthorised repair should be accepted after obtaining proof that the all steps of the repair process were carefully monitored, recorded and the quality of the welds meet the requirements imposed on construction of the RPL.
4. Weldability testing carried out at CSIRO MIT showed that the circular welds were not prone to hot/solidification cracking due to high delta ferrite content.
5. Metallographic examination carried out on sections of the Circular Patch Test welds electrolytically etched in oxalic acid revealed that the HAZ of the welds have acceptable microstructures.

10 APPENDIX A