1. Introduction

The recirculation system of the conventional boiling water reactor (BWR) consists of two recirculation loops including recirculation pumps, piping, flow control valves, jet pumps and so on. The recirculation system is designed to provide sufficient flow to remove heat from the fuel and to adjust reactor thermal power generation. In addition, the recirculation system piping is part of the reactor coolant pressure boundary, and the jet pump is also part of the reactor internals and designed to maintain the core reflooding capability at the loss of coolant accident (LOCA). The licensee implemented invessel visual inspection (IVVI) for the reactor internals and inservice inspection (ISI) programs for piping system during each scheduled outage to ensure the integrity of the systems, structures or components (SSC). The scope of the inspection embodies the safety related and non-safety related components. If any flaw detected during the refueling outage, licensee must conduct the safety evaluation and/or repair/replacement depending on the condition. This paper mainly focuses on the recent inspection results of BWR's recirculation piping and jet pumps.

Intergranular stress corrosion cracking (IGSCC) on the weldments in BWR recirculation system has been awarded for decades. The early cases were found in small-diameter piping. In 1980s, cracks were also identified in large-diameter piping in BWR recirculation system piping. Since then, the subject of IGSCC in BWR piping has been of continuous concern and extensive inspection programs have been conducted on BWR recirculation system piping. BWR piping weldments made of austenitic stainless steel are susceptible to IGSCC. The cause of the IGSCC is a combination of sensitization of the conventional austenitic stainless steel by welding, high residual tensile stresses on the inside surface near the welds, and dissolved oxygen and other aggressive environment in the BWR primary coolant.

In Taiwan, there are two BWR nuclear power plants, Chinshan (BWR4) and Kuosheng (BWR6). Both NPPs have 2 units respectively and are operated over 20 years by the Taipower Company (TPC). Cracks were also found through the ultrasonic testing (UT) on recirculation piping in both plants from 1980s. To mitigate IGSCC problems, the major betterment work which had been done in Chinshan included conducting induction heating stress improvement (IHSI) for part of the welds and replacements of risers as shown in Table 1. The major betterment work in Kuosheng included conducting IHSI for part of the welds. Since 1995, TPC established augmented inservice inspection plans according to Generic Letter 88-01 [1] and NUREG 0313 Rev.2 [2], which were even more conservative than the recommendation. Last year, TPC submitted the revised inservice inspection plans for Kuosheng units by citing EPRI BWRVIP-75-A report [3] and considering the past inspection results. Similar application will be submitted for Chinshan NPP as well. All the relevant welds of the recirculation system piping are fundamentally arranged to be inspected every 2
refueling cycles. Besides, the personnel who perform ultrasonic examinations must meet the requirements of Appendix VIII of Section XI of the ASME Code.

In the conduct of ISI, flaws in components may be indicated. The information concerning the crack must be recorded and submitted to the regulatory authority, the Atomic Energy Council (AEC), for the evaluation of the structural integrity and justification of the corrective actions needed. During the recent scheduled refueling outages for both plants, crack indications were found at the dissimilar metal welds connecting vessel nozzle to austenitic stainless steel piping of the reactor recirculation piping system of Chinshan Unit 1 and Kuosheng Unit 2 in addition to the cracks seen at austenitic stainless steel piping welds. Together with foreign experiences, it seems that the trend of crack found in dissimilar metal welds is increasing globally and worthy of more attention.

Jet pumps are generally examined through the routine invessel visual inspection (IVVI) with remote VT-1, VT-3 and EVT-1 during the refueling outages. TPC conducted the inspection program to jet pumps in accordance with Section XI of the ASME Boiler and Pressure Vessel Code, BWRVIP Guidelines, the manufacturer’s suggestion and the experience of other nuclear power plants. In general, all jet pumps of each unit were inspected every 4 refueling cycles. Crack indications had been reported at the riser brace and the diffuser intermediate ring of the jet pumps of Kuosheng Unit 1 and 2, respectively, during the recent scheduled refueling. These indications appeared to be caused by IGSCC because the weldments made of austenitic stainless steel were susceptible to IGSCC.

For the reported findings, the AEC will organize special review task forces to review the safety analysis evaluation, the proposed corrective action and the justification for continued operation, if necessary. In the following sections of this paper, the inspection results of the recent relevant refueling outages regarding the recirculation systems of both Chinshan and Kuosheng are summarized. The related regulatory activities and enforcement requirement of AEC are also discussed.

2. Inspection Results of the Recirculation System Piping

2.1 Historical Inspection Results

Table 1 and 2 show the inspection results and the repairs of the recirculation system piping at Chinshan and Kuosheng since their commercial operation. Although parts of welds on the recirculation system piping had been treated by a stress-improved process, the effect to mitigate IGSCC is not obvious from the Kuosheng historical inspection results. There were 10 cracked welds found at the risers of the recirculation system piping at Chinshan-1 during EOC-7 outage August 1986. In addition, Chinshan-2 was also found some cracks at the similar locations to Chinshan-1 during EOC-7 outage July 1987. According to the historical inspection reports, there were 25 cracks found at that time. TPC decided to repair the 11-in-diameter recirculation riser pipes fabricated from the 316NG material instead of the 304SS material at Chinshan-1 EOC-9 outage April 1989 and Chinshan-2 EOC-8 outage November 1988. It was intended to mitigate the IGSCC. No cracks occurred at the riser pipes for both Chinshan units through the routine inspections until
now. Furthermore, Chinshan-2 has a good performance that no cracks are inspected at the recirculation system piping after repaired. A through-wall crack was found at the weld connecting the outlet of the recirculation pump to piping at Kuosheng-1 EOC-14 outage March 2003. It caused slight leakage and was repaired temporarily by weld overlay reinforcement. Then TPC repaired it by renewing the partial piping of the cracked piping at Kuosheng-1 EOC-15 outage September 2001. In view of the cracks found, TPC cited ASME sec. XI code to assess those in order to assure the structural integrity or followed ASME code case N-504-1 and USNRC NUREG 0313 Rev.2 to repair it by weld overlay.

2.2 Recent Inspection Results
Through a series of scheduled examinations, it is shown that the trend of the amount of the crack indications found decreases in the last years as shown in table 1 and 2. The inspection results of the last 5 years are discussed in detail as follows.

Chinshan
Slight leakage was first detected through PT testing at the AH-J1 weld at the header end of the recirculation system piping during the unit 1 EOC-19 outage September 2002, as shown in Figure 1 and 2. The scale was found on the outer surface of the pipe. This crack was investigated again by using UT testing. The result showed a measured length of 1 inch in axial direction. Weld overlay reinforcement was used to repair it. A hydrostatic pressure test was performed after weld overlay reinforcement in accordance with IWA 5000 of Section XI of the ASME Boiler and Pressure Vessel Code. During the unit 2 EOC-21 outage, there were 2 crack indications found at the 22-in-diameter vessel nozzle to austenitic stainless steel piping of the reactor recirculation system piping. These 2 axial cracks were 0.8 inch in length by 0.49 inch in depth and 0.4 inch in length by 0.36 inch in depth. Though the evaluation of these flaws was justified to assure the structural integrity in the as found condition in accordance with the criteria of Section XI of the ASME Boiler and Pressure Vessel Code, these flaws will be inspected again at next refueling outage.

Kuosheng
During the unit 2 EOC-15 outage December 2002, a circumferential crack having 25.32 inches in length by 0.233 inch in depth was detected at the N2E-J4 weld of the rise pipes [4]. Though the result of the evaluation was justified to assure the structural integrity in the as found condition, TPC took a conservative action to repair it by weld overlay reinforcement. During the unit 2 EOC-17 outage October 2005, an axial crack at the N1B-F1 weld like the same location found at Chinshan-2 EOC-21 outage was inspected having 1 inch in length by 0.63 inch in depth, as shown in Figure 3. A weld overlay reinforcement project was conducted for repairing the dissimilar weld in accordance with ASME Code Case N-504-2, Code Case N-638-1, Code Case 2142-2, and USNRC Docket No.50-293. At next refueling outage, the repaired volume will be inspected again in accordance with the modified in service inspection program for Kuosheng units.

2.3 AEC Regulatory Activities on the Recirculation Piping
Crack indications were found at the recirculation piping at Chinshan and Kuosheng. Those appeared to be caused by IGSCC. There is no practical way to reduce the sensitization of weldments already installed, so the
only way to reduce the susceptibility of the material is to replace the piping with material that is resistant to sensitization by welding. There are several repair methods available for at least short-term operation. In view of crack indications, TPC usually use weld overlay reinforcement method to repair the welds. AEC has paid great attention on the recirculation piping inspection results during outages. Relevant regulatory activities regarding the crack indications reported were as follows:

1. When the crack indication was found, AEC generally requested TPC to conduct parallel expansion examining the similar location of the recirculation piping.

2. Considering some cracks found at the dissimilar welds connecting the vessel nozzles to the safety related piping in domestic BWRs and the related foreign experience, AEC request TPC to review the adequacy to inspection frequency and inspection technique for Chinshan and Kuosheng units because all of the dissimilar welds was inspected every 10 years in accordance with Section XI of the ASME Boiler and Pressure Vessel Code.

3. After the cracked weld is repaired by weld overlay reinforcement, AEC request TPC to perform the primary shrinkage stress evaluation to assure the structural integrity before the unit re-start.

4. In order to enhance the structural integrity, AEC request TPC to establish an aging management program on recirculation piping for Kuosheng units.

3. Jet Pump Assembly Inspection

Jet Pump Assembly inspection is always performed inspection plan through invessel visual inspection every outage. Until now, there were 2 crack indications being inspected at Kuosheng. No flaws were identified at Chinshan. The inspection detail, AEC’s regulatory activities and actions taken by TPC and for cracks identified are given as follows.

3.1 Inspection detail and action

Kuosheng-1

All of the jet pump riser pipe to riser brace yoke welds were inspected during EOC-16 outage March 2003. The RS-9 weld on the riser pipe of jet pumps No.15/16 contained a crack indication with a measured length of 6.6 inches [5]. This indication was approximately 21% around the circumference of this riser pipe, as shown in Figure 4. The riser brace was designed to provide the lateral support for the riser pipe. Therefore, the designed function may be degraded by the cracked weld. However, based on the results of the conservative stress evaluation of the flaw, it was justified that Kuosheng-1 can continue for at least one cycle of operation even with the RS-9 weld completely cracked. The flaw evaluation methodology used in the evaluation was consistent with BWRVIP-41. After then TPC and the manufacture vendor had designed an external mechanical clamping system to structurally replace both of the two riser brace yoke to riser welds as a contingency repair for use. The safety analysis report analytically demonstrated the structural integrity and functional adequacy of the repair clamp, and supported continued operation of the cracked jet pump assembly with the clamp [6]. It was installed during EOC-17 outage September 2004 and examined again to assure the structural integrity of the repair clamp during EOC-18 outage March 2006. The inspection result showed no abnormal condition at the repair clamp.
Kuosheng-2

A mistake in the jet pump inspection items was noticed by the AEC inspector during EOC-15 outage (November 2002) of Kuosheng-2. The locations of the welds shown in the inspection procedures were not fully consistent with the actual design of Kuosheng. TPC was immediately requested to parallel extend the inspection scope to cover similar welds on the other jet pumps either scheduled to be inspected or not. During EOC-16 outage (March 2004), jet pump diffuser welds were examined by using enhanced visual examination (EVT-1) technique. The diffuser intermediate ring weld DF-3B on jet pump No.12 had a circumferential crack indication in the heat-affected-zone, as shown in Figure 5. The length of the flaw was measured to be 12.06 inches. This indication was approximately 26% around the circumference of this diffuser. The flaw was not a through-wall crack by examined from the inner surface of the jet pump. No cracks were found on all of the jet pumps except the jet pump No.12 at that time. One more 18-month cycle of operation in the as found condition was justified by analysis per BWRVIP-41. Though the leakage for a through-wall crack has been estimated to be accepted, the cracked jet pump was monitored by the daily jet pump flow monitoring during operation to EOC-17 (September 2005). TPC and the manufacture vendor had designed an external mechanical clamping system to structurally replace the cracked weld. The safety analysis report analytically demonstrated the structural integrity and assessed the functional adequacy of the repair clamp [7]. The clamp consists of four grippers symmetrically placed on the pockets machined on the diffuser wall against the diffuser loads. It was installed during EOC-17 outage (September 2005).

3.2 AEC Regulatory Activities on Jet Pump Assembly

Crack indications were found at the riser brace and the diffuser intermediate ring of the jet pumps of Kuosheng Unit 1 and 2, respectively. Those appeared to be caused by IGSCC. The cracked at the jet pumps had been repaired by using mechanical clamping systems to replace the crack welds. In addition, after noticing the inconsistency in the inspection work mentioned above, AEC has paid great attention on the jet pump assembly inspection at Kuosheng units during recent refueling outages through on-site inspection. Besides the enhanced on-site audit, other major regulatory activities were as follows:

1. When the crack indication was found, AEC requested TPC to conduct parallel examination on the similar location of all jet pumps and take the same actions to the other unit during the next closest refueling outage.

2. To justify continued operation in as-found condition for at least one fuel cycle of operation, TPC needed to submit safety evaluations to AEC for approval before re-start. After thorough review of the safety evaluations, the units were approved to re-start with limitations due to the assumptions used in analysis. The limitations on operation before repair were: should not exceed 100% core flow and should not consider the single loop operation for Kuosheng-1 and should not exceed 100% core flow and should conduct the cracked jet pump flow monitoring for Kuosheng-2.

3. In addition to conducting safety review and on-site inspection for the repair work, AEC request TPC to conduct a structural integrity inspection after repair and examine again at the next refueling outage. If the repair clamp showed a good performance, the inspection period of the repaired jet pumps can be returned to the original inspection schedule.

4. For the inconsistency found between inspection procedures and actual design locations of part of the
welds, TPC was required to review and revise the accuracy of the inspection procedures in accordance with actual reactor internals' design.

4. Conclusions

The integrity of recirculation systems of BWR nuclear power plants, Chinshan and Kuosheng, in Taiwan are under periodic inspection. Reported inspection results show that SCC is the most common degradation mechanism for the systems. The 304 stainless steel, very susceptible to SCC, is used extensively in the recirculation systems. A complete procedures including the inspection program, flaw evaluation, repair and quality control for the recirculation piping have been established in Chinshan and Kuosheng. If any crack indications reported, structural evaluations should be conducted to justify the safety margin for continued operation or if repair/replacement is needed immediately to maintain the structural integrity and the intended function.

For the recent cracks reported on recirculation systems of Chinshan and Kuosheng, structural evaluations have been conducted for justification. Required and acceptable repairs have been completed immediately or at the very next refueling outage. In the mean time, enhanced regulatory activities and requirements on safety review, parallel extension of inspection, on-site inspection, reinforced continue operation requirement, etc. have been taken during the relevant refueling outages and/or the operation period. However, crack indications found at the dissimilar metal welds and at the weld of the Jet pumps are new experiences to the licensee. Through the recent experience, the licensee is suggested to put in more effort in the following areas: establishing short term and long term aging management for the system; continuously reinforcing recirculation piping axial and circumferential crack inspection technique; enhancing inspectors' qualification and retraining program including inspectors' aging problem; in addition to the current similar metal weld overlay technique, building up self-owned dissimilar metal weld overlay technique; revising inspection procedures according the actual design of Kuosheng because the general procedures provided by the vendor may not be totally appropriate to the plant-specific design; tracing the effectiveness of HWC when it is implemented in the near future.

Due to the improvement of the inspection techniques, periodic in-service inspection and buildup of inspection data base, most degradation associated with the austenitic stainless steels can be found in its early development now. However in addition to the fact that the aforementioned reactors have been operated for more than twenty years, the real situation is more a trade-off because compared to the early days, now reactors operate in a more complicate conditions such as longer operation cycle, higher fuel performance, hydrogen and/or normal metal water chemistry, shorter refueling outage, operation life extension, etc. Therefore, in the future more comprehensive aging management and more regulatory attention on the aging problem of SCC are needed for nuclear power plant operation safety.

5. References


Table 1 Recirculation Piping Inspection at Chinshan

<table>
<thead>
<tr>
<th>Unit</th>
<th>welds</th>
<th>Stress improvement and replacement</th>
<th>Crack inspected</th>
<th>Location and No. of cracks</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>10×</td>
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</tbody>
</table>
| 1    | 115   | 1) IHSI for 94 welds at EOC-5 in 1983  
2) Replacement for riser at EOC-9 | EOC-7  
1986.8 | 10  | 0 | 2 | 12 |
|      |       |                                   | EOC-8  
1987.11  | 1* | 0 | 3 | 4 |
|      |       |                                   | EOC-9  
1989.04  | 0 | 0 | 4 | 4 |
|      |       |                                   | EOC-16  
1998.02  | 0 | 0 | 2 | 2 |
|      |       |                                   | EOC-17  
1999.09  | 0 | 0 | 1 | 1 |
|      |       |                                   | EOC-19  
2002.09  | 0 | 1 | 0 | 1 |
|      |       |                                   | EOC-21  
2005.09  | 0 | 0 | 0 | 1 |
| 2    | 115   | 1) IHSI for 94 welds at EOC-4 in 1983  
2) Replacement for riser at EOC-8 | EOC-7  
1987.07  | 25* | 0 | 0 | 25* |
|      |       |                                   | EOC-8  
1988.11  | 0 | 0 | 0 | 0 |

Note: □ defects before replacement
Table 2 Recirculation Piping Inspection at Kuosheng

<table>
<thead>
<tr>
<th>Unit</th>
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<th>Stress Improvement and Replacement</th>
<th>Crack Inspected</th>
<th>Location and No. of Cracks</th>
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<td>IHSI for 69 welds at EOC-2 in 1984</td>
<td>EOC-6 1989.10</td>
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Figure 1 Chinshan Unit 1 Recirculation System Loop A
Figure 2 Two Axial Crack Indication found at the AH-J1 Weld at Chinshan Unit 1

Figure 3 Axial Crack found at the N1B-F1 Weld at Kuosheng Unit 2
Figure 4 Crack Indication and the Location Related to Jet Pump Assembly

Figure 5 Crack Indication and the Location Related to Jet Pump Assembly