RELIABILITY TESTS FOR REACTOR INTERNALS REPLACEMENT TECHNOLOGY

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Abstract

Structural damage due to aging degradation of LWR reactor internals has been reported in several nuclear plants. NUPEC has started a project to test the reliability of the technology for replacing reactor internals, which was directed at preventive maintenance before damage and repair after damage for the aging degradation. The project has been funded by the Ministry of International Trade and Industry (MITI) of Japan since 1995, and it follows the policy of a report that the MITI has formally issued in April 1996 summarizing the countermeasures to be considered for aging nuclear plants and equipment. This paper gives an outline of the whole test plans and the test results for the BWR reactor internals replacement methods; core shroud, ICM housing, and CRD Housing & stub tube. The test results have shown that the methods were reliable and the structural integrity was appropriate based on the evaluation.

1. INTRODUCTION

LWRs will provide a major part of the nuclear power generation in future in Japan. It is important to have measures against aging degradation in order to improve the reliability and the safety for LWRs, since structural damage of reactor internals results in a plant shutdown and it takes a long time to resolve the problem. The MITI report states that countermeasures should be considered because it can be anticipated that components similar to those that have been damaged in aging nuclear plants in other countries may become damaged in Japanese nuclear plants. Repair of reactor internals is complicated due to difficult access and working in high radiation areas. Therefore a demonstration test of the replacement method, which depends on very precise remote control techniques, is required using full-scale mockup. This must precede the application to actual plants. To conduct the demonstration test at the government level will go a long way towards getting public acceptance in the actual plant work. The other advantage of a test is to obtain much data that can be referred during the examination by the MITI for a construction permit under the regulations. The executive committee of the NUPEC project includes some members of the technical sub-committee in MITI concerned with construction permits. The examination by the executive committee will be a means of prior consultation for judging the reliability and structural integrity of the plant after the replacement has been done.

NUPEC has planned this project for technologies for rejuvenating reactor internals for the eight year period from 1995 to 2002 based on the background described above and as scheduled in Table I. The project consists of six tests for the methods to replace an in-core monitor (ICM) housing, a core shroud, a control rod drive (CRD) housing & stub tube, a jet pump riser brace (for BWR), a core barrel, and a bottom mounted instrumentation (BMI) adapter (for PWR), as illustrated in Figure 1. Each reliability test includes full scale mockup test for the replacement method. Replacement procedure reliability and structural integrity of new replaced structure are planned to be evaluated for each replacement method.

TABLE I. SCHEDULE FOR RELIABILITY TESTS OF REACTOR INTERNALS REPLACEMENT TECHNOLOGY

JFY	1995	1996	1997	1998	1999	2000	2001	2002
Plan and Design								
Manufacturing and Installation								
Tests								
ICM housing								
Core Shroud								
CRD Hsg. /Stub								
J/P riser brace								
Core Barrel								
BMI Adaptor								
Evaluation								

Following paragraphs summarize the test results obtained from three BWR reactor internals replacement methods (Core shroud replacement method, In-core monitor housing replacement method, and CRD housing & stub tube replacement method), that have already finished the mockup test and evaluation.

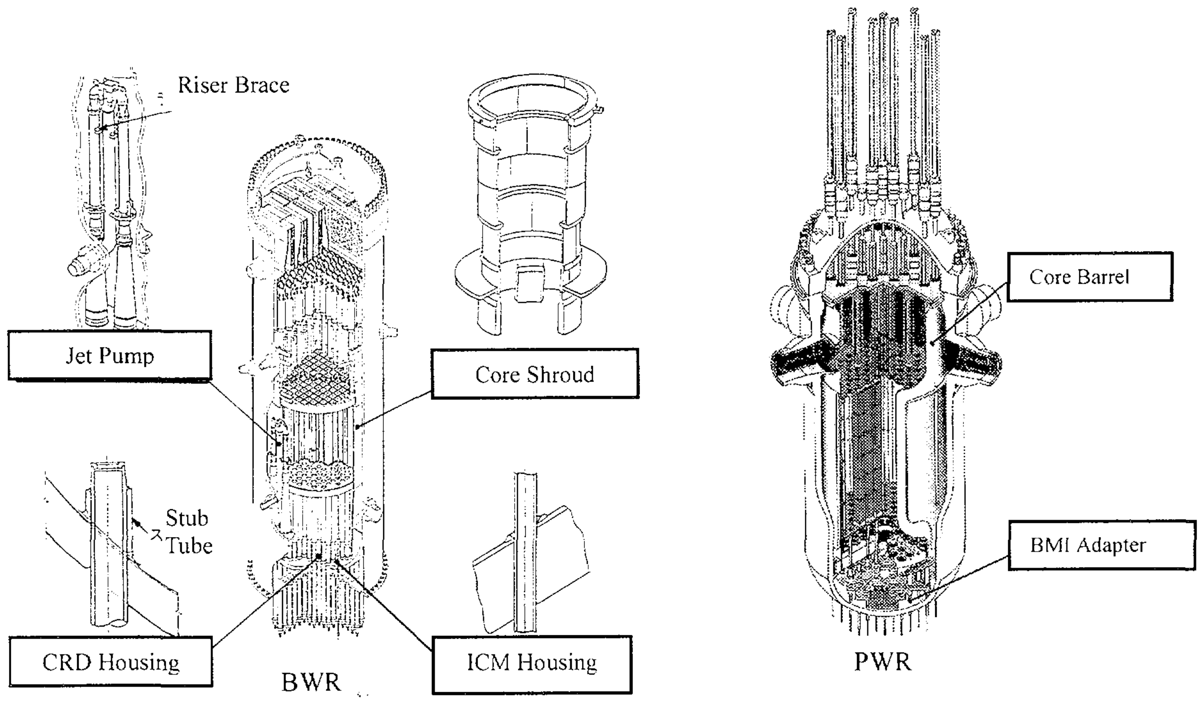

FIG 1. Replacement of reactor internals.

2. BWR CORE SHROUD REPLACEMENT METHOD

2.1. Test plan

Fundamental techniques of the shroud replacement method have been developed in a joint study program between utilities and manufacturers. The main objective of the test was to demonstrate and verify a series of steps of fitting up and welding a new core shroud using a full-scale mockup before actual application in a plant. The test consisted of the following steps:

(1) Shroud fitting-up
(2) Shroud welding
(3) Core plate installation
(4) Top guide installation.

The replacement method aims to avoid the potential stress corrosion cracking (SCC) damage of a core shroud made of SUS304 by replacing it with the new shroud made of SCC resistant materials. Figure 2 shows the shroud structures before and after replacement. Figure 3 shows the sequence of the replacement method. The test results were evaluated by considering the items of (1) alignment of the shroud and (2) structural integrity, and the reliability of the method was examined accordingly.

2.2. Test results

2.2.1. Reliability of the replacement procedure

It was confirmed that all operations were carried out successfully and the requirements were satisfied at each step.

2.2.2. Shroud fitting-up

The full-scale model of the core shroud with a height of 7 meters and a diameter of 4.5 meters was installed on the shroud support. In the test, the maximum root gap between them provided 0.15 mm which was sufficiently smaller than the specified value of 1.1 mm. The welding conditions for the test also allowed for the case in which the gap exceed 1.1 mm.

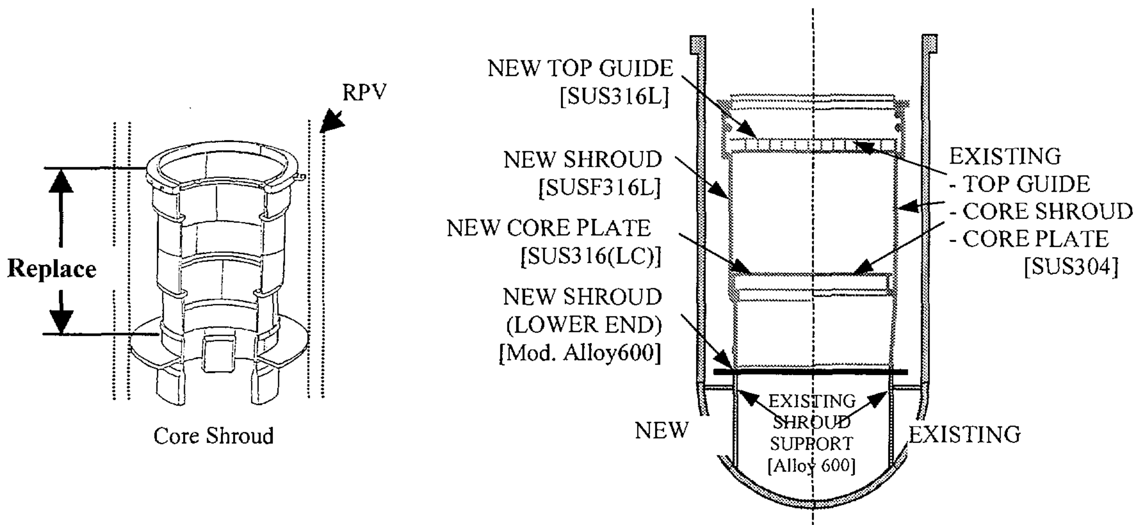

FIG. 2. New core shroud structure.

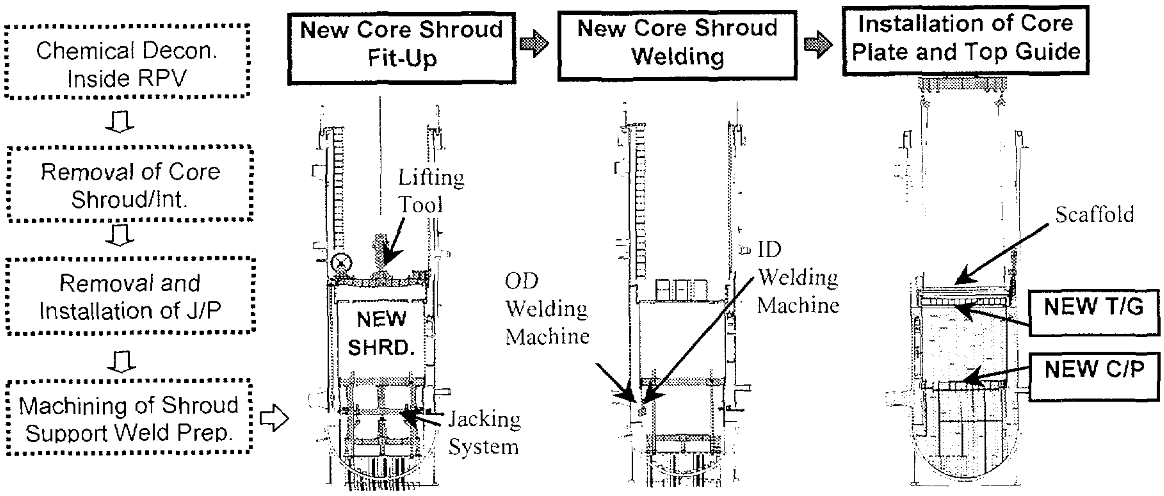

FIG 3. Core shroud replacement sequence.

2.2.3. Shroud welding

Welding between the shroud and the shroud support was conducted by automatic TIG welding technique with narrow gap weld preparation. Full automatic outside welding machine was used to make two passes on the outside, and semi automatic inside welding machine made 26 passes of narrow gap welding as shown in Figure 4. Visual tests (VT) after welding (by a video camera on the outside and direct observation on the inside) found no defects.

2.2.4. Alignment of the shroud

Deviation of the concentricity between the shroud and vessel was measured with laser alignment tools on three occasions; before, during and after the welding. The measured results met the criterion of equal to or less than 6.0 mm. The verticality of the shroud was also measured with similar laser alignment tools. The result was about 0.1mm over the 4 meter distance between the upper and lower templates installed on top guide and core plate location.

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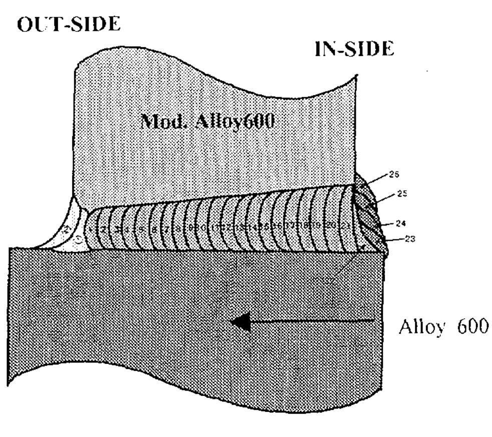

FIG. 4. Welding sequence.

These results showed that the deviation of the alignment of the shroud to the vessel had been prevented by two operating procedures designed to minimize distortion. One of these was to use simultaneously two sets of welding machines operating on opposite sides and the other was to change the starting point of each welding pass based on data from monitoring the alignment.

Deviation of the concentricity of the core plate and that of the top guide were measured in the same way. For both components the criteria were met. Deviation data at mockup test was summarized in Table II.

2.2.5. Structural integrity tests

The penetrant testing (PT) was performed on the inside weld after the first welding pass, the middle pass and the last pass instead of volumetric testing. No defects were found by PT on any pass. Two samples were cut out from the weld. No defect was observed by metallographic examination of the etched specimens (see Figure 5). The integrity of the welded joint was confirmed by these test results.

TABLE II. ALIGNMENT OF NEW SHROUD

INSTALLED COMPONENTS	Permissible deviation (mmDIA)	Measured deviation [tool-No 1 /tool -No2] (mmDIA)
CORESHROUD CENTER	6.0	1.6/3.6
CORE PLATE CENTER	3.8	3.1/2.9
TOP GUIDE CENTER	2.0	0.6/0.4

NOTE: 2 Alignment tools were used to measure the concentricity deviation

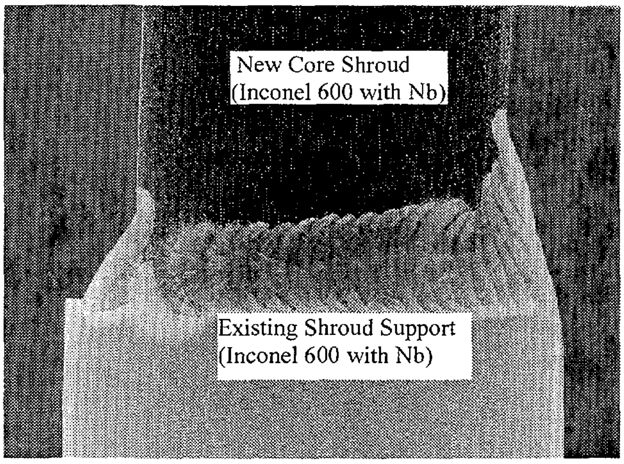

FIG. 5. Cross section view of shroud welding.

2.3. Structural integrity evaluation

Structural integrity of the replaced shroud was evaluated by the mockup test results and other study results including joint study program of utilities and manufacturers. To qualify installation welding, not only mockup test results but also tensile test, bend test, and hardness test data were evaluated. Investigations of material susceptibility, water chemistry, and stresses in the material against SCC were performed using the creviced bend beam (CBB) test. The low susceptibility of the Inconel 600 used for the replaced structures has been evaluated using the data referred to in the joint study program of utilities. These evaluation results are summarized in Table III.

2.4. Summary

The mockup test of the core shroud replacement method was performed in 1997. The test demonstrated the reliability of the prescribed construction procedures for shroud fit-up, shroud welding, core plate installation and top guide installation for a BWR-4 (800MW(e)).

The method was applied in the preventive maintenance of actual plants; the core shroud replacement of TEPCO's Fukushima Daiichi Unit #3 and Unit #2.

TABLE III. SUMMARY OF STRUCTURAL INTEGRITY EVALUATION

EVALUATED PORTION	ITEM	EVALUATION METHOD	RESULTS
Shroud/ Shroud Support Installation Welding	Quality of Welding	(1) NDT(VT,PT) of welding during mockup test. (2) Metallographic observation of the welding cross-section (3) Hardness measurements of the welding cross-section. (4) Mechanical property test - Tensile test - Bend test	(1) No defect was found by NDT and Metallographic examination (2) Mechanical properties of the welding portion were found to be good enough.
	Corrosion Resistance	(1) Creviced bend beam (CBB) test	(1) No Stress Corrosion Cracking was found in the new installation welding on this test.
	Residual Stress caused by Welding	(1) Measurements of welding residual stress	(1) Residual stress was found to be low enough
	Influence of Neutron Irradiation to the shroud support	(1) Evaluation of dissolved Helium concentration around the installation welding	(1) Analysis has shown that Helium generation by Neutron irradiation around welding portion was low.

3. BWR ICM HOUSING REPLACEMENT METHOD

3.1. Test plan

The method involves a repair technique (replacement) to avoid potential damage of the ICM housing due to stress corrosion cracking (SCC) of SUS304 housing welding and an evaluation of the structural integrity after the replacement. A comparison of the ICM housing structures before and after the replacement is shown in Figure 6. New ICM housing and ICM guide tube is made of SUS316L, which is a SCC resistant material.

The replacement method consisted of the four conceptual steps using full remote technique of machining, welding, and testing, to ensure the work at highly activated environment inside the Reactor Vessel. These four conceptual steps are described below and are illustrated in Figure 7. The full scale mock-up test was conducted through (2) to (4) steps described below that should influence structural integrity of new replaced structure.

(1) The existing ICM guide tube, housing and weld buildup are removed.
(2) A new weld buildup is formed and machined.
(3) A new housing made of SCC resistant material is inserted and welded to the weld buildup.
(4) A new guide tube is connected to the new housing by a coupling made of shape memory alloy (SMA).

3.2. Test results

3.2.1. Reliability of the replacement procedure

It was confirmed that all operation were carried out successfully and requirements were reviewed at each step.

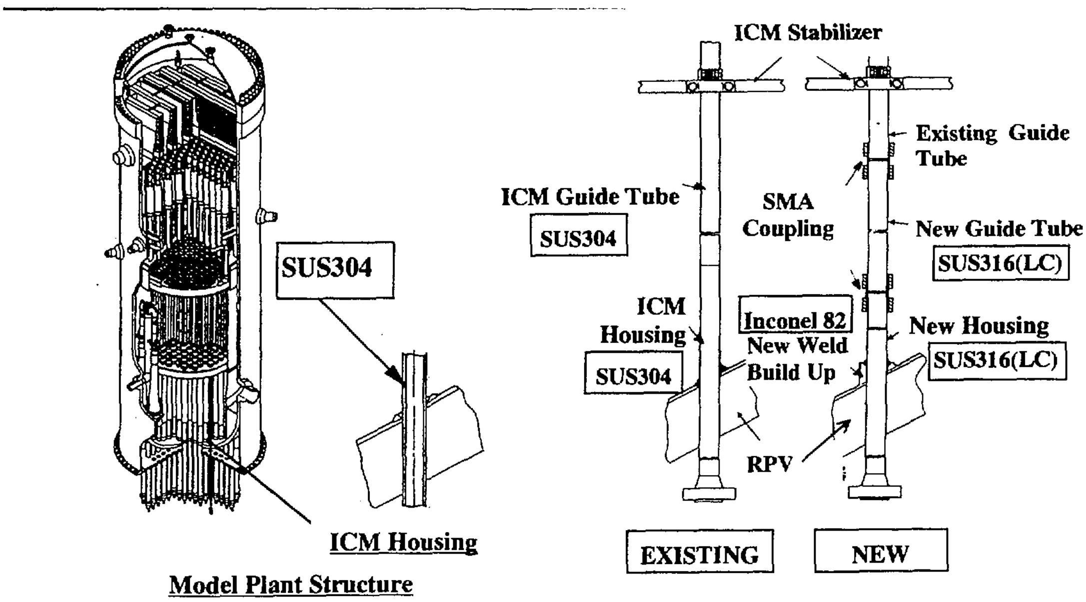

FIG. 6. New ICM housing structure.

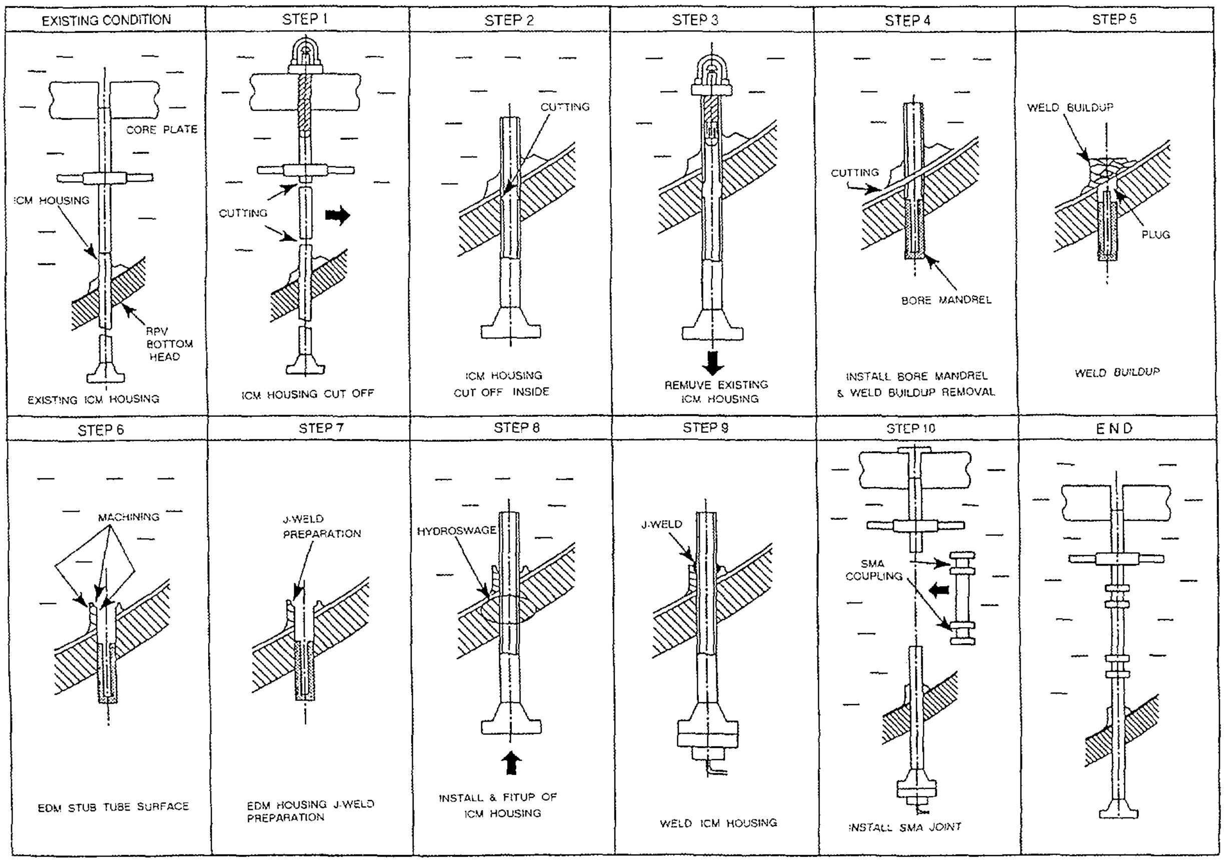

FIG. 7. ICM housing replacement sequence.

3.2.2. Welding buildup and machining

The new weld buildup was formed on the bottom surface of the reactor pressure vessel (RPV) using a remote controlled welding device and machined with electric discharge machining tools. No flaw was detected in the weld buildup by a penetrant testing (PT), and an ultrasonic testing (UT).

3.2.3. Housing connection welding

After installation in the RPV bottom, the new housing was connected to the weld buildup by a J-weld using a remote controlled welding machine. PT and UT inspections discovered no defect in the weld during the test or by subsequent visual checks.

3.2.4. SMA coupling joint

The new guide tube with an SMA coupling at each end was installed between the new ICM housing and the existing guide tube. The coupling was heated up and connected at the both ends. The structural adequacy of the connection was evaluated by an eigenvalue analysis compared the frequencies before and after the replacement and by a flow induced vibration analysis. Figure 8 shows the new ICM housing after SMA coupling installation.

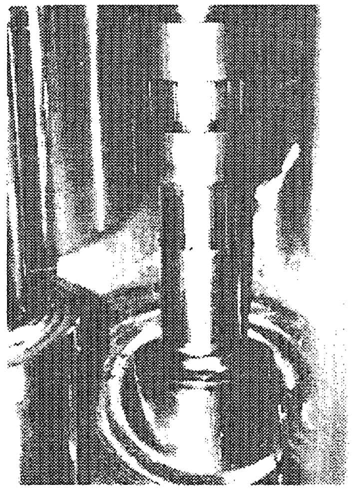

FIG. 8. New ICM housing with SMA coupling joint.

3.2.5. Structural integrity tests

PT and UT inspections of weld build-up and housing J-welding were performed. Metallographic examination of a section cut through the welding material and SMA couplings were performed after these nondestructive tests (Figure 9). No defect was found by these tests. Hardness of the welding material cross section was measured and the obtained data has shown good results.

3.3. Structural integrity evaluation

Structural integrity of replaced ICM housing is evaluated by the mockup test results and the results of joint study program of utilities and manufacturers. It has been confirmed that the dimensions of the welded part met the tensile test, bend test, and hardness test. Investigations of material susceptibility, water chemistry, and stresses in the material against SCC were performed by accelerated SCC test. The low susceptibility of the SUS316L and Inconel 82 used for the replaced structures has been evaluated using the data referred to in the joint study program of utilities. Evaluation results are summarized in Table IV.

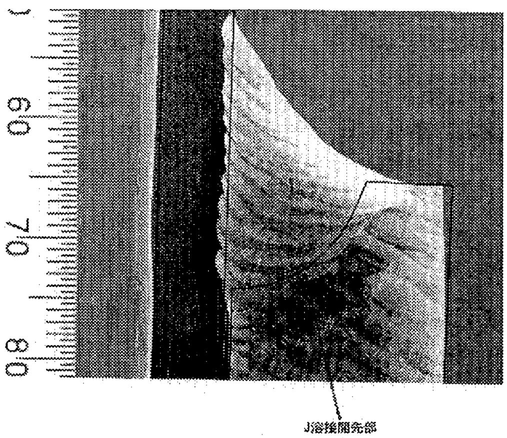

FIG. 9. Cross-section view of ICM housing J welding.

TABLE IV. SUMMARY OF STRUCTURAL INTEGRITY EVALUATION

EVALUATED PORTION	ITEM	EVALUATION METHOD	RESULTS
(1) Buildup Welding (2)Housing J- Welding	Quality of Welding -	(1) Non Destructive Test (PT, UT) (2) Metallographic observation (3) Hardness measurements (4) Constitution analysis (5) Mechanical property test. (Tensile test, Bend test)	(1) No defects were found by NDT and Metallographic observation (2) Mechanical properties of the welding portion were found to be good enough
	Corrosion Resistance	(1)Accelerated SCC test	(1) No SCC was found on the welding portion on this test
	Residual stress caused by welding	(1) Measurements of welding residual stress	(1) Residual stress was found to be low enough
	Thermal effects of the build-up welding to the RPV low alloy	(1) Metallographic observation of mockup test piece (RPV) cross section	(1) Observation results showed no metallurgical effects on low alloy
	Fatigue evaluation of J welding toe	(1) Fatigue analysis under estimated stress concentration factor	(1) Analysis shows small fatigue damage
(3) Shape Memory Alloy (SMA)	Characteristics of Shape Memory Alloy (Ni-Ti-Nb alloy)	(1) Composition analysis (2) Metallographic examination (3) Measurements of mechanical and thermal property (4) Corrosion resistance (5) Characteristics under high temperature environment (Creep, aging, transformation, etc) (6) Irradiation effect	(1) It was recommended that Ni-Ti-Nb alloy was suitable for In-Reactor use because of its good mechanical strength, corrosion resistance and irradiation characteristics
	Evaluation of SMA coupling parts	(1) Evaluation of shape recovery treatment temperature (2) Coupling strength test of SMA joint (3)Coupling strength test under repeated load (4)Corrosion resistance evaluation (5) Creep characteristics evaluation	(1) Mechanical joint strength of SMA coupling was evaluated under the seismic load, fluid vibration load and other thermal load under operating condition, and it was found to be suitable.

3.4. Summary

The test of the ICM housing replacement method was performed in 1996. The mockup test results have shown that the ICM replacement could be performed using the prescribed procedure. These evaluations indicated that the test of the ICM housing replacement method had demonstrated that the procedure was reliable. The method has been applied to the repair of an actual plant; ICM housing replacement was done at TEPCO's Fukushima Daiichi Unit #4 in 1997.

4. BWR CRD HOUSING & STUB TUBE REPLACEMENT METHOD

4.1. Test plan

CRD housings & stub tubes as shown in Figure 10 are the penetration for control rod drive mechanism and located on the RPV bottom head. For most of aged plants, CRD housings are made of SUS304, which has a SCC susceptibility similar to ICM housings. Figure 10 illustrates the CRD housing and stub tube structures before and after replacement.

The sequence of the CRD housing & stub tube replacement method is shown in Figure 11. Because of the structure and location of the CRD housings are similar to the ICM housings, some of the basic replacement technique such as electric discharge machining, remote UT and remote PT techniques are common technologies. On the other side, CRD housing needs severe alignment accuracy and special three-dimensional welding technique. Then the mock up test plan is optimized to demonstrate the characteristic technology of this method such as welding steps with on-line alignment measurements. Main steps of the mockup test are described below:

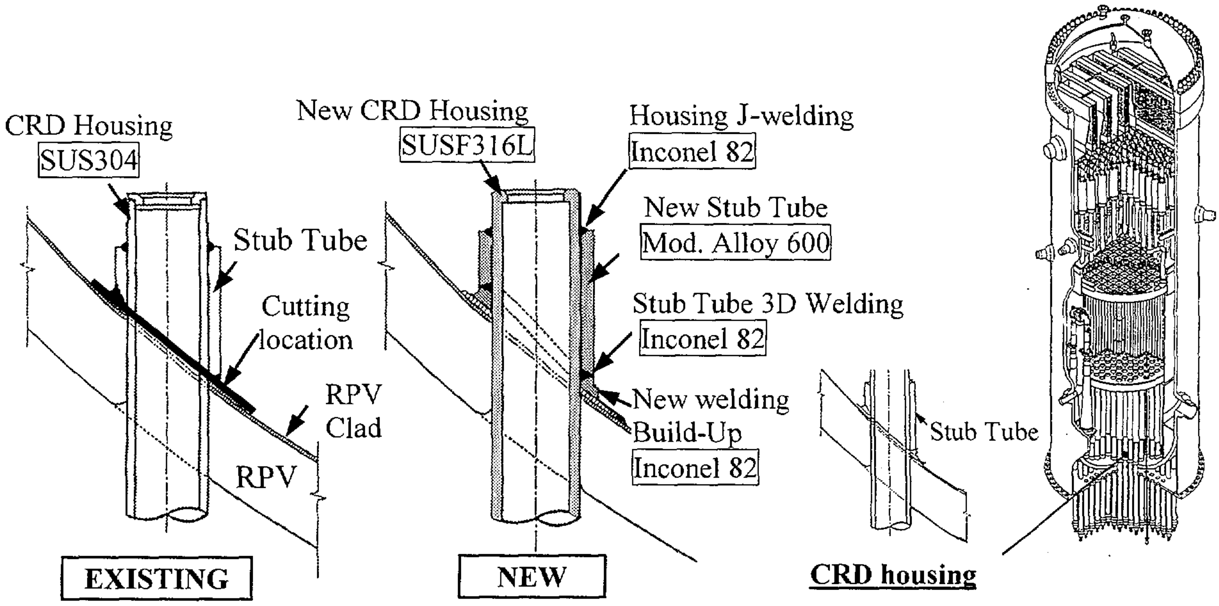

FIG. 10. New CRD housing and stub tube structure.

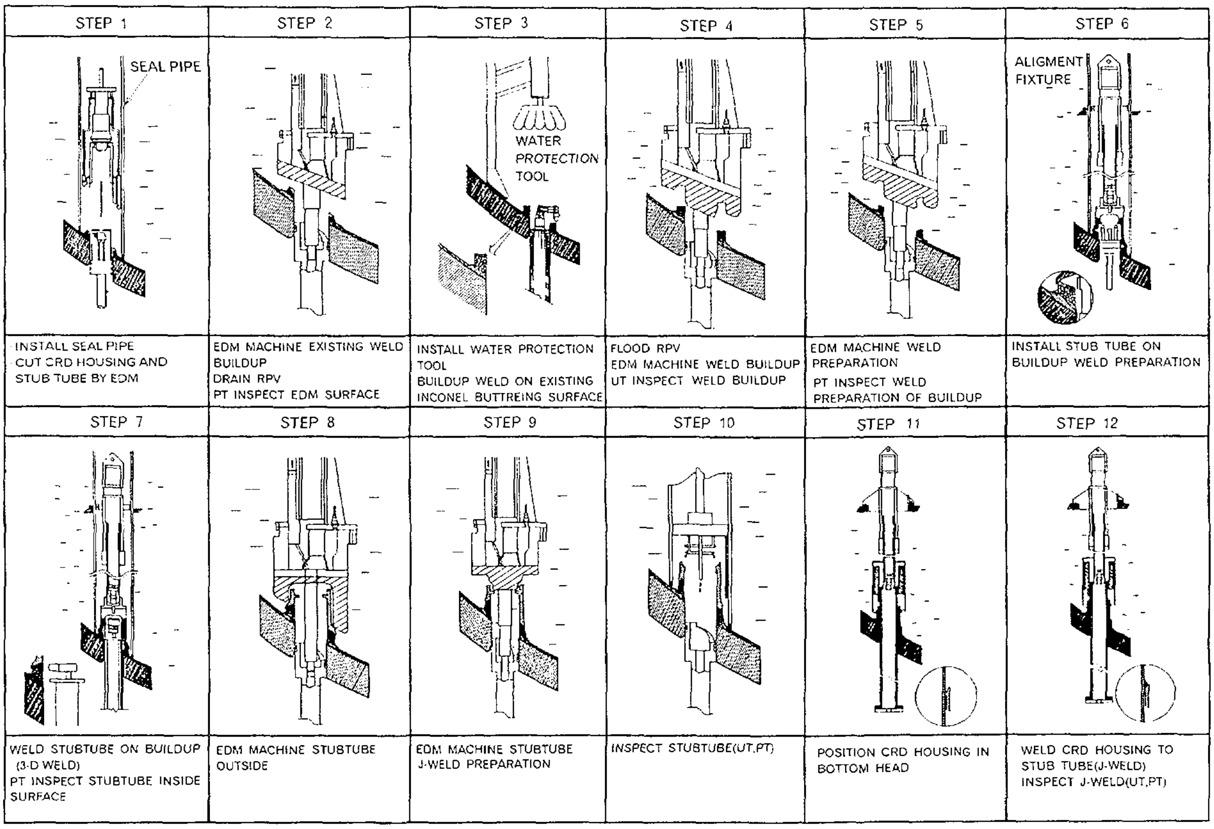

FIG. 11. CRD housing & STUB tube replacement sequence.

(1) Welding build-up and PT inspection of stub tube weld preparation.
(2) New stub tube fit-up and Stub tube 3-D welding with laser alignment tool
(3) Inside machining after stub tube welding and PT inspection
(4) New CRD housing fitting up and J welding with laser alignment tool

4.2. Test results

4.2. 1. Reliability of the replacement procedure

It was confirmed that all mockup test operation was carried out successfully and requirements were reviewed at each step. Other steps were also evaluated by the ICM housing replacement mockup test data and the results of joint study program. of utilities and manufacturers.

4.2.2. Welding buildup

The new welding buildup was formed on the bottom surface of the reactor pressure vessel (RPV) using a remote controlled welding machine. No flaw was detected in the weld buildup by a penetrant testing (FIT), and an ultrasonic testing (UT).

4.2.3. Stub tube 3D welding

The new stub tube was connected to the weld buildup by a three-dimensional shaped preparation welding after installation on the RPV bottom, using a remote controlled welding machine. To reduce radiation exposure of the worker, welding was executed under water for shielding with seal pipe device, which made partial dry condition. The alignment of stub tube was measured during and after welding as shown in Fig. 12.

After the installation, inside surface of the stub tube welding was machined by remote precise grinding machine. PT and UT inspections after ID machining discovered no defects in the connection.

4.2.4. Housing installation welding

The new CRD housing was installed inside the new stub tube and welded by the remote housing J welding machine. Figure13 shows the new stub tube and CRD housing after installation. The alignment of CRD housing was measured during and after welding. The test results met the required alignment deviation as shown in Table V.

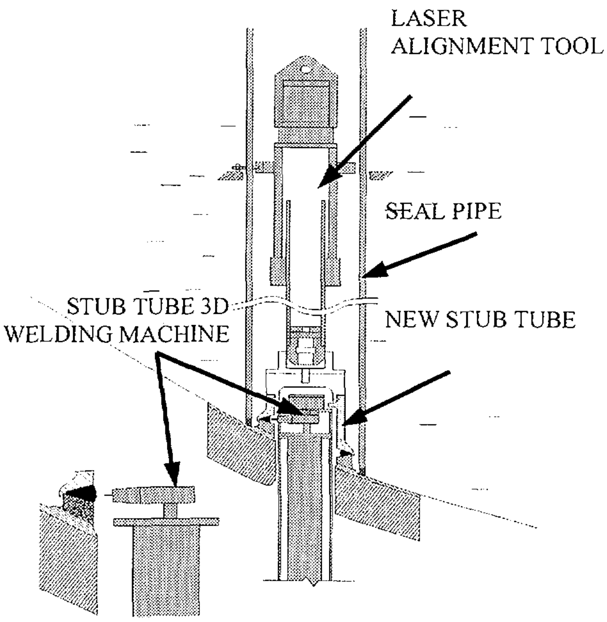

FIG. 12. New STUB tube welding.

TABLE V. ALIGNMENT OF STUB TUBE AND CRD HOUSING

INSTALLED COMPONENTS	Permissible deviation (mmDIA)	Measured deviation (mmDIA)
Stub tube center	1.5	0.7
CRD housing center	0.8	0.5

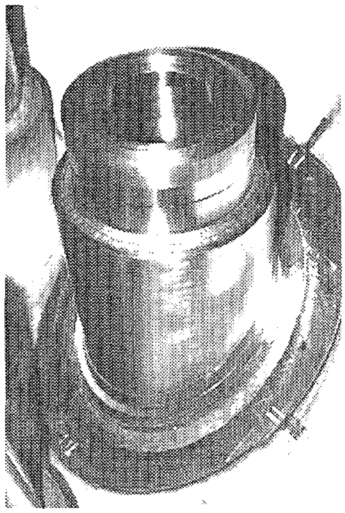

FIG. 13. New CRD housing and STUB tube.

4.2.5. Structural integrity tests

PT and UT examinations of build-up welding, stub tube welding and housing J-welding were performed. Metallographic examination of a section cut through the welding material was performed. No defects were found by these tests. Hardness of the welding material cross section was measured and the obtained data has shown good results.

4.3. Structural integrity evaluation

Structural integrity of replaced CRD housing & stub tube is evaluated by the mock up test results and the results of joint study program of utilities and manufacturers. Evaluation results are summarized in Table VI.

4.4. Summary

The test of the CRD housing replacement method was performed in 1998. The mockup test results have shown that the replacement could be performed using the prescribed procedure and these evaluations indicated that the test of the CRD housing & stub tube replacement method had demonstrated that the procedure was reliable.

5. SUBSEQUENT EFFORTS

As shown in Table I, NUPEC is now executing the reliability test for PWR Core Barrel replacement method, from 1997 to 2000. Full-scale mockup test will be demonstrated in the early 2000. Two additional tests of PWR BMI adapter replacement method and BWR jet pump riser brace replacement method are planned after the Core Barrel replacement method mockup test. These test results will be reported after their reliability tests have finished.

TABLE VI. SUMMARY OF STRUCTURAL INTEGRITY EVALUATION

EVALUATED PORTION	ITEM	EVALUATION METHOD	RESULTS
(1) Buildup Welding (2) stub tube welding (3) Housing J-Welding	Quality of Welding	(1) Non Destructive Test (PT, UT) (2) Metallographic observation (3) Hardness measurements (4) Mechanical property test (Tensile test, Bend test)	(1) No defects were found by NDT and Metallographic observation (2) Mechanical properties of the welding portion were found to be good enough
	Corrosion Resistibity	(1) Creviced Beam Bend test	(1) No SCC was found on the welding portion on this test
	Residual stress caused by Welding	(1) Measurements of welding residual stress	(1) Residual stress was found to be low enough
	Thermal effects of the build-up welding to the RPV low alloy	(1) Metallographic observation of mockup test piece (RPV) cross section	(1) Observation results showed no metallurgical effects on low alloy
	Fatigue evaluation of J welding toe	(1) Fatigue analysis under estimated stress concentration factor	(1) Analysis shows small fatigue damage

6. CONCLUSIONS

Plans to test the technologies used in the methods to rejuvenate reactor internals and results obtained so far have been presented. Especially, a summary has been given to show how the reliability of various steps in the replacement work such as machining, welding, inspection, and so on have been demonstrated in the tests using full scale model mockups. It is concluded that NUPEC activities concerned with countermeasures for the aging degradation of nuclear plants have been successful in Japan because the ICM and the shroud replacement methods have already been applied to actual plants after the NUPEC tests were completed.

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