Status of Reactor Pressure Vessel Embrittlement Study in Japan

by
Hiroyuki SASAJIMA
Japan Power Engineering and Inspection Corporation (JAPEIC),
279; Business Court Shin Urayasu Bldg., 9-2, Mihama 1-chome,
Urayasu-shi, Chiba; Japan

《ABSTRACT》

Since the construction of Japanese first commercial nuclear power plant in 1966, 52 nuclear power plants have been commissioned in Japan to commercial operation. Japanese first nuclear power plant has now been in service for 30 years and the aging of nuclear power plants is steadily progressing in general.

Under these circumstances, the Japan Power Engineering and Inspection Corporation (JAPEIC) is executing, under consignment by the Ministry of International Trade and Industry (MITI), the development and verification test programs for plant integrity evaluation technology by which nuclear power plant aging can be appropriately handled. This paper shows the outline of study dealing with embrittlement of RPV caused by neutron irradiation, as one of the activity of JAPEIC.

The embrittlement of RPV caused by neutron irradiation is manifested as a shift of transition temperature and as a reduction in Upper Shelf Energy (USE). In JAPEIC, the study dealing with a shift of transition temperature was conducted in the "Reactor Pressure Vessel Pressurized Thermal Shock Test Project (the PTS Project)", and the study dealing with a reduction in USE has been conducted in the "Nuclear Power Plant Life Management Technology (the PLIM Project)". And the reconstitution technology of surveillance test specimen has been conducted in PLIM Project as one of the measures to improve monitoring above material characteristic changes.

The integrity evaluation under the Pressurized Thermal Shock (PTS) events including the effect of neutron irradiation embrittlement was initiated in 1983 FY as the PTS Project and was completed in the 1991 FY. The study verified that plant integrity could be assured at not only the end of design life, but also an extended service life even when the severest PTS events were postulated.

The PLIM Project, designed to develop and verify the integrity evaluation technology dealing with reduction of USE by neutron irradiation, was started in the 1996 FY as a 10-year project. This project includes the development of neutron irradiation embrittlement prediction equations and the correlation equations between USE of Charpy V-notch and fracture toughness, and the verification to standardize surveillance test specimen reconstitution practices to deal with the extended service life of RPV.

This paper presents the achievements made by the PTS Project and the current status of the PLIM Project.

Keywords: Neutron irradiation embrittlement, Pressurized Thermal Shock (PTS), Upper Shelf Energy (USE), Reactor Pressure Vessel (RPV), reconstitution of test specimen

1. INTRODUCTION

Since the construction of Japanese first commercial nuclear power plant in 1966, 52 nuclear power plants have been commissioned in Japan to commercial operation. Japanese first nuclear power plant has now been in service for 30 years and the aging of nuclear power plants is steadily progressing in general.

Under these circumstances, JAPEIC is executing the development and verification test programs for plant integrity evaluation technology by which nuclear power plant aging can be appropriately handled under consignment by MITI.

The embrittlement of RPV material caused by neutron irradiation is manifested as a shift of transition temperature and as a reduction in USE. In JAPEIC, the study dealing with a shift of transition temperature was conducted in the PTS Project, and the study dealing with a reduction in USE has been conducted in PLIM Project. And the reconstitution technology of surveillance test specimen has been conducted in PLIM Project as one of the measures to improve monitoring above material characteristic changes.

The integrity of embrittled RPV was evaluated under postulation of PTS events in the PTS Project (completed in 1991 FY), and the development of embrittlement evaluation equation for neutron irradiation and verification tests for plant integrity evaluation are being planned in the PLIM Project (scheduled from 1996 FY to 2002 FY).

One of the reconstitution method of Charpy impact test specimen had been developed using non-irradiated test specimen in the PLEX Project as the feasibility study of RPV toughness monitoring technology. (It was completed in 1996 FY). The verification test of the reconstitution technology for various surveillance test specimens employing irradiated test pieces, is being planned in PLIM Project (scheduled from 1996 FY to 2005 FY).

2. INTEGRITY EVALUATION OF RPV

2.1 Evaluation of PTS events

The evaluation of the RPV integrity subjected to neutron irradiation embrittlement under PTS events had been completed in the PTS Project which was started in 1983 FY as a 9-year project and completed in 1991 FY.

The integrity evaluation scheme of this verification test is presented in Figure-1. In this test, the identification of the degree of embrittlement by neutron irradiation, the changes of temperature, pressure, etc. under PTS events, and the RPV stress evaluation employing thermo-hydraulic analysis were conducted to evaluate the integrity of RPV under PTS events at the end of its design lives and at extended design lives.

In evaluating the integrity, the fracture toughness (K_{IC}) of RPV at the end of design life and at extended design life was compared to the stress intensity factor (K_I) of the vessel (with considerations of flaw at inside surface of the vessel), to evaluate the possibility of unstable crack propagation.

The estimated value of K_{IC} after neutron irradiation was obtained by shifting the relationship between transition temperature and fracture toughness of RPV (the $K_{IC}-T$ diagram) to the high temperature side considering that the temperature shift of K_{IC} transition curve is equal to the shift value of the transition temperature RT_{NDT} due to neutron irradiation.

In order to estimate the shift value of RT_{NDT} (ΔRT_{NDT}) by neutron irradiation, the prediction equations of ΔRT_{NDT} for the base metal and weld metal, represented in equations (1) and (2) below, were formulated based on the surveillance test data and accelerated test data in Japan, as well as the surveillance test data of the USA.

(Base metal)

$$\Delta RT_{NDT} = (-16 + 1230P + 215Cu + 76\sqrt{Cu \cdot Ni}) \times f^{0.27} \quad + 2\sigma_b \qquad (1)$$

(Weld metal)

$$\Delta RT_{NDT} = (27 - 23Si - 58Ni + 290\sqrt{Cu \cdot Ni}) \times f^{0.24-0.09\log f} \quad + 2\sigma_w \qquad (2)$$

where

P,Cu,Ni,Si = contents of chemical composition (wt%)

f = neutron fluence ($\times 10^{19}$ n/cm^2, E > 1 MeV)

σ_b, σ_w = standard deviation (℃) : $\sigma_b = 12$℃, $\sigma_w = 16$℃

The shift value of transition temperature estimated by this equation (ΔRT_{NDT}) was compared to the surveillance data of an comercial plant in Figure-2. This comparison indicates that the dispersion of predicted ΔRT_{NDT} is within 2σ for both base metal and weld metal. From this comparision, the appropriateness of this prediction equations was verified.

Based on the above prediction equations, the equations for $K_{IC} - T$ of RPV at the end of design life and at extended design life has been estimated. The equations for $K_{IC} - T$ at extended design life (1×10^{20}n/cm^2) were formulated based on the servaillence test data, represented in (3) and (4) as follows.

(Base metal)

$$K_{IC} = 65 + 419\exp\{0.0161(T-125)\} \qquad (3)$$

(Weld metal)

$$K_{IC} = 65 + 419\exp\{0.0161(T-112)\} \qquad (4)$$

where

K_{IC} = fracture toughness (kgf/mm$^{3/2}$)

T = evaluation temperature (℃)

In postulating the transients of temperature and pressure caused by PTS events, main steam line break (MSLB) and small LOCA were defined as the severest events to the integrity of RPV. In addition, large LOCA was also selected as a postulated event, because it is recognized as a sever event to the integrity of RPV, although it is not a PTS event in original meaning as the reactor pressure is reduced. The temperature and pressure transient curves were produced for each postulated event.

In formulating the temperature vs. pressure transient curves for PTS events, tests and analysis were conducted with a 1/3 scale plant mockup model to identify the temperature distribution at water injection to the cold legs and down comers.

By this test and analysis, the temperature distributions within the RPV during PTS events were also evaluated.

K_I during PTS events was calculated in reference to the above test results. This value was compared with K_{IC} and it was seen that sufficient integrity is maintained, not only at the end of design life (6×10^{19} n/cm^2), but also at extended design life (1×10^{20} n/cm^2). This analysis result is presented in Figure-3.

A model test simulating the stress conditions in a actual RPV was then conducted to verify the propriety of integrity evaluation method. The configurations of the test facilities and test pieces are presented in Figure-4,5. In this test, membrane stress due to internal pressure was simulated by tensile stress on the test piece, the thermal bending stress by temperature was simulated by bending stress on the test piece, and the local thermal stress caused by rapid cooling was simulated using coolant adjoined to the opposite side of heater on the test piece.

Low toughness steels for test specimens were manufactured by the appropriate selection of chemical compositions and heat treatment to simulate the toughness at the end of design life (6×10^{19} n/cm^2) and at extended design life (1×10^{20} n/cm^2). Two types of the surface defect were provided, one has 10 mm depth and 60 mm length, and another one has twice larger dimension.

The comparison of experimentally obtained K_I vs. temperature curve with lower bound of K_{IC} curve at the end of design life is presented in Figure-6. The comparison of experimentally obtained K_I vs. temperature curve with lower bound of K_{IC} data at extended life is presented in Figure-7. These results show that RPV integrity is maintained under PTS events, not only design life but also extended design life.

The test results using the test pieces which have twice as large surface defects as above tests indicated that more than a twice allowance is maintained concerning the flaw dimensions. (See Figure-8).

At the standardization , the prediction equation of ΔRT_{NDT} (1), (2) were revised as follows considering the surveillance test data of Japanese BWR plants.

(Base metal)

$$\Delta RT_{NDT} = (-16+1210P+215Cu+77\sqrt{Cu \cdot Ni}) \times f^{0.29-0.04\log f} + 2\sigma_b \qquad (5)$$

(Weld metal)

$$\Delta RT_{NDT} = (26 - 24Si - 61Ni + 301\sqrt{Cu \cdot Ni}) \times f^{0.25-0.10\log f} + 2\sigma_w \qquad (6)$$

where

P,Cu,Ni,Si = contents of chemical composition (mass%)

f = neutron fluence ($\times 10^{19}$ n/cm^2, E > 1 MeV)

σ_b, σ_w = standard deviation (℃) : σ_b = 12℃, σ_w = 15℃

2.2 Development of evaluation equation for USE

The embrittlement of RPV caused by neutron irradiation is manifested as a reduction in USE, in addition to increase of transition temperature.

In Japan, it is regulated in JEAC4206 that the USE of Charpy absorption energy should be more than 68 J during service life. However, there is no method to evaluate the integrity of RPV material in case of low toughness under 68 J.

In the USA, R.G.1.99 Rev.2 provides the prediction equation of USE reduction and R.G.1.161 provide the evaluation method for energy below 68J concerning the reduction of USE by neutron irradiation.

However, this prediction equation was developed for RPV steel materials used in the USA and these steel materials are different from the reactor vessel materials used in Japan, particularly concerning the chemical compositions of weld metals. It is, therefore, necessary to develop a prediction equation adequate to Japanese steel materials.

To develop the USE prediction equation for Japanese pressure vessel steel materials and to verify the integrity of RPV, the verification test in PLIM Project was, therefore, started in 1996. In this project, the following tests will be conducted to evaluate the integrity at the upper shelf region on domestic RPV steel materials by fracture mechanics methodology.

* Verification test for prediction equation of the reduction of USE

* Verification test for correlation equation between USE and fracture toughness

The above tests are being implemented under a schedule for their completion by 2001, and the standards on USE will be established under relevant agency. The test plans are presently being discussed in the project.

The evaluation procedures in these verification tests are presented in Figure-9. Concerning the fracture mechanics evaluation methods for RPV, pioneering research has been conducted in other projects. In the PLIM Project, the test to identify the reduction of USE caused by neutron irradiation will be conducted first, and then the procedures for evaluation of RPV integrity will be formulated using the correlation equation between USE and fracture toughness.

3. ESTABLISHMENT OF TOUGHNESS MONITORING METHOD FOR RPV

MITI Notification No. 501 requires that nuclear power plants in Japan are provided with surveillance test specimens in order to monitor the toughness of RPV periodically during their service lives. The addition of surveillance test specimens is required in order to deal with the extended service life of nuclear power plants. Meeting this requirement, it is necessary to develop and standardize the reconstitution technology of surveillance test pieces. Under these circumstances, JAPEIC verified the feasibility of the Charpy test specimen reconstitution technology in the PLEX Project. In the PLIM Project, JAPEIC is also engaged in technology development and verification test for reconstitution of Charpy test specimen, tensile test specimen, and C/T test specimen.

3.1 Research in PLEX Project

The feasibility study of the reconstitution technology for Charpy test specimen was one of the major themes of the PLEX Project. The procedure of Charpy test specimen reconstitution is schematically illustrated in Figure-10. The plastic deformation area of the test specimen generated by the original test is removed first, and the remaining part is joined on both side with tab material. In this Project, the amount of the plastically strained area generated in the original test and the test after reconstitution, and the heat annealed area generated by the welding during the reconstitution process were estimated for laser welding, resistance welding, friction welding, etc.. Based on this estimation, the necessary length of the original test piece to be inserted between the tab materials was determined as 22.5 mm.

The test results of the Charpy test specimen reconstituted by laser welding are presented in Figure-11. These results indicated that when the inserted part is 22.5 mm long, the Charpy test value after reconstitution was same as the value of original test specimen. Therefore it is recognized that the reconstitution of Charpy test specimen is applicable to actual plants as one of the suitable method.

3.2 Research in PLIM Project

The feasivility of Charpy test specimen reconstitution technology was verified in the PLEX Project. In commercial plant, surveillance tests of RPV to be conducted on test specimen include a tensile test and C/T test in addition to the Charpy test, the reconstitution technology for these test pieces will be verified in the PLIM Project. As the standardization of reconstitution technology is intended in this Project, tests employing neutron irradiated materials will be conducted to simulate the real surveillance test specimens more exactly.

The final target of this research is to analyze and define the technical requirements on reconstitution of irradiated test piece. And it is planned to conduct reconstitution tests with advanced jointing method, for example friction welding, electron beam welding, laser welding, etc.. This Project was started in 1996 FY scheduled for completion in 2005 FY.

4. CONCLUSION

To deal with the extended service lives of nuclear power plants, research on neutron irradiation embrittlement of RPV materials has being conducted in Japan under the guidance of MITI.

In JAPEIC, the study dealing with a shift of transition temperature caused by neutron irradiation was conducted in the PTS Project, the study dealing with a reduction in USE caused by neutron irradiation has been conducted in PLIM Project, and the study dealing with a reconstitution technology of surveillance test specimens has also been conducted in PLIM Project.

The PLIM Project will continue to 2005 FY, and the progress at the pertinent stages of the Project will be reported.

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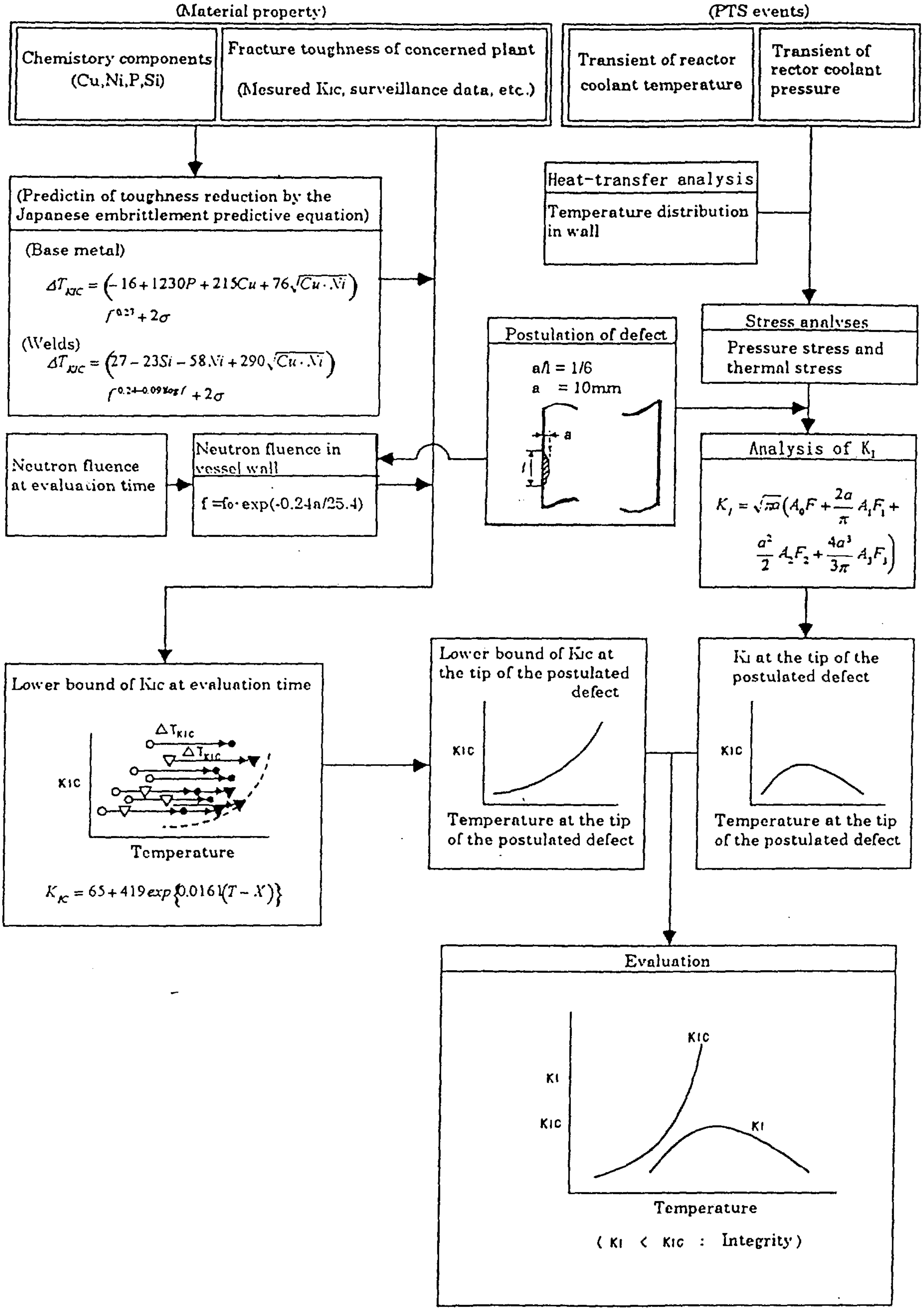

Figure 1 Integrity evaluation scheme in PTS project

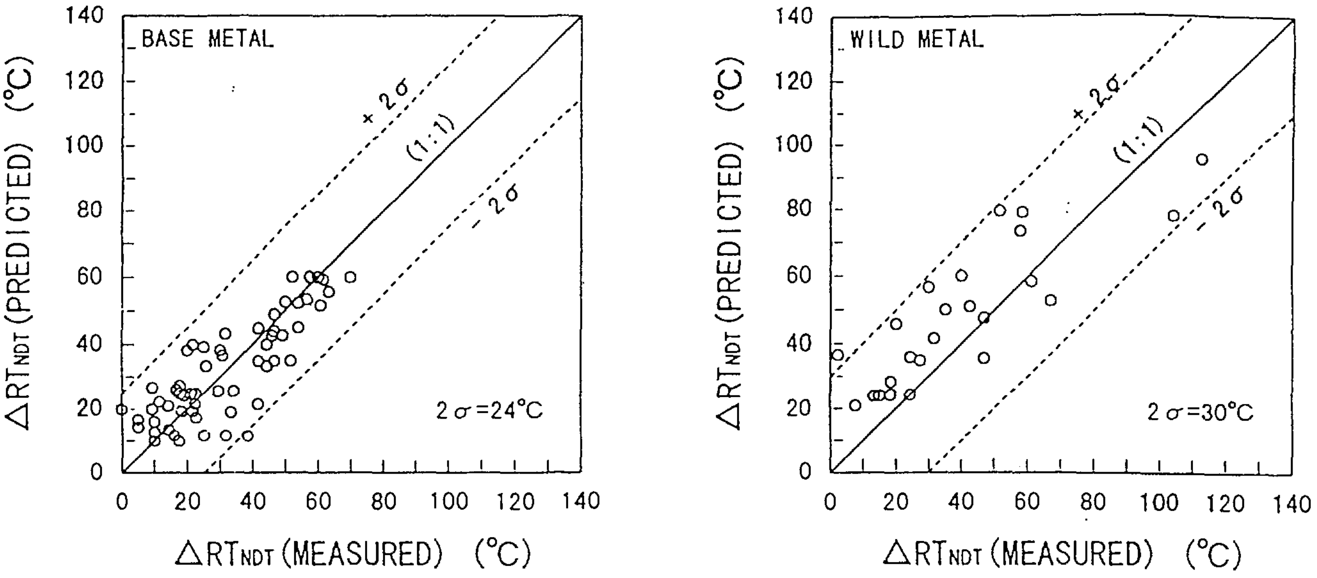

Figure 2 Comparison between the predicted ΔRT_{NDT} and measured ΔRT_{NDT} for Japanese plant's surveillance data

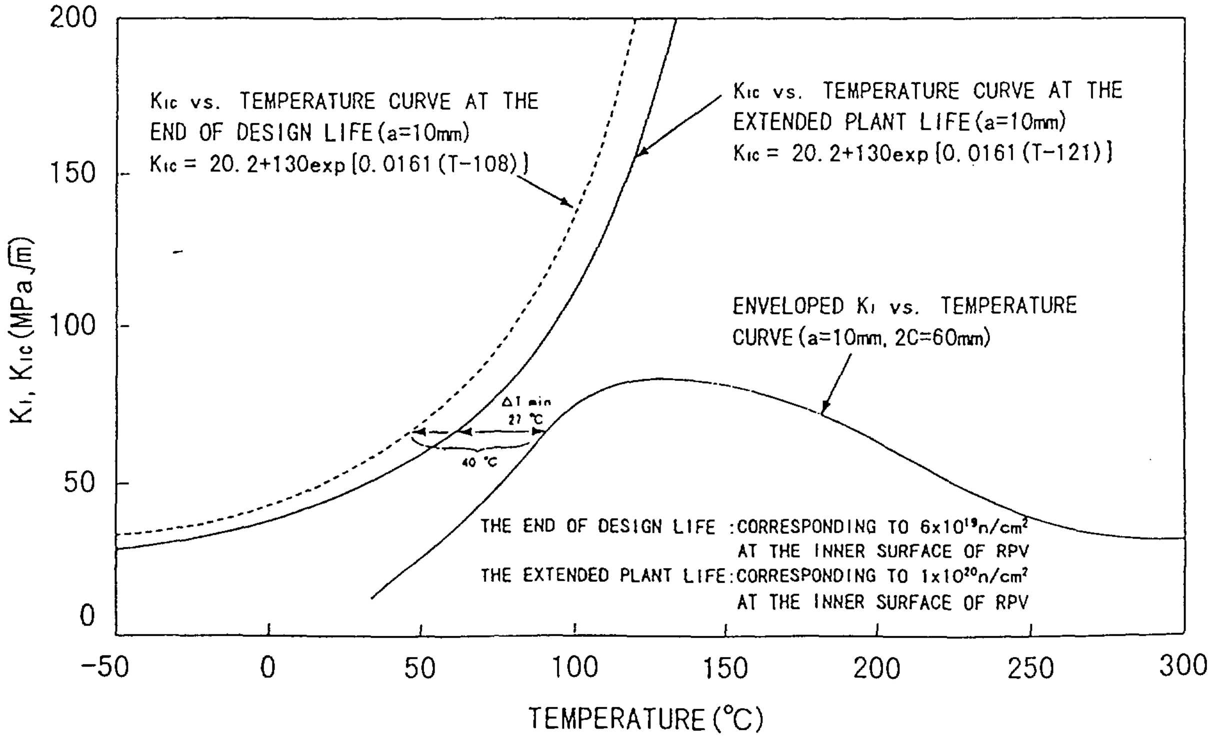

Figure 3 Comparison of enveloped K_I vs. Temperature curve with K_{IC} vs. Temperature at the end of design life and extended life

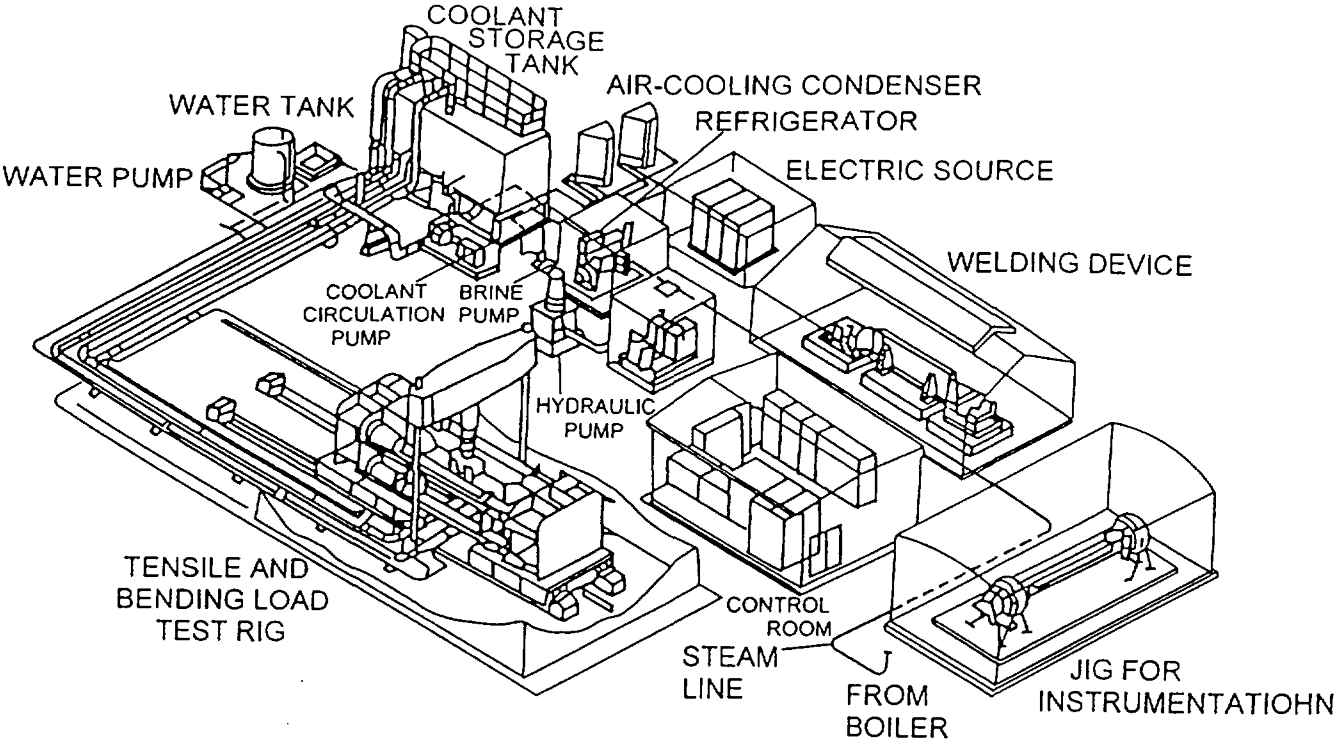

Figure 4 Schematic drawing of test facility

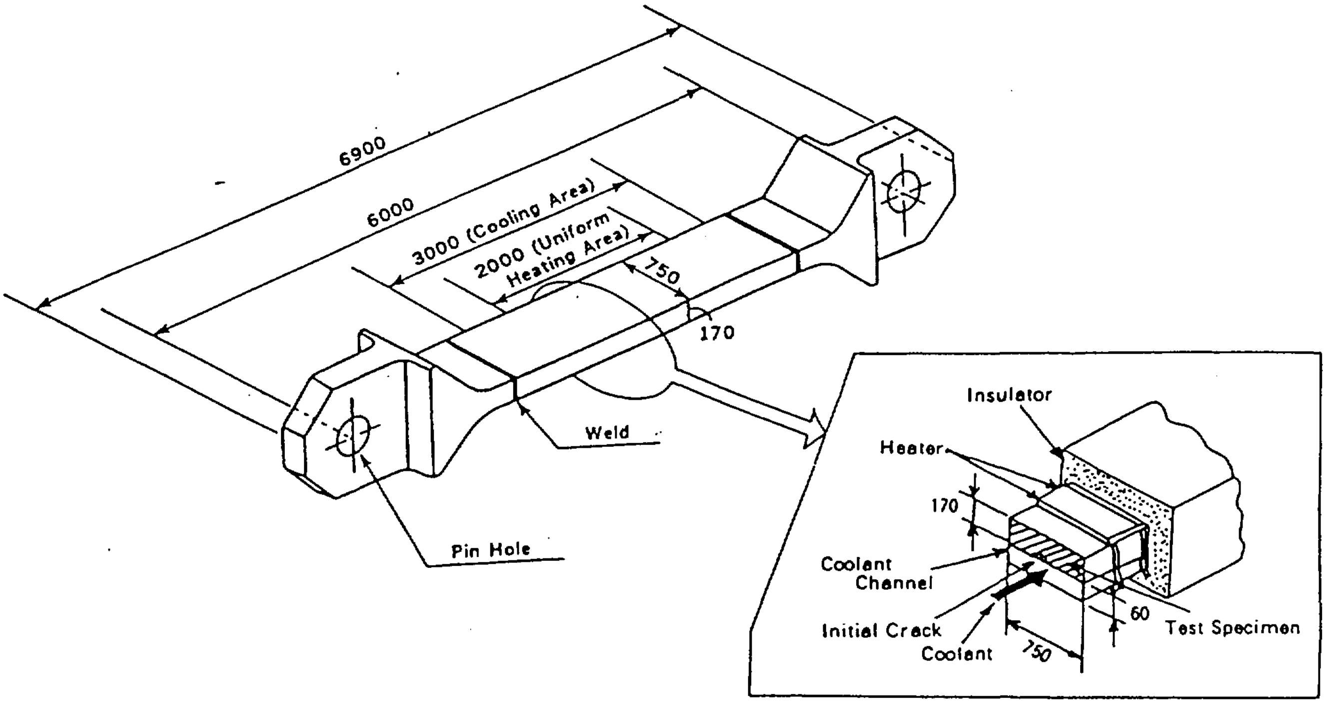

Figure 5 A large flat specimen for model test

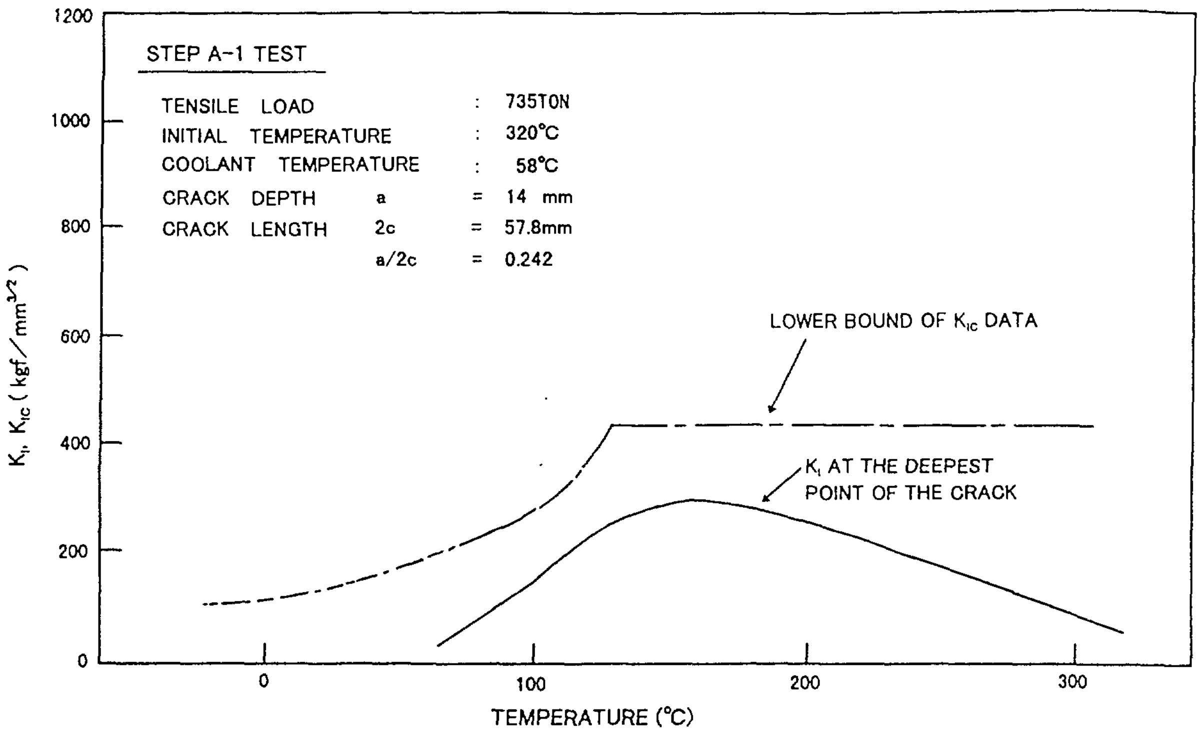

Figure 6 Comparison of experimentally obtained K_I vs. Temperature curve with lower bound of K_{IC} data (The toughness of specimen at the end of design life is simulated)

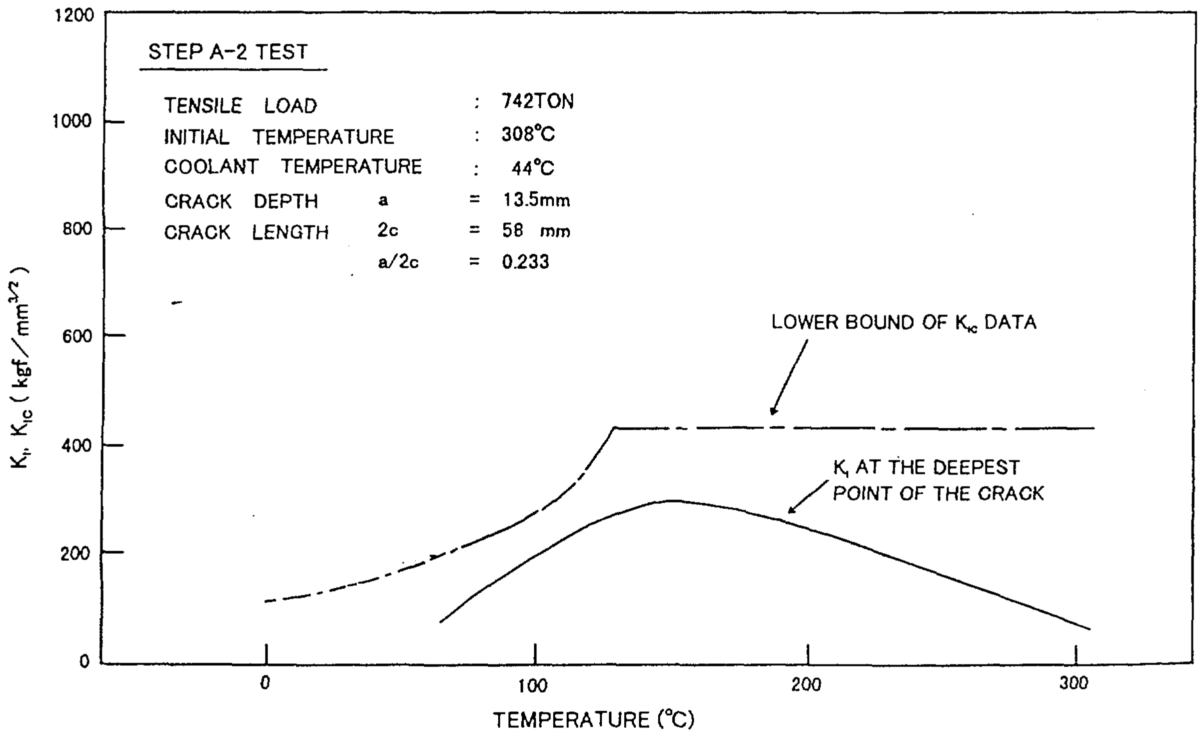

Figure 7 Comparison of experimentally obtained K_I vs. Temperature curve with lower bound of K_{IC} data (The toughness of specimen at the extended life is simulated)

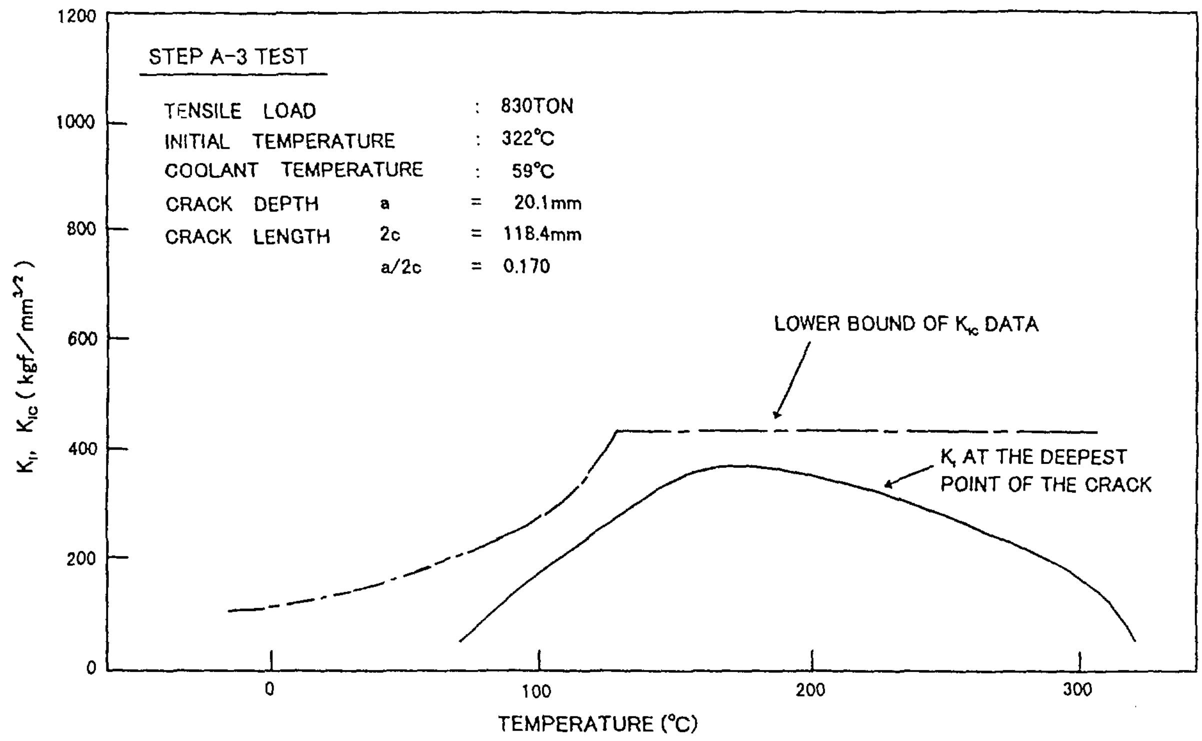

Figure 8 Comparison of experimentally obtained K_I vs. Temperature curve with lower bound of K_{IC} data (The toughness of specimen at the end of design life is simulated, and the internal flaw has twice as large as supposed value for actual plant)

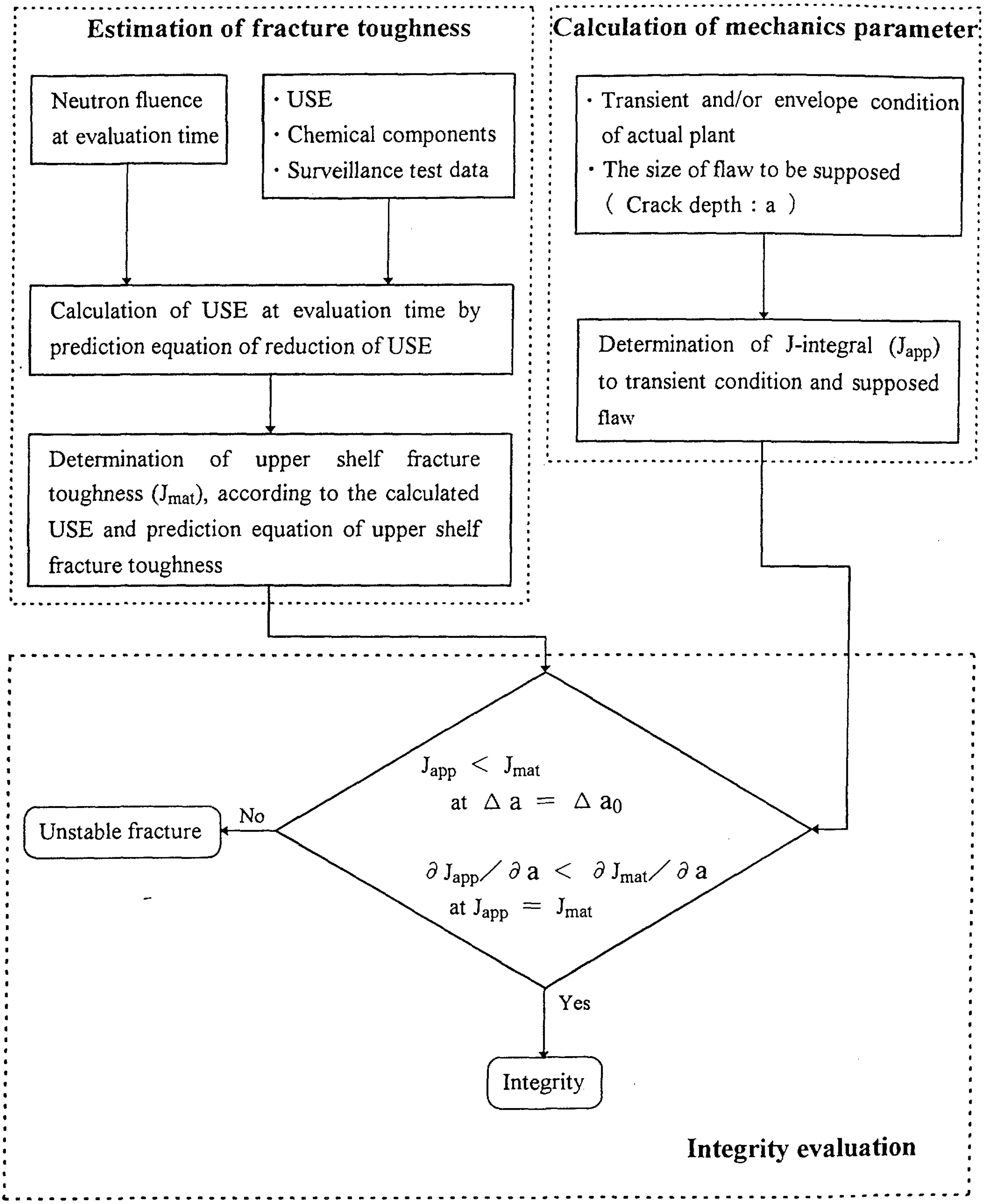

Figure 9 Evaluation scheme for RPV integrity considering the reduction of USE in PLIM project

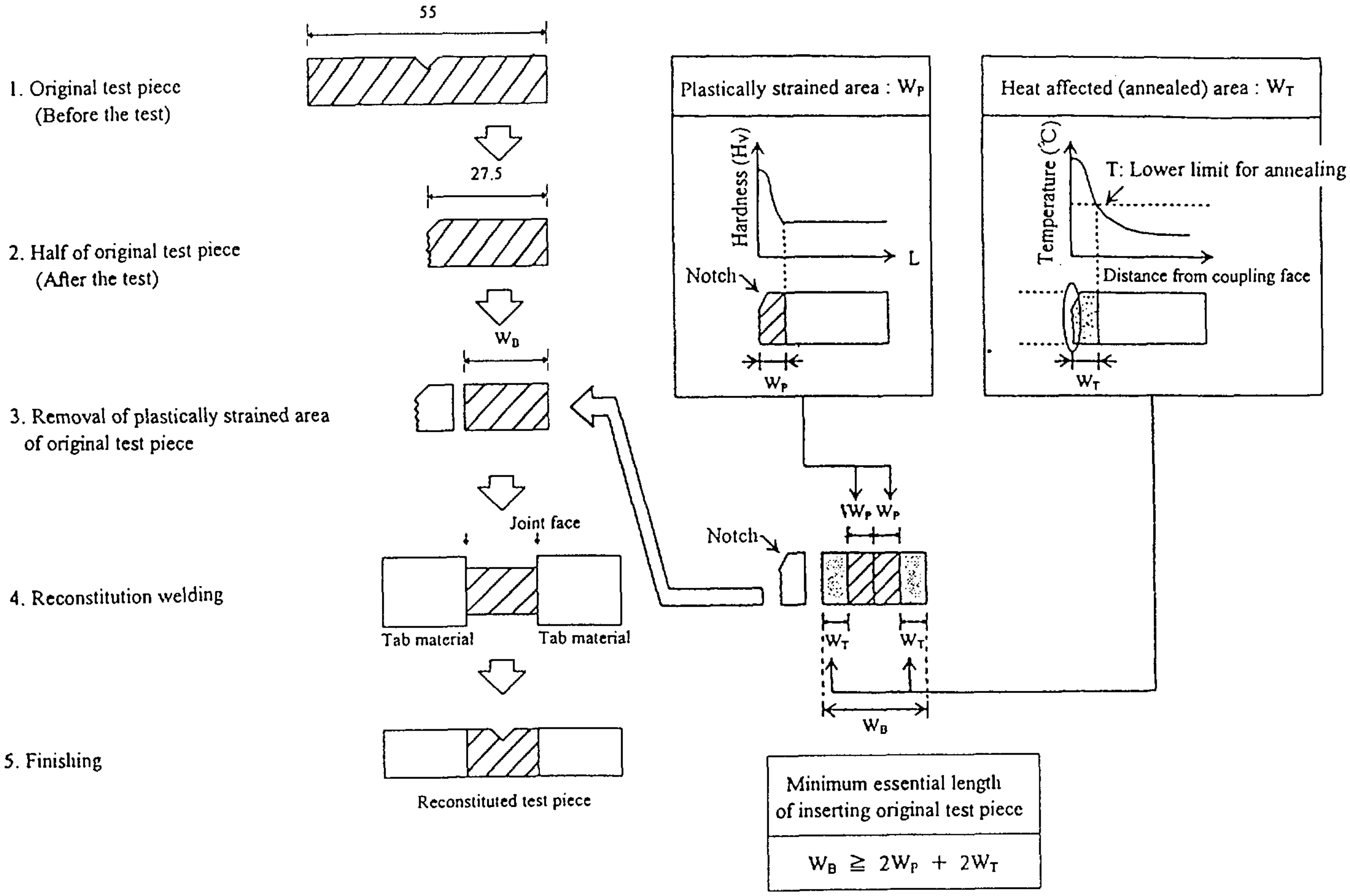

Figure 10 Illustration of reconstitution procedure of Charpy test piece

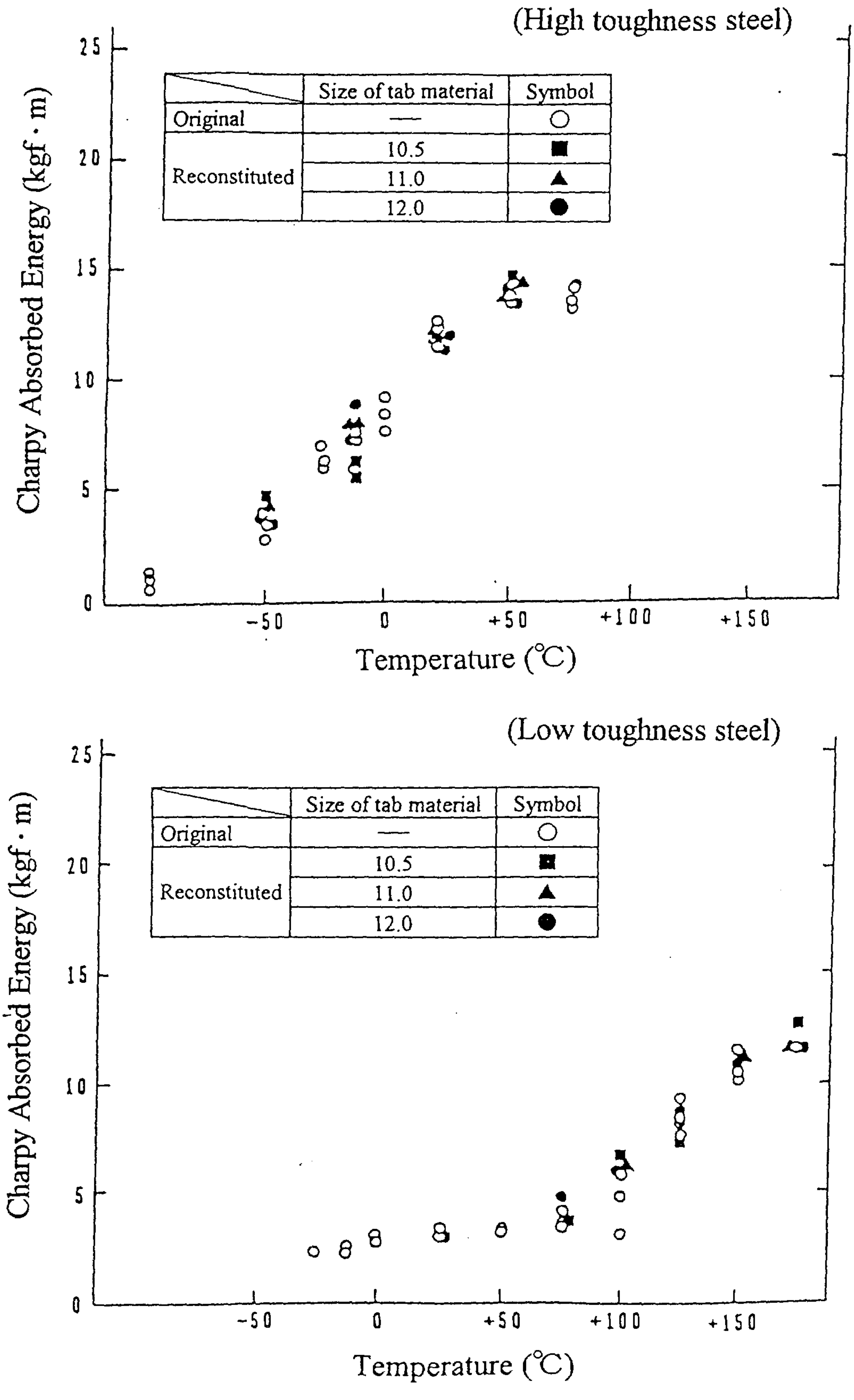

Figure 11 Test results on the Charpy test piece reconstituted by laser welding