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# Leak Before Break Experiments on H.T. Zr-2.5wt%Nb Pressure Tubes

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POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

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# Leak Before Break Experiments on H.T.Zr-2.5wt%Nb Pressure Tubes [*]

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## ABSTRACT

Pressure tubes of Advanced Thermal Reactor (boiling-light-water-cooled heavy-water-moderated pressure-tube-type reactor) in Japan are made of Heat Treated Zr-2.5wt%Nb alloy and the both ends are mechanically joined with stainless steel extension tubes. Sharp artificial cracks were introduced in the rolled jointed pressure tube specimen and the cracks were propagated and penetrated the tube wall by fatigue and DHC in high-temperature high-pressure water loop. From the results, it was shown that the LBB phenomena were valid for the rolled jointed pressure tube under the reactor operating conditions and that the critical crack length was more than 50mm. Moreover, calculations were performed about the leak rate using critical flow data.

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## 1. INTRODUCTION

Power Reactor and Nuclear Fuel Development Corporation (PNC) in Japan has developed the ATR-Fugen, a 165MWe prototype boiling-light-water-cooled heavy-water-moderated pressure tube-type reactor of Japan, which has operated satisfactorily since the start of commercial operation in March 1979. It achieved the total electrical generation of $9.8\times 10^{9}$ KW·h in July 1989. A 606MWe ATR Demonstration Plant has been designed on he basis of the experience of the Fugen and is scheduled to begin commercial operation at the end of 1990's. The ATR is a unique reactor designed mainly to use plutonium-uranium mixed oxide (Mox) fuels[1].

The vertical section of reactor and primary cooling system of the Fugen is shown in Fig.1. The Fugen has 224 pressure tubes made of Heat Treated( to be referred to as H.T. hereafter) Zr-2.5wt%Nb alloys. One fuel assembly consisting of a bundle of 28 fuel rods is stored in each pressure tube. The pressure tube is a zirconium alloy tube of approximately 5 meter length with an inner diameter of 117.8mm and a wall thickness of 4.3 mm,which is mechanically rolled jointed with stainless steel pressure tube extensions at the top and bottom as shown in Fig.2(a). There has been no trouble about pressure tubes of the Fugen since the start of operation.

As the pressure tubes are located at the reactor core with fuel assemblies and constitute the pressure boundary of the high-temperature high-pressure reactor cooling water, material that has lower absorption rate of neutron and possesses high strength at high temperature under high irradiation is required for the pressure tubes. Zirconium alloy satisfies these conditions, and for the pressure tubes of the Fugen H.T.Zr-2.5wt%Nb alloy which possesses superior high temperature strength and corrosion resistance was selected from among zirconium alloys. The H.T.Zr-2.5wt%Nb alloy is a material that has strength increased by heat treatment.

The manufacturing process of pressure tubes of the Fugen reactor is as follows. The billet of Zr-2.5wt% Nb is extruded at high temperature by the use of a horizontal extrusion press, cold-drawn and then solution-heat-treated by quenching the material from the heating furnace (at a temperature of 887℃ )into water. By the performance of this solution heat treatment our pressure tubes are called heat-treated (HT) pressure tubes. After the solution heat treatment the material is cold-drawn up to the cold working degree of 5-15%. Then the material is aged in a vacuum furnace at 500℃ for 24 h,and by the final forming pressure tube is made with inner diameter of 117.8 mm, thickness 4.3 mm and length about 5500 mm. The chemical composition of HT Zr-2.5 wt% Nb pressure tube is as follows: Nb=2.40-2.80 wt%, $O_2$=900-1300 ppm,$H_2$=max.25 ppm and the balance is Zr.As for the manufacturing specification of mechanical properties of the pressure tube, the ultimate tensile strength is ≧ 537 MPa at 300℃ and ≧ 763 MPa at RT, the 0.2% proof stress is ≧ 392 MPa at 300℃ and ≧ 529 MPa at RT, the elongation is ≧ 10% at 300℃ and RT, the hardness is ≧ HV235, and the primary $\alpha$ phase is >5%.

The pressure tubes correspond to the pressure vessels of light water reactors, and are designed to fulfill the conditions of class 1 components regulated in Japan MITI notification 501 which corresponds to those regulated in ASME SectionⅢ . In the case of the pressure tubes, the material used is zirconium alloy which is not used in the light water reactors, and therefore design evaluation was performed at the construction stage of the Fugen with particular consideration of the characteristics of the pressure tube material.

In undertaking the design of the pressure tubes, safety evaluation against ductile fracture and unstable fracture was performed . In regards to the evaluation against unstable fracture, particular attention was paid to the characteristics of fracture toughness degradation due to the pressure tube material absorbing hydrogen under operating conditions. Also,as the pressure tube material will creep due to high neutron irradiation, creep strain was therefore evaluated and the limiting value was established[2].

The pressure tubes for the Fugen were manufactured on trial basis by Chase Brass Co. of U.S.A.who possessed manufacturing technology of zirconium alloy pressure tubes at the time of construction of the Fugen, and the manufacturing specifications of the pressure tubes were concluded using the specifications of AECL of Canada as reference. In advance to the manufacture of pressure tubes for use in the actual reactor, approximately 120 pressure tubes were manufactured on trial basis to investigate tensile strength, fracture toughness and metallographical structure, and the manufacturing specifications were established as well as characteristics of the material were confirmed.

Lately, manufacturing technology of pressure tubes has been developed in Japan and the domestically developed pressure tubes have been manufactured. In order to reduce the residual stress of the pressure tube near the rolled joint, structures of the rolled joint and manufacturing conditions of the rolled joint for the Demonstration Plant were slightly changed from those of the Fugen.

It is very important from the standpoint of the reactor design to examine that the pressure tube with rolled joint has Leak Before Break characteristics under the reactor operating conditions(temperature≃ 280℃ ,inner pressure≃ 7MPa),because the pressure tubes are designed to be class 1 vessel described before like the pressure vessels of light water reactors.

Therefore, in the present study LBB experiments were conducted using mock-up rolled joint specimens under high-temperature high-pressure water, and critical crack length (CCL)of the pressure tube with rolled joint was also estimated.

Pressure tubes before use might have very small size initial cracks (postulated defect) due to the fabrication process. The maximum allowable size of the initial crack for the Fugen pressure tube is 3.3mm in length and 0.15mm in depth which was determined by the flaw inspection precision at the fabrication stage. On the other hand, the minimum detectable size of the crack by In-Sevvice-Inspection (ISI) for the Fugen pressure tubes is determined at the construction stage of the Fugen to be 5.0mm in length and 0.4mm in depth. According to ASME Code SecⅢ the conservative evaluation on the initial crack (5.0mm in length, 0.4mm in depth) propagation by fatigue cycles due to start-up and shutdown of the reactor was performed at the construction stage of the Fugen, and the propagated crack size after 30 years operation was estimated to be 6.3mm in length and 1.05mm in depth.

The crack initiation or propagation of the pressure tube might be induced by hydride precipitates (DHC), residual stress near the rolled joint portion and sagging of the pressure tube as well as fatigue cycles. In respect of the sagging of the pressure tube, we have no necessity to consider this phenomenon because our ATR is the vertical pressure tube type reactor.

The fracture toughness of the pressure tube is degraded when it absorbs hydrogen under operating conditions. The design value of hydrogen concentration absorbed in the pressure tube after 30 years reactor operation is about 200ppm for the Fugen, which was concervatively determined by the reference of Gentilly-1 reactor design. Actually, H.T.Zr-2.5wt% Nb pressure tube is estimated to absorb hydrogen less than 100ppm after 30 years operation by the use of Fugen surveillance test (PIE) deta[3]

For the straight portion of the pressure tube, fracture toughness values of both as-received tube (<25ppm hydrogen) and hydrogen absorbed tube (about 200ppm hydrogen) were obtained at about 280℃ by internal pressurizing tests and bend tests[4]. The value obtained is approximately >80 MPa $\sqrt{m}$. The critical crack length (CCL) of the straight portion pressure tube is estimated to be approximately > 70mm at operating hoop stress of 100MPa. Here, stress intensity factor $K_I$ is calculated by the use of Newman's equation[5] for part-through-wall flaw cylindrical geometry as

$$K_I = F\sigma\sqrt{\pi C} \tag{1}$$

where

$$\sigma = \frac{PR}{t} \tag{2}$$

$$F = \sqrt{1+0.52\lambda_t+1.29\lambda_t^2-0.074_t^3} \tag{3}$$

$$\lambda = C/\sqrt{Rt} \tag{4}$$

$$0 \leqq \lambda_t \leqq 10 \tag{5}$$

where $\sigma$ is nominal stress, C is the half crack length, P is internal pressure, t is wall thickness and R is internal radius of cylindrical pressure vessel. F is the boundary-correction factor expressed as equation (3), which accounts for the effects of shell curvature [6,7] on stress intensity.

The shape of the rolled joint is of sandwich type as shown in Fig.2 (a). The pressure tube near the sandwiched rolled joint has residual stress (circumferential stress: approximately 50~ 200MPa for the Demonstration Plant) due to rolled joint fabrication, which is more severe for crack initiation or propagation than that of straight pressure tube portion. As the shape of the rolled joint is complicated and the residual stress distributes with complexity, the fracture toughness value of the pressure tube near the rolled joint cannot be estimated with high precision. Therefore, the mock-up rolled joint specimens with axial sharp artificial crack at the residual stress portion were made as shown in Fig.2 (b), and LBB experiments were performed under high-temperature high-pressure circulated water. Some sharp cracks were propagated to the penetration of the wall by inner pressure cycles (fatigue LBB experiments), other sharp cracks were propagated to the penetration of the wall by constant inner pressure (DHC LBB experiments). From these experiments LBB phenomena for the rolled joint portion can be observed for fatigue crack and DHC crack under mock-up conditions, and CCL also can be obtained.

For the leak detection system of the Fugen, dryed $CO_2$ gas flows in the annulus between pressure tube and calandria tube and the dew point of $CO_2$ gas is measured with high sensitivity of $10^{-3}$ Acc/sec. In the LBB experiment, the leak detection was performed by the same $CO_2$ gas system as well as TV observation system.

## 2.EXPERIMENTAL

For the LBB experiments specimens simulating the actual rolled joint portions were manufactured as shown in Fig.2(b) for lower rolled joint specimen for example.
Both ends of the specimen must be sealed for the experiments under high-temperature high-pressure water. One end was sealed by the use of Grayloc flange and the other was sealed by the use of copper seal packing. In the manufacturing process of the rolled joint, residual stress is produced in the pressure tube near the sandwiched rolled joint portion. In the residual stress region large sharp artificial defect was made in the inner surface of the specimen by EDM method before experiments. The length of the large defect was 50 or 70mm, the depth of it was 3mm and the width (sharpness) of it was about 0.08mm. Also some small defects were made as shown in Fig.2(b) for a typical example. The length of the large defect (50mm or 70mm) was chosen with the reference of the critical crack length of the straight pressure tube as described in section 1. It is estimated with hope that the critical crack length of the pressure tube near the sandwiched rolled joint portion is slightly smaller but nearly equal to that of the straight portion pressure tube.

Rolled joint specimens consist of Fugen type lower rolled joint specimen designated as FL, Demonstration Plant type lower rolled joint specimen (DL) and Demonstration Plant type upper rolled joint specimen (DU).

Table 1 shows the rolled joint specimen list in which indicated are specimen No., type of rolled joint, the size of the large befect and hydrogen concentration. In the present study LBB experiments were performed on the nine rolled joint specimens. Six specimens indicated H in the specimen No. are high hydrogen concentration specimens (approximately 200 ppm,Fugen design value) in which hydrogens were intentionally absorbed using hydrogen absorption apparatus before experiments. Hydrogen was absorbed into the specimen by holding the specimen in hydrogen gas at 350℃ for about 15 hours.

Fig.3 shows the schematic of high-temperature high-pressure LBB experimental loop in which the rolled joint specimen is settled. Water chemistry of the fluid such as pH, conductivity (CON) and dissolved oxygen content (DO) is automatically controlled in this loop so that it is like the same as that of ATR (pH≃ 7,CON≃ 0.3μ S/cm, DO≃ 300ppb). The flow rate in the loop is approximately 40kg/hour. Before experiments, several strain gauges were put and pasted on the outer surface of the specimen near the crack, in order to measure the strain increase due to crack propagation during experiments. Also, acoustic emission probes were fixed on the outer surface of the specimen near the crack,in order to measure the acoustic emission events due to crack propagation during experiments. To observe and examine the LBB phenomenon in which steam spouts from penetrated crack TV camera was settled, and the measurement of dew point of $Co_2$ gas which is circulated passing the outer surface of the specimen was performed using hygrometer as shown in Fig.3.

The temperature and the pressure of the water in the loop were raised up to approximately 280℃ and 7 MPa, respectively, of which values are those of the Fugen operating conditions (maximum design pressure:8MPa). For some of the specimens pressure cycles of the water was applied automatically by the pressure cycle controller in order to propagate the crack of the specimens (Fatigue LBB experiments). For other specimens with absorbed hydrogen pressure was held to be constant (7MPa) in order to propagate the crack of the specimens by DHC mechanism (DHC LBB experiments). After the steam leakage was detected and observed from the penetrated wall, the leak rate was measured for some specimens, and for many specimens internal pressure was held to be constant (approximately 7 MPa) for some hours to maintain steam leakage.

After the LBB experiments, residual stress measurements of the pressure tube near the rolled joint were performed by cutting the specimen, on which many strain gauges were pasted, into small pieces. Fracture surface observations were conducted using optical microscope, scanning electron microscope(SEM) and transmission electron microscope(TEM). Metallographic photographs near the large defect and other portions were taken such as microstructure, primary $\alpha$ phase and hydride. Also performed was hydrogen analysis near the large defect and other portions.

## 3. Experimental Results

LBB experiments were performed totally on nine rolled joint specimens listed in Table 1. LBB phenomena were observed for 8 specimens , and an unstable fracture was observed for 1 specimen above reactor operating pressure. In Table 2 typical LBB experimental results are shown for DL-1 specimen (Fatigue LBB experiment) and DU-1H specimen (DHC LBB experiment). For DL-1 specimen internal pressure cycles were applied at 280℃ in order to propagate the sharp artificial defect from 7.4MPa⟷ 7.8MPa to 7.4 MPa⟷ 11.8MPa as shown in the Table. At the internal pressure of 11.8 MPa, steam leakage from the penetrated wall was detected and observed. For DU-1H specimen internal pressure was maintained constant (7.3MPa) at 280℃ in order to propagate the defect by DHC mechanism. And, after 160 hours at 280℃ , leaking was detected and observed.

Figure 4 illustrates the dew point change of $CO_2$ gas which is circulated passing the outer surface of the specimen as a function of time. When the crack propagated and penetrated the tube wall by the inner pressure cycle or by the constant pressure, water spouted as steam from the penetrated crack into $CO_2$ gas flow, so that the dew point of $CO_2$ gas increased rapidly because it contained moisture, which phenomenon is shown in Fig. 6 for DL-1 specimen as an example. The leak detection capability of $CO_2$ system is very high, more than $1\times 10^{-3}$ Acc/sec of leak water ,which is the same as that of the Fugen, and 30 seconds after the leakage leak detected signal was obtained. Besides, steam leak was observed by TV camera. Strain measurements and acoustic emission measurements were also conducted on the outer surface of the specimen near the crack during experiments. Circumferential strain on the center of the crack was observed to increase as the crack propagated because the crack opens circumferentially, however axial strain on the center of the crack did not change as the crack propagated. The number of AE events above noise level was counted as a function of time, and AE events increased when the crack penetrated the tube wall.

In Fig.5, photograph of the fracture surface of DL-1 specimen after the LBB experiment by optical microscope is shown, in which the artificial crack, propagated crack by fatigue and penetrated region are to be observed. Fracture surface by SEM observation is also shown in Fig.6. By the fracture surface and shape observation for all specimens, it was shown that defect length did not propagate so much, large defects at most 2mm and all smaller defects 0mm. In respect of the sharp smaller defects for 3 specimens without much hydrogen (FL-1,DL-1,DU-2),the depth as well as length of all defects (length 5~ 10mm,depth 1~ 2mm) were observed to propagate 0mm. For the sharp smaller defects for hydrogen enriched specimens, some defects (length 5~ 20mm, depth 1~ 2mm) did not propagate at all and other defects (length 10~ 20mm,depth 0.5~ 3mm) were observed to propagate somewhat (length increment 0mm, maximum depth increment 0.9mm).

After the LBB experiments residual stress in the pressure tube near the rolled joint was measured by the strain gauge method, of which result is shown in Fig.7 for DL-1 specimen. Circumferential residual stress on inner surface of the pressure tube was less than 88MPa. In Table 1 maximum circumferential residual stress is listed for all specimens. Also listed is hydrogen concentration at the large crack for all specimens, which were analyzed after the LBB experiments. The range of the hydrogen concentration for hydrogen enriched specimen is comparative large , which is considered to be due to the hydrogen absorption process intentionally before LBB experiments. Metallographical photographs of the pressure tube are shown in Fig.8, in which the microstructure of martensite phase, primary $\alpha$ phase indicated as white circles and hydride indicated as black lines are shown. For the hydrogen enriched material like DL-4H specimen many hydrides were observed, some of which were precipitated in the radial direction. From the metallographical hydrides photographs for all specimens, it was shown that some hydrides were precipitated in the radial direction near the defect portion and inner wall portion of the tube.

LBB phenomena were observed and examined on eight rolled joint specimens in the present experiments, however, FL-2H specimen was broken by unstable fracture,in which through-wall crack propagated rapidly in the axial direction and LBB phenomenon was not established because of the high hydrogen concentration in the material and the high applied internal pressure of 10.3 MPa. FL-2H specimen was broken at the internal pressure of 10.3 MPa which is higher than the reactor operating pressure (normal pressure 7.3 MPa, maximum design pressure 8.0 MPa). From the LBB data of DL-2H, DL-4H and DL-3H specimen, the pressure tube of lower rolled joint with approximately 200 ppm hydrogen and 50mm or 70mm length crack is considered to have LBB phenomena under reactor operating conditions.

After the leak was detected and observed, all of the specimens with 50mm length defect could be held at the internal pressure above 7.3 MPa, which is reactor operating pressure, and steam leakage was continued for 1~ 75 hours. In Table 2 typical examples for DL-1 and DU-1H specimens were shown. For DL-1 specimen, after the leakage the internal pressure above 7.3 MPa was held for 11 hours. For DU-1H specimen, after the leakage the internal pressure of 7.3 MPa was held for 6 hours during which steam leak was continued.

## 4. DISCUSSION

The relation between crack length and the inner pressure is shown in Fig.9 when the crack penetrated the tube wall, and is also shown in the figure whether the LBB characteristic was valid or not. White circles indicate the LBB data and solid circle indicates the unstable fracture datum in the figure. After the leakage inner pressure was maintained at 280℃ above 7MPa (7MPa is reactor operating pressure) for most of specimens and leaking was continued. For DL-3H specimen leaking (280℃ ,>7MPa) continued for 75 hours, for DL-4H specimen for 8 hours, for DU-1H specimen (DHC) for 6 hours and DU-3H specimen for 18 hours. Also, at the leaking leaking was detected by $CO_2$ gas dew point measurement with high sensitivity of $10^{-3}$ Acc/sec.

As the shape of the rolled joint is complicated and the residual stress distributes with complexity, the fracture toughness value of the pressure tube near the rolled joint cannot be estimated with high precision (calculations or small size experiment is incredible for the rolled joint estimation). However, by the present mock-up LBB experiment CCL can be obtained. CCL is defined as the bowndary crack length between with LBB and with unstable fracture under reactor operating conditions. For the pressure tube near the Demonstration Plant rolled joint with absorbed hydrogen approximately 200ppm, CCL for fatigue and DHC was obtained to be more than 50mm under reactor operating conditions (280℃ ,7MPa). On the other hand, CCL for the straight portion pressure tube was already estimated to be more than 70mm described before. So that, CCL for the pressure tube near the rolled joint is considered to be comparable to that for the straight portion pressure tube.

The initial postulated crack of 5.0mm in length and 0.4mm in depth for the pressure tube is estimated to propagate by fatigue cycles to the crack of 6.3mm in length and 1.05mm in depth after 30 years reactor operation, which is described before. On the fatigue, propagated crack length of 6.3mm after 30 years operation is much smaller than CCL (>50mm) obtained here. On the DHC, in general, natural crack length when it penetrates the pressure tube wall is considered to be about 4 or 5 times of the wall thickness (16~ 20mm),which was shown by the fracture observations of Pickering DHC pressure tubes[8]. Besides, the minimum detectable length of the crack by ISI for ATR is less than 5mm.

The leak detection sensitivity of dryed $CO_2$ gas system (dew point measurement)is $10^{-3}$ Acc/sec, which is very high. In this experiment leak was detected by $CO_2$ gas system about 30 seconds after the leakage, and generally for about several hours leak was maintained at the pressure of about 7.4 MPa described before. The penetrated crack length at the outer surface of the pressure tubes was measured after LBB experiments and obtained to be 5~ 50mm in length. The leak rate measurements were performed for some specimens and leak rate of $>30\times 10^3$ Acc/hour (>8 Acc/sec) was obtained for penetrated outer surface crack length of 14 mm (DU-1H specimen).

The leak rate estimation under actual ATR reactor conditions was conducted with the calculation of crack opening area A and critical flow rate Gc as follows. The crack opening area A was calculated using the equation by

Tada[9] as

$$A=\frac{\sigma}{E}(2\pi Rt)\cdot G(\lambda) \qquad (6)$$

$$G(\lambda)=\lambda^{2}+0.625\lambda^{4} \qquad (0\leq \lambda \leq 1)$$

$$=0.14+0.36\lambda^{2}+0.72\lambda^{3}+0.405\lambda^{4} \qquad (1\leq \lambda \leq 5) \qquad (7)$$

$$\lambda=C/\sqrt{Rt}$$

$$\sigma=PR/t$$

where E is Young's modulus. The critical flow rate Gc for two-phase flow was summarized by Akagawa[10] on experimental results and theories . As the critical pressure Pc is about 3.4 MPa in this case, critical flow leak rate Gc× A was calculated for steam quality of 15% (ATR condition) as follows.

(i) 2C=5mm : Gc× A=1Acc/sec

(ii) 2C=14mm : Gc× A=8Acc/sec

(iii) 2C=50mm : Gc× A=240Acc/sec

The agreement between calculated leak rate and the present experimental one for 2C=14mm was rather good. The sensitivity for leak detection by dryed $CO_2$ gas system is very high for the actual ATR reactor, therefor it is considered that there is no problem about the leak detection sensitivity.

## 5. CONCLUSIONS

According to the LBB experimental findings and analyses, the following conclusions can be drawn for the H.T.Zr-2.5wt%Nb pressure tube near the ATR Demonstration Plant type rolled joints with absorbed hydrogen approximately 200ppm :

(1)The LBB phenomena for fatigue and DHC crack propagations were valid for the rolled jointed pressure tube under reactor operating conditions ( temperature≃ 280℃ ,inner pressure≃ 7MPa).

(2)The critical crack length for fatigue and DHC crack propagations was obtained as > 50 mm for the rolled jointed pressure tube under reactor operating conditions.

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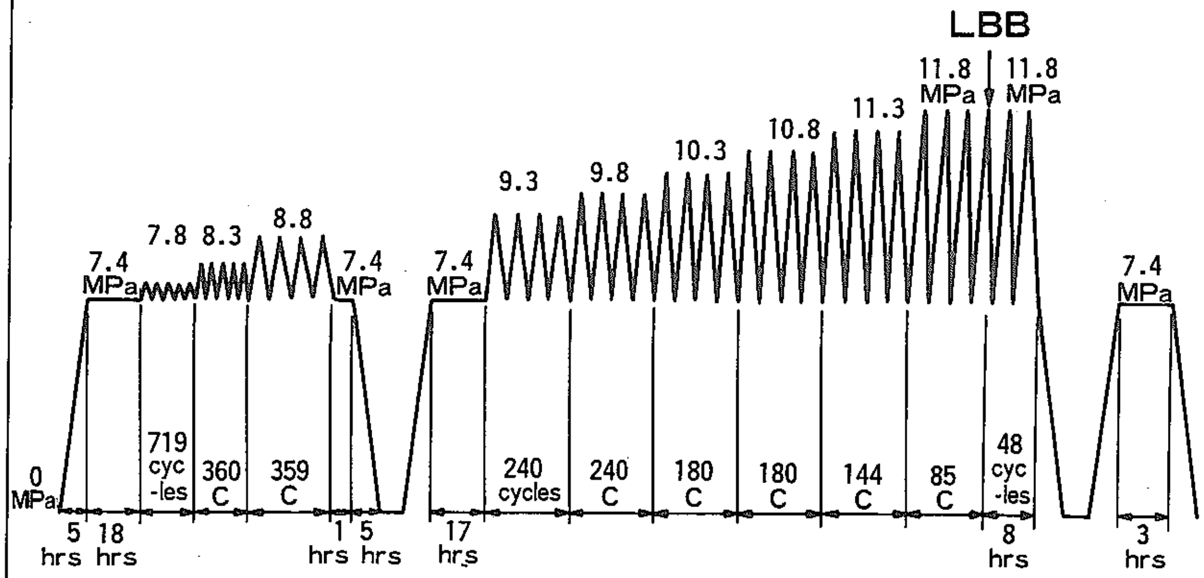
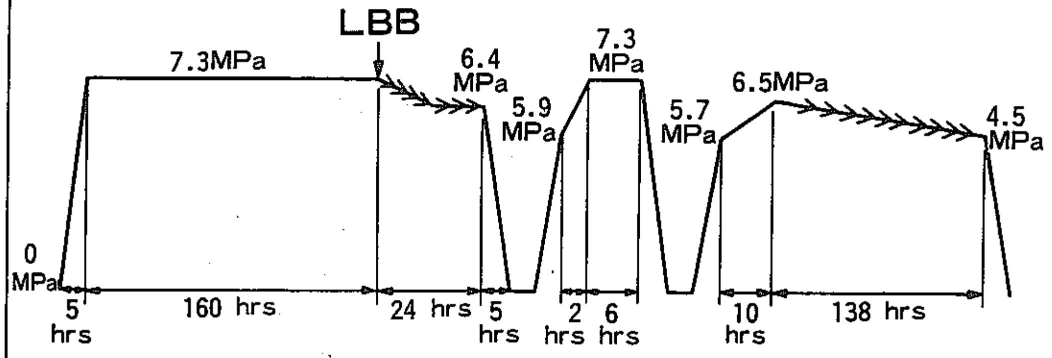
Table 1 Experimental Results for LBB, Hydrogen Conc. and Residual Stress

| Specimen No. | Large Artificial Defect (Length × Depth) | LBB or Unstable Fracture | Internal Pressure at Leaking | Hydrogen Conc. at Large Crack | Maximum Circumferenti-al Residual Stress |
|---|---|---|---|---|---|
| FL-1 | 50mm× 3 mm | LBB (Fatigue) | 11.8 MPa | 14～15 ppm | 69 MPa |
| FL-2H | 50mm× 3 mm | Unstable Fracture | 10.3 MPa | 59～233 ppm | 380 MPa |
| DL-1 | 70mm× 3 mm | LBB (Fatigue) | 11.9 MPa | 10～21 ppm | 88 MPa |
| DL-2H | 70mm× 3 mm | LBB (DHC) | 7.4 MPa | 133～203 ppm | 36 MPa |
| DL-3H | 50mm× 3 mm | LBB | 8.8 MPa | 43～254 ppm | 74 MPa |
| DL-4H | 50mm× 3 mm | LBB | 8.1 MPa | 57～133 ppm* | 70 MPa |
| DU-1H | 50mm× 3 mm | LBB (DHC) | 7.8 MPa | 262～269 ppm | 88 MPa |
| DU-2 | 70mm× 3 mm | LBB (Fatigue) | 10.0 MPa | 37～38 ppm | 105 MPa |
| DU-3H | 50mm× 3 mm | LBB | 8.3 MPa | 211～254 ppm | 108 MPa |

*Maximum analysed hydrogen concentration of the pressure tube DL-4H is 188 ppm.

# Table 2 Typical LBB Experimental Results for Cycles and Holding Time (Test Temp. : 280℃, Water Chemistry : 300 ppb DO, 0.3 $\mu$S/cm)

| Specimen No. | Operational Histry of the Specimen | Total Cycles up to LBB | Total Time at 280℃ up to LBB |
|---|---|---|---|
| DL-1 |  | 2507 cycles | 240 hours |
| DU-1H |  <br>→→ : pressure is changed spontaneously | 0 cycles | 160 hours |

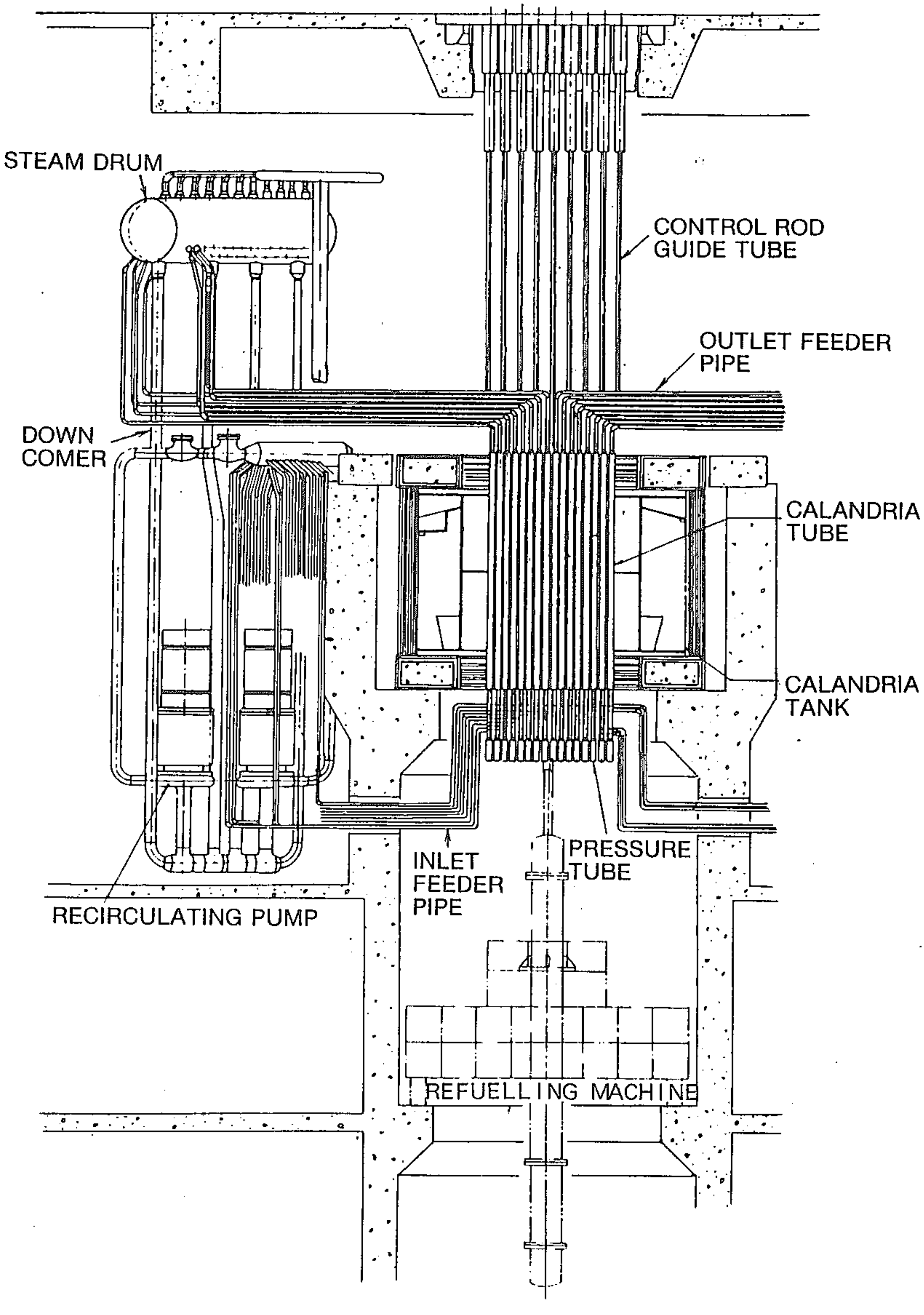
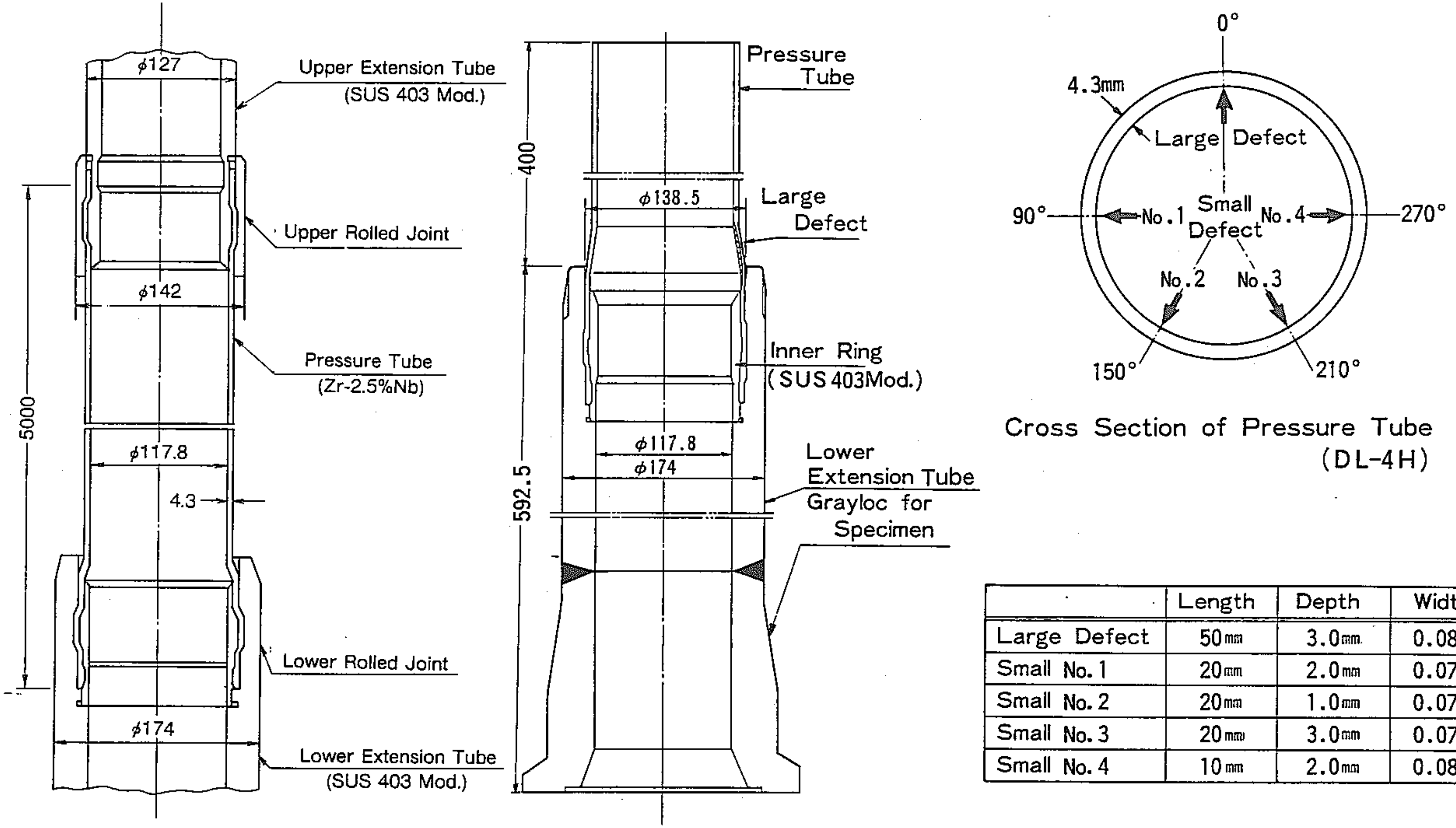


Fig.1 Vertical section of reactor and primary cooling system of the Fugen



| | Length | Depth | Width |
|---|---|---|---|
| Large Defect | 50mm | 3.0mm | 0.08mm |
| Small No. 1 | 20mm | 2.0mm | 0.07mm |
| Small No. 2 | 20mm | 1.0mm | 0.07mm |
| Small No. 3 | 20mm | 3.0mm | 0.07mm |
| Small No. 4 | 10mm | 2.0mm | 0.08mm |

(a) Pressure Tube Assembly with Rolled Joint

(b) Lower Rolled Joint Specimen with Sharp Defects

Fig.2 Pressure tube assembly with rolled joint portions and lower rolled joint specimen with sharp defects

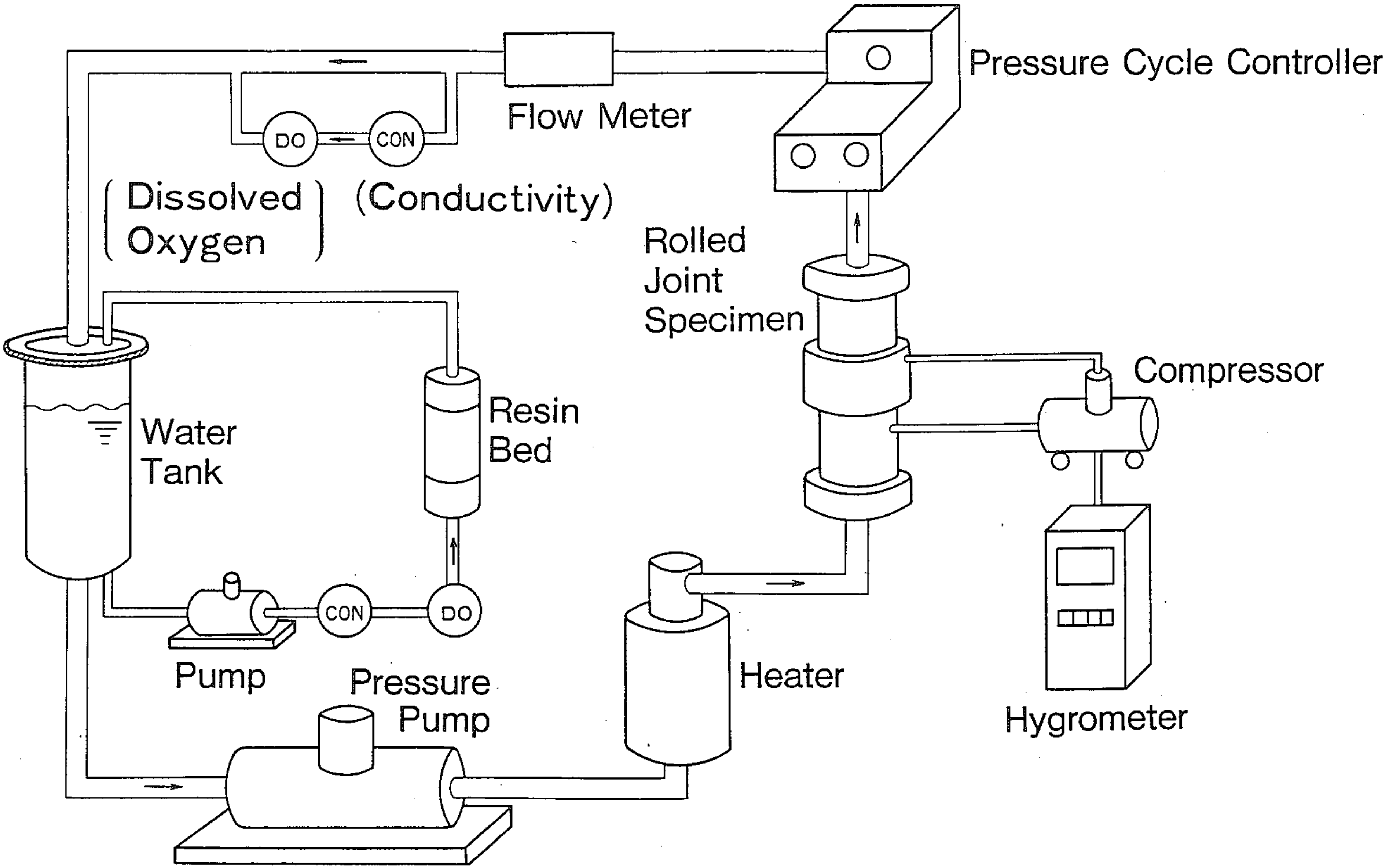


Fig.3 Schematic of high-temperature high-pressure loop

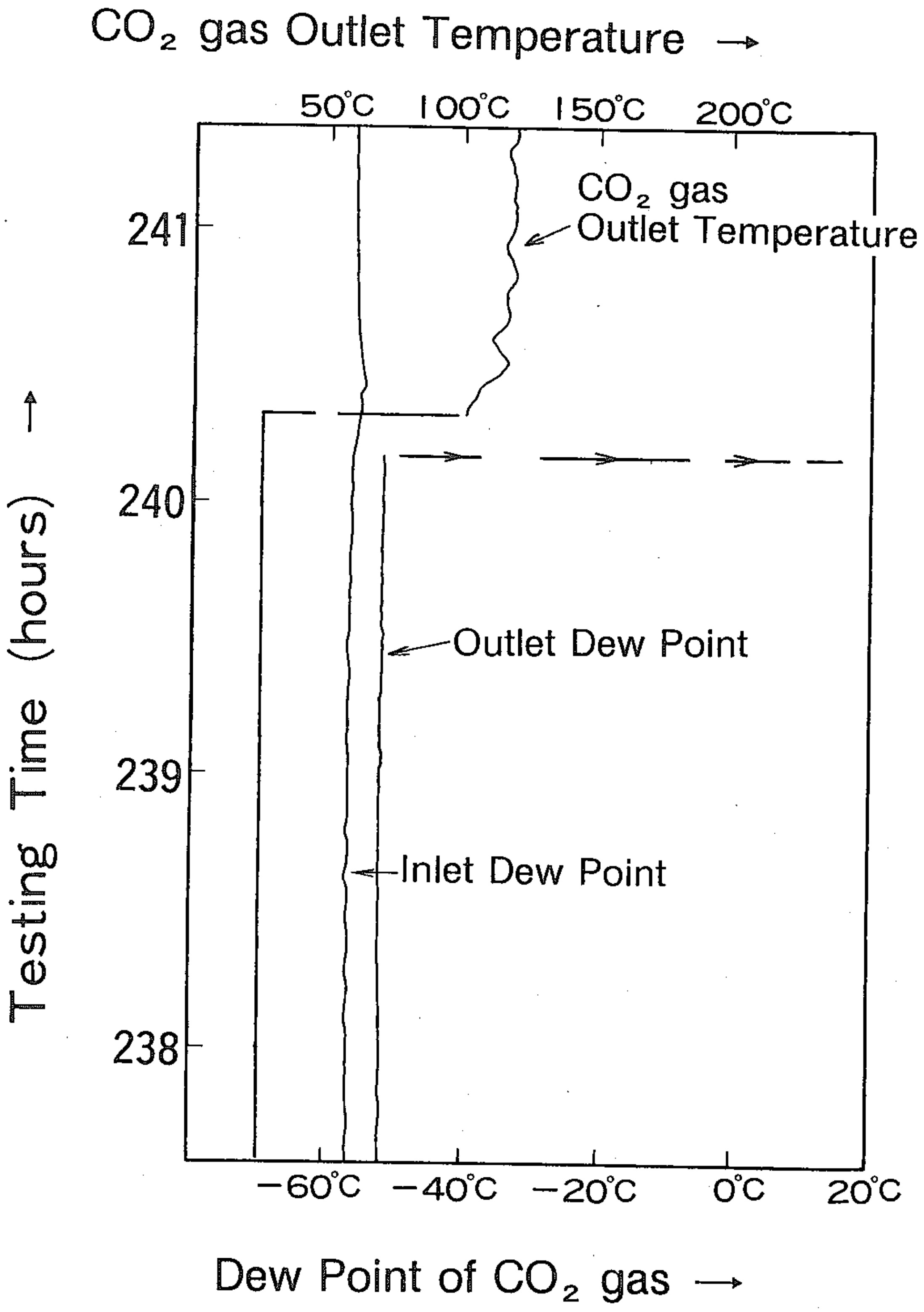


Fig.4 Dew point change at leaking (LBB) for DL-1 specimen

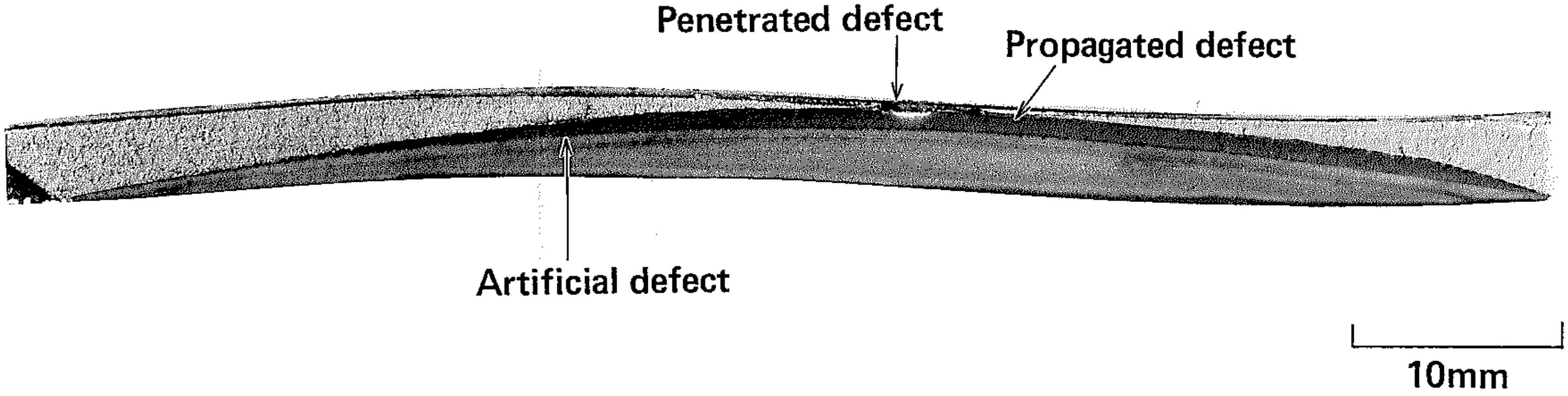


Fig.5 Fracture surface of large defect for DL-1 specimen

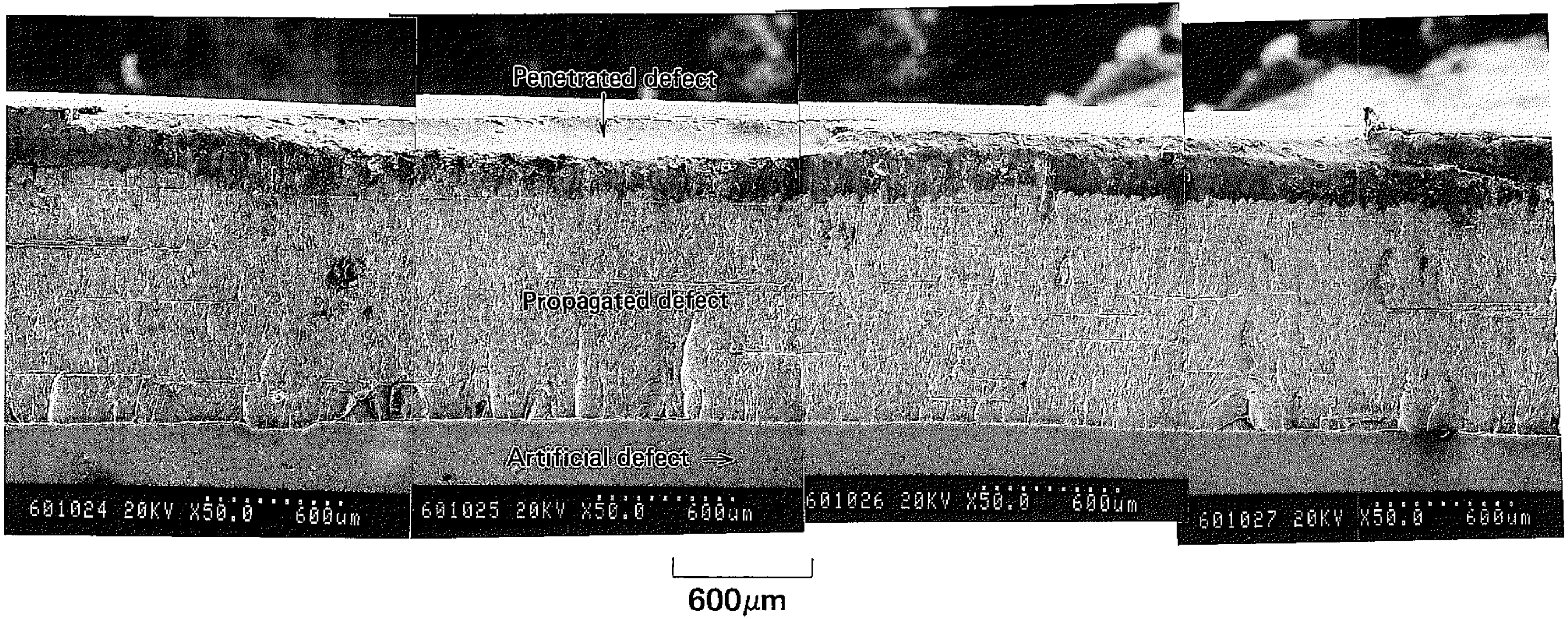
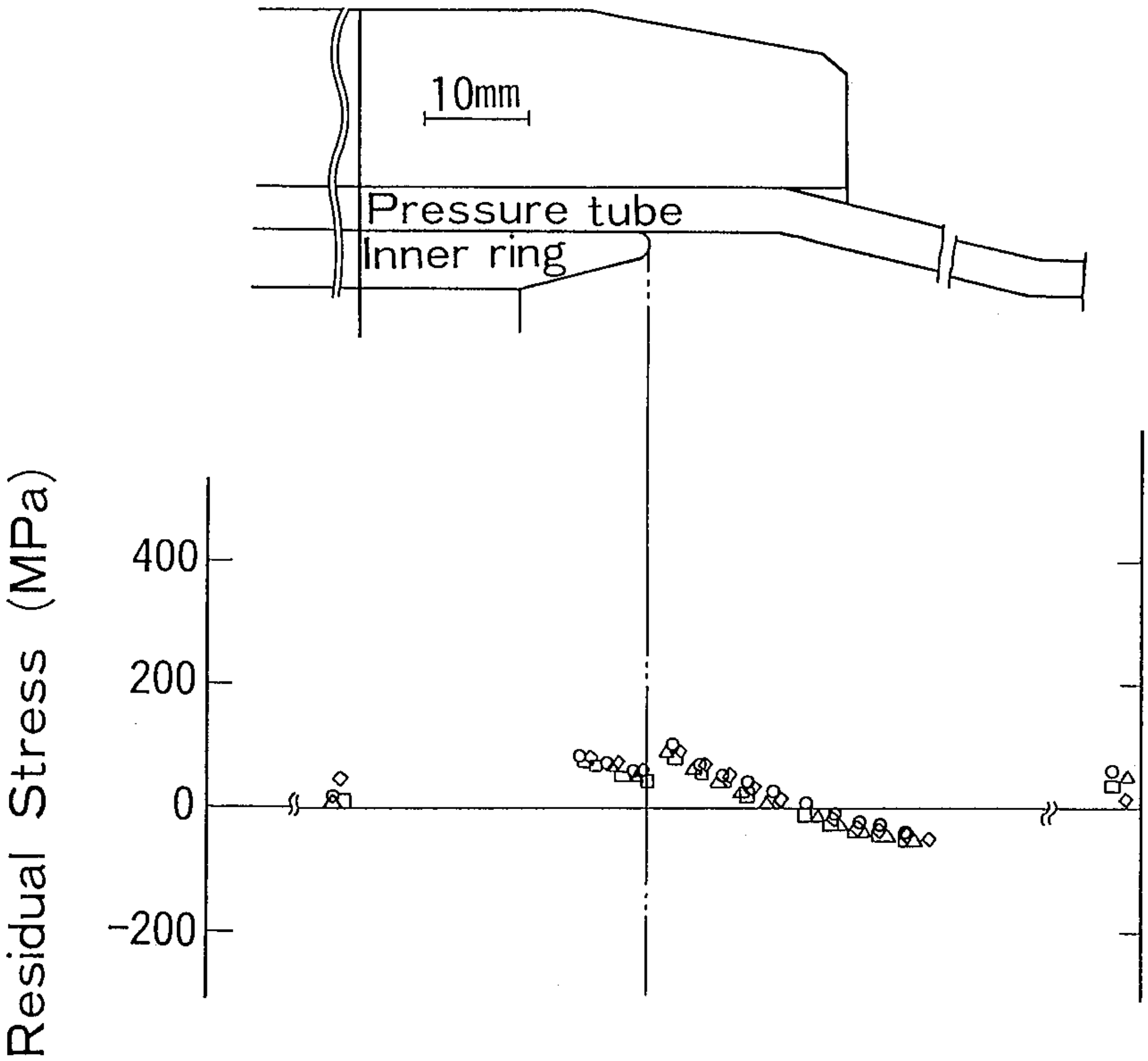
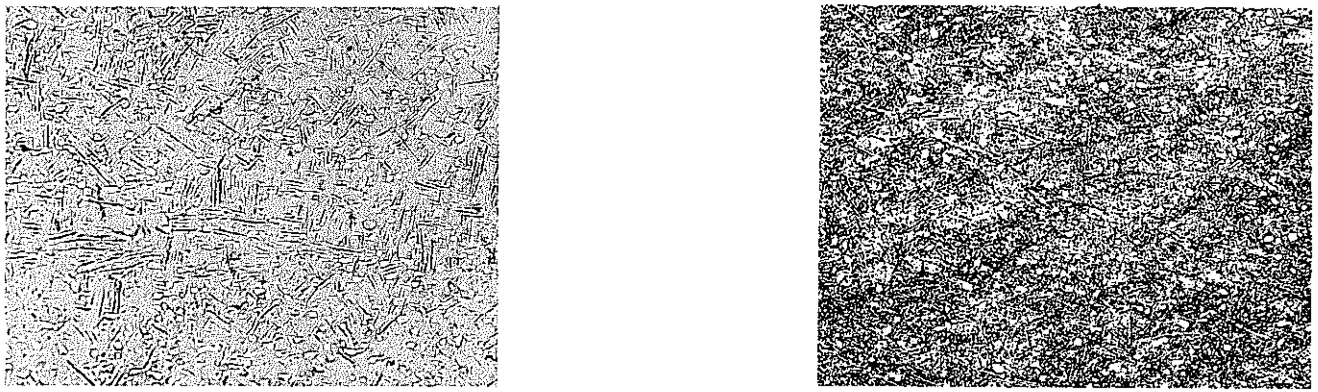


Fig.6 SEM topography of large defect for DL-1 specimen



| Radial direction | 0° | 90° | 180° | 270° |
|---|---|---|---|---|
| Pressure tube | ○ | △ | □ | ◇ |

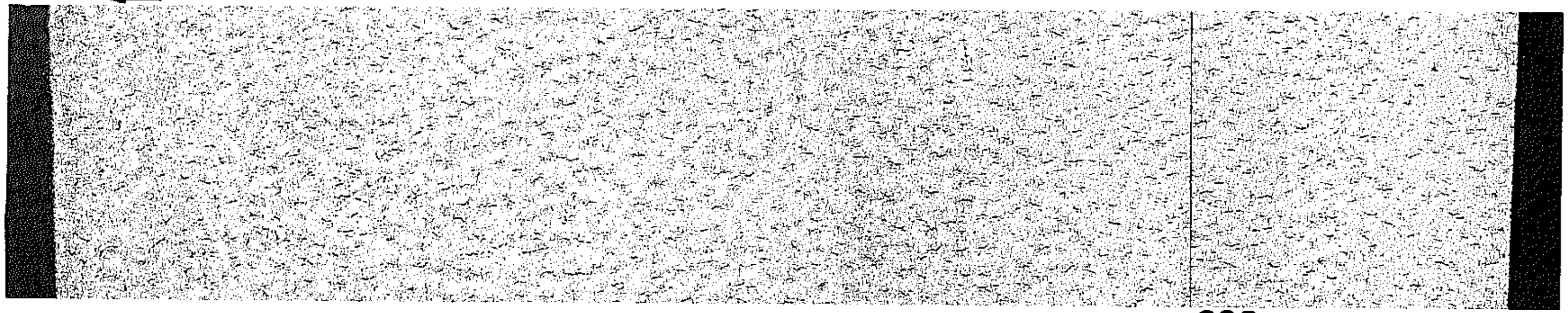
Fig.7 Residual stress on the inner surface of the pressure tube near the rolled joint for DL-1 specimen



Microstructure (DL-1) 20$\mu$m

Primary $\alpha$ Phase (DL-1) 20$\mu$m

Outer surface ←



Hydride (DL-1) Radial-Circumferential Plane 200$\mu$m

Hydride (DL-4H) Radial-Axial Plane

Fig.8 Metallographic photographs of H.T.Zr-2.5wt%Nb pressure tube

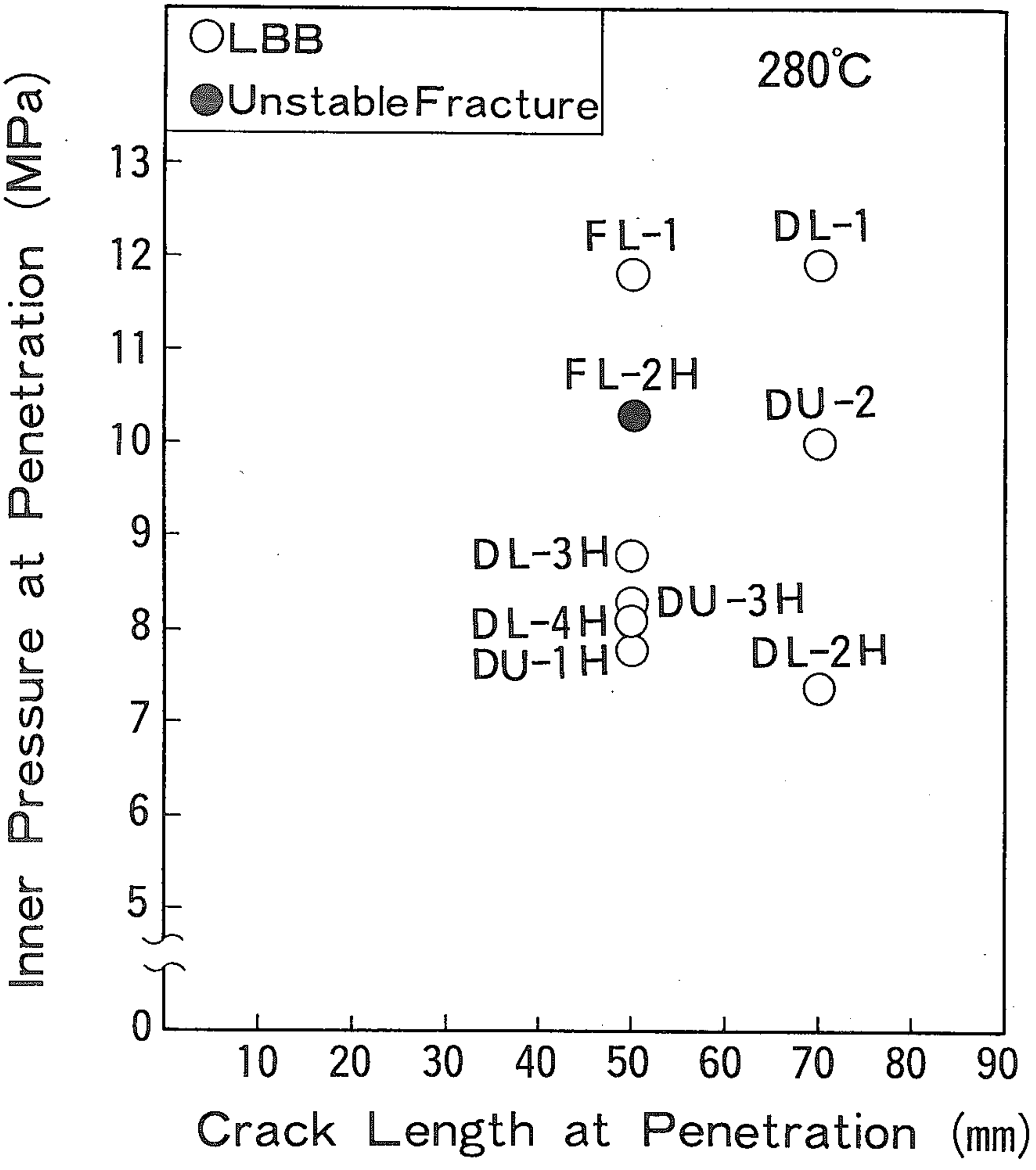


Fig.9 Relation between crack length at penetration and inner pressure at penetration for nine specimens in the present study