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JSN251 74—09

# Creep Test of Fuel Cladding Tubes for Fast Breeder Reactor (Part Ⅲ)

February, 1974

POWER REACTOR AND NUCLEAR FUEL
DEVELOPMENT CORPORATION

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4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki, 319-1184
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This is the translation of the report

SJ209 73-01 issued in October, 1973.

NOT FOR PUBLICATION
SN251 74-09
February, 1974

登録区分
2006.11.30
変更表示

# Creep Test of Fuel Cladding Tubes for Fast Breeder Reactor (Part III)*

Teruo Yukitoshi,** Kunihiko Yoshikawa,** and Kenichiro Ueno**

## Abstract

This work, which involved high temperature tensile test, internal pressure creep rupture test and examination of the ruptured test pieces, was undertaken as the third program of a series of experiment by contract with Power Reactor and Nuclear Fuel Development Corporation (PNC) for the purpose of determining the high temperature performance of clad tubing for the Fast Experimental Reactor "JOYO".

The materials tested under this experiment were SUS 316 tubes of 6.3 mm diameter and 0.35 mm thickness supplied by two different manufacturers. These materials were classified and designated for convenience sake as B-material and A-material respectively according to their manufacturers.

As the result of this experiment, it was confirmed that both A and B materials demonstrated sufficient strength and elongation under 600°C - 700°C temperature range satisfying the specifications given by PNC, and that in respect of their creep rupture strength, A-material showed a higher strength over that of B-material while A's rupture elongation was lower than that of B under the applied stress at a temperature of 650°C.

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* Work performed under contracts between Power Reactor and Nuclear Fuel Development Corporation and Sumitomo Metal Industries, Ltd.

** Central Research Laboratories, Sumitomo Metal Industries, Ltd.

# C O N T E N T S

## I. Preface

This experiment was performed for the purpose of determining allowable tensile stresses for the fuel cladding tube of the Fast Experimental Breeder Reactor (FEBR) under high temperatures as the third program of the project undertaken by this Central Research Laboratory by contract with the Power Reactor & Nuclear Fuel Development Corporation (PNC).

## II. Research Plan

### 1. Experiment Target

This work is the third program of a series of experiment project involving tests of strength and performance of FEBR'S cladding tube under high temperatures. The first one was undertaken in 1970 and the second one in 1972, and this one which is the third experiment is to conduct a series of internal pressure creep tests to study high temperature properties of the cladding tube, and will involve internal creep rupture tests, post-rupture metallographic tests, and high temperature tensile test.

### 2. Kinds of Test and Test Conditions

(1) High temperature tensile test

Test temperatures: 600, 650, 700 and 750°C.

(2) Internal pressure creep rupture test

Test temperature: 650°C

Rupture time target: 100, 300, 1000 and 3000 hrs.

(3) Examination of ruptured test pieces

Photographing of appearance of test pieces

Observation of microstructures

Hardness measurement

Dimensional measurement

## III. Test Materials

### 1. Type of steel

SUS 316

### 2. Dimension of test materials

$6.3^{\phi} \times 0.35^{t}$

### 3. Test Pieces

#### 3-1. High temperature tensile test pieces

The following 24 pieces were used. Gauge length was 50 mm and total length was 1000 mm.

| | | | |
|---|---|---|---|
| K2771 | K2722 | K2737 | K2738 |
| K2795 | K2756 | K2778 | K2752 |
| K2746 | K2792 | K2789 | K2764 |
| S0514 | S0511 | S0512 | S0513 |
| S0510 | S0519 | S0521 | S0518 |
| S0517 | S0515 | S0516 | S0520 |

#### 3-2. Internal creep rupture test pieces

The form and configuration of the internal creep rupture test pieces are given in Fig. 1. Preparation of the test pieces was performed by PNC. The following nine pieces were used for this test:

| | |
|---|---|
| K2703-5 | S0522-1 |
| K2705-6 | S0526-8 |
| K2701-5 | S0528-5 |
| K2706-3 | S0523-6 |
| | S0524-7 |

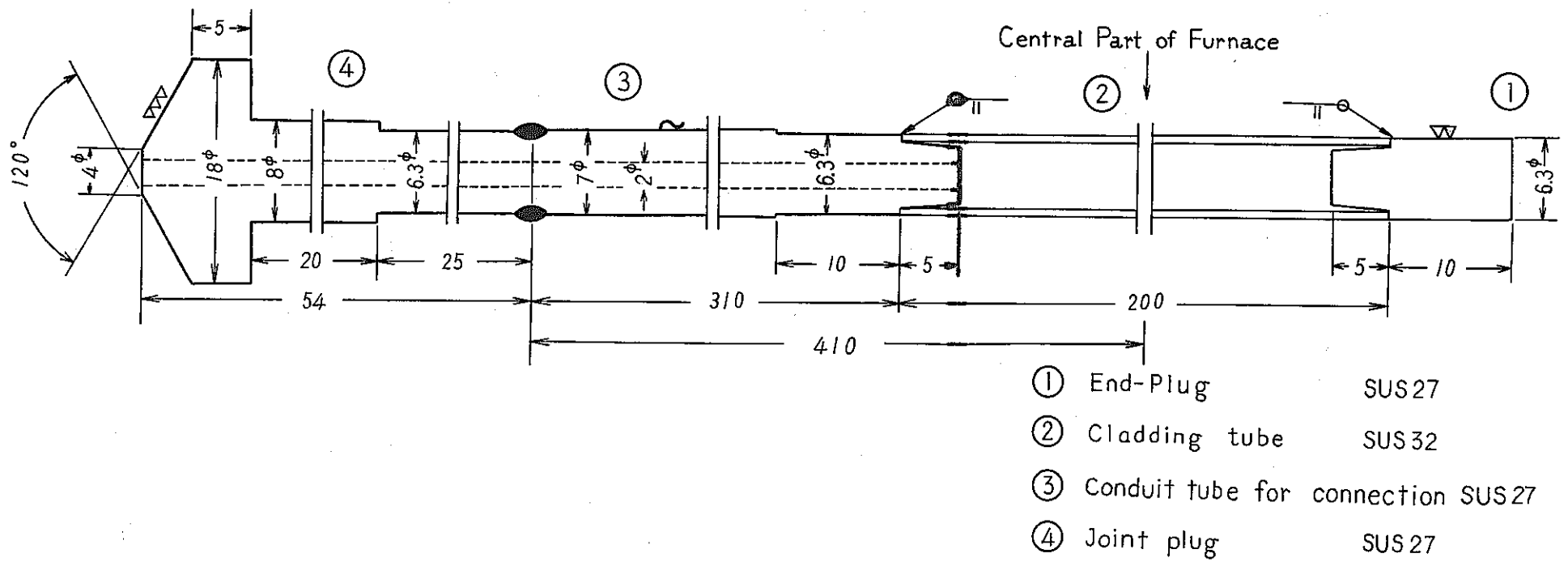



Fig. 1. Configuration of Internal Pressure Creep Test Piece

## IV. Test Method

### 1. High Temperature Tensile Test

The equipment used for this high temperature tensile test was Electron Tube Self-balancing Universal Tester (10 tons) which is hydraulically loaded. The strain velocity is automatically controled upto the proof stress, and thereafter, it is controled manually by use of a strain-pacer.

The test pieces used for this test had a length of 1000mm, and were tested by JIS G0567-1966 under the following conditions:

Up to the proof stress: Strain measurement by D.T.F. at 50 mm G.L.; Strain rate of 0.3%/min.

After the proof stress: Strain rate of 7.5 mm/min was aimed at with assumed G.L. of 100 mm

### 2. Internal Pressure Creep Rupture Test

Fig. 2 shows the piping system of the test equipment. Its working pressure range is 0 - 500 $kg/cm^2$, test temperature range 200 - 800°C. It is consisted of a pressurizer, a pressure regulator, an atmospheric apparatus and a temperature controler. The pressurizer, which operates a pressure pump by a compressor, uses water as the pressure medium to apply a load on the test pressure. In the course of this process, the pressure medium is converted from water to argon gas in the accumulator and applies load on the test piece in the heating furnace. Test pressure is adjusted through the control of the pressure pump by detecting the pressure using a strain gauge type detector. The atmospheric apparatus is provided with a vacuum pump to

replace the air inside the test piece with argon gas, and a device to fill the heating furnace with argon atmosphere. In this experiment, we used the air for the outer atmosphere.

The heating apparatus is consisted of five horizontal resistance furnaces with 5 temperature controlling zone and five temperature controllers.

In this test, the test pieces as shown in Fig. 1 were used, and argon gas was used as the pressure medium. The temperature of the test piece was measured at the three points by placing thermocouples at the end-plug of the test piece, the conduit tube and the center of the dummy test piece arranged in parallel to the real test piece. Other tests followed the creep rupture test method of JIS Z2272-1968.

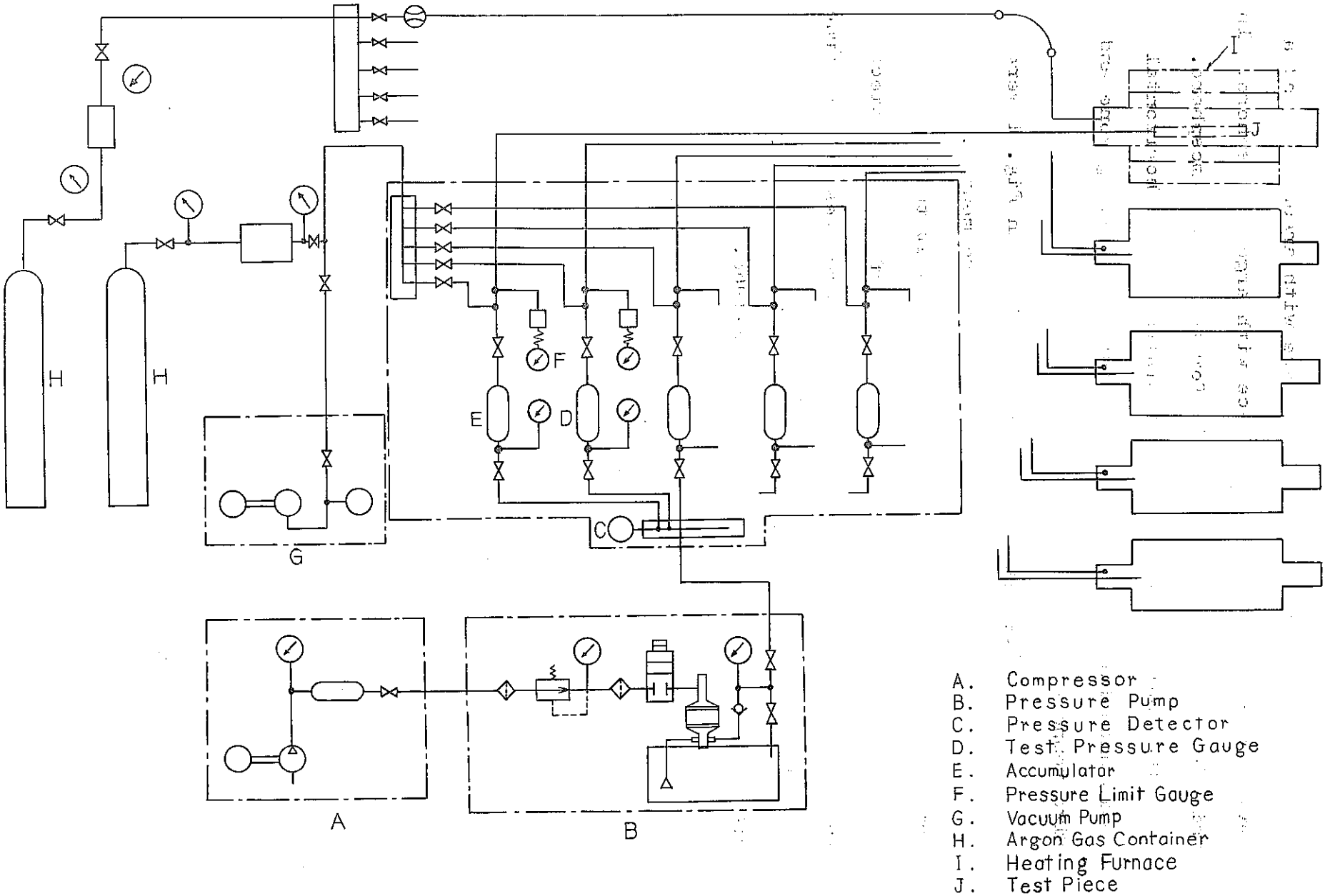



Fig. 2. Internal Pressure Creep Testing equipment

## V. Test Results

### 1. Results of High Temperature Tensile Test

Table 1-1, 1-2, and Fig. 3 show the results of the high temperature tensile test.

Both materials of A and B showed similar values as to their tensile strength and proof stress, showing an approximately linear decline as temperature going up from 600°C to 750°C. While their elongation showed an increase as temperature rising, and scatter range was comparatively small. Both the strength and elongation satisfied the requirements at 650°C of PNC (0.2% proof stress : above 20 $kg/mm^2$, tensile strength : above 30 $kg/mm^2$, elongation : above 15%).

### 2. Results of Internal Pressure Creep Rupture Test

Table 2 and Fig. 4 show the results of the internal pressure rupture test at 650°C.

Table 1-1. Results of High Temperature Tensile Test

A-material

| Temperature °C | Test Pieces No. | 0.2% Proof Stress, Kg/mm$^2$ | Tensile Strength, Kg/mm$^2$ | Elongation, % |
|---|---|---|---|---|
| 600 | K2771 | 42.9 | 51.6 | 16.8 |
| | K2795 | 42.4 | 51.2 | 16.0 |
| | K2746 | 41.7 | 50.8 | 18.0 |
| 650 | K2722 | 35.6 | 43.2 | 20.0 |
| | K2756 | 36.4 | 45.9 | 18.0 |
| | K2792 | 36.5 | 44.3 | 17.8 |
| 700 | K2737 | 30.3 | 35.8 | 26.4 |
| | K2778 | 30.9 | 36.4 | 24.2 |
| | K2789 | 30.4 | 36.4 | 24.8 |
| 750 | K2738 | 24.2 | 29.1 | 27.8 |
| | K2752 | 24.1 | 29.1 | 30.0 |
| | K2764 | - | - | - |

Note 1: The proof stress and rupture elongation are measured as G.L = 50 mm

Note 2: The cross section area: 6.6 mm$^2$

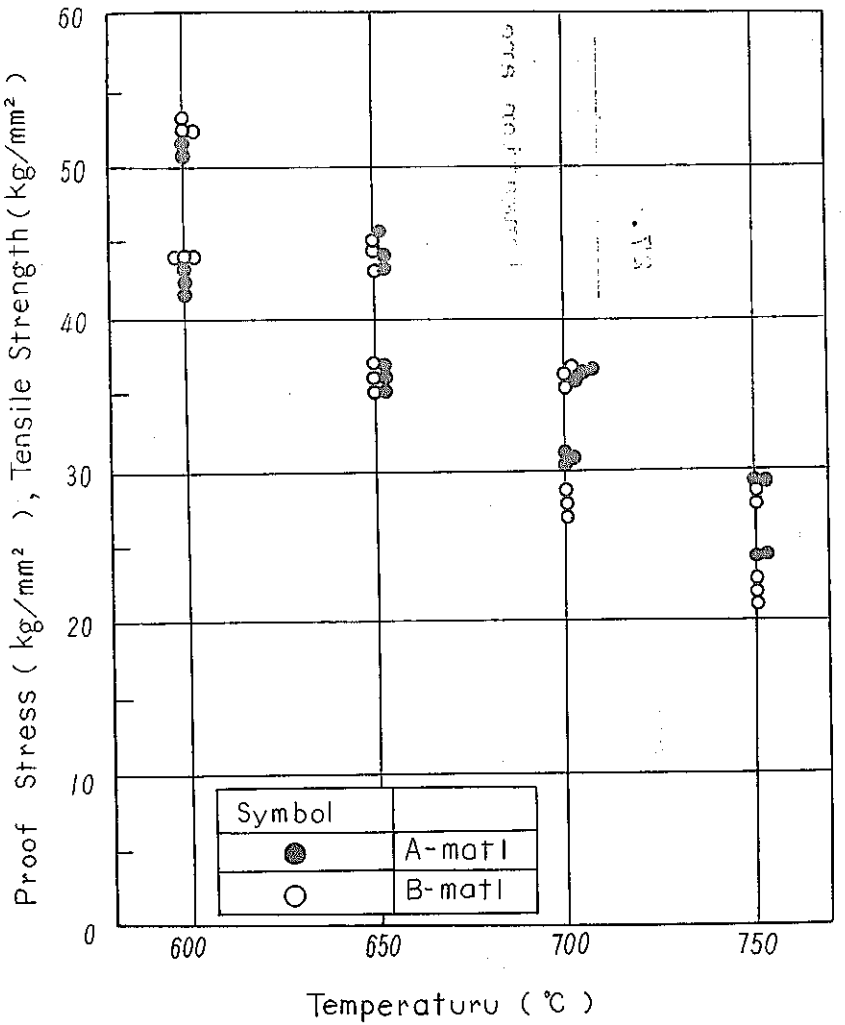
Table 1-2. Results of High Temperature Tensile Test

B-material

| Temperature °C | Test Pieces No. | 0.2% Proof Stress, Kg/mm$^2$ | Tensile Strength, Kg/mm$^2$ | Elongation, % |
|---|---|---|---|---|
| 600 | S0514 | 44.1 | 53.4 | 20.2 |
| | S0510 | 44.1 | 52.3 | 15.6 |
| | S0517 | 44.0 | 52.4 | 15.6 |
| 650 | S0511 | 34.9 | 43.2 | 23.0 |
| | S0519 | 37.0 | 45.0 | 18.6 |
| | S0515 | 35.8 | 44.3 | 22.2 |
| 700 | S0512 | 27.3 | 36.4 | 30.0 |
| | S0521 | 27.6 | 36.5 | 29.6 |
| | S0516 | 28.5 | 35.2 | 28.6 |
| 750 | S0513 | 22.7 | 28.0 | 45.8 |
| | S0518 | 22.0 | 28.3 | 35.6 |
| | S0520 | 21.2 | 27.6 | 34.6 |

Note 1: The proof stress and rupture elongation are measured as G.L = 50 mm

Note 2: The cross section area: 6.6 mm$^2$



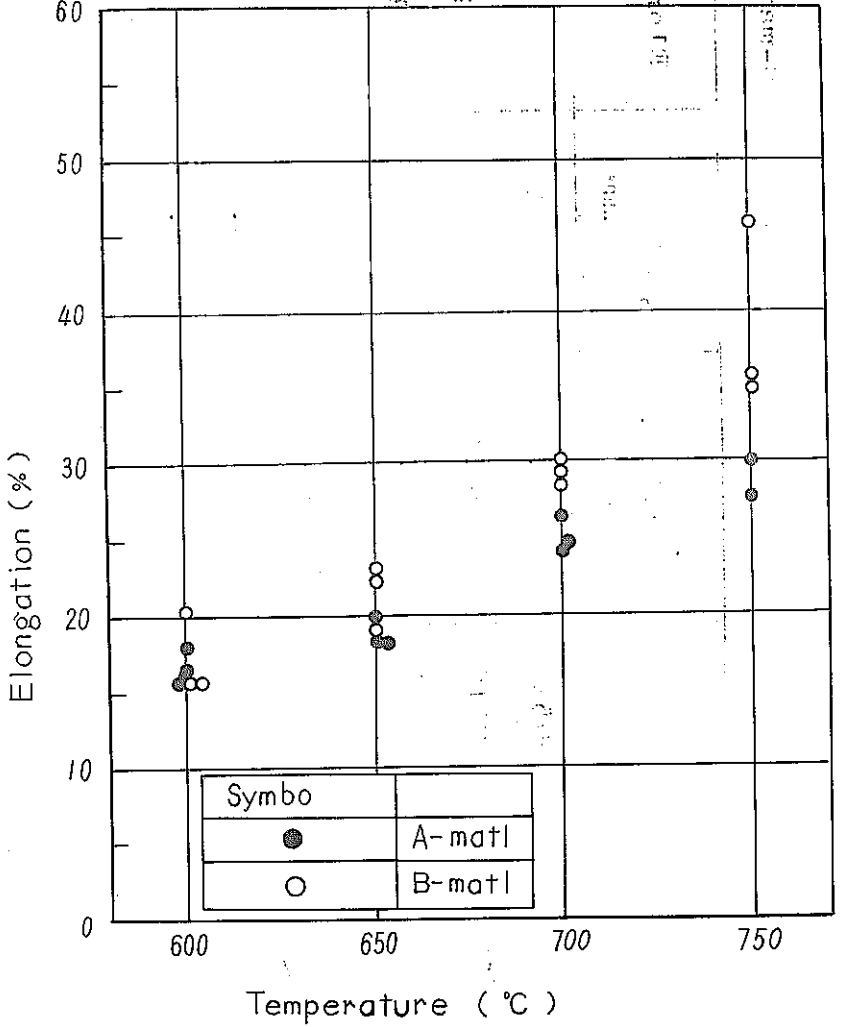




**Fig. 3. Result of High Temperature Tensile Test**

Table 2. Result of Internal Pressure Creep Rupture Test

| Temperature, °C | | Test Pieces No. | Test Pressure, Kg/cm² | Rupture Time, hr. |
|---|---|---|---|---|
| 650 | A-material | K2703-5 | 300 | 171.2 |
| | | K2705-6 | 270 | 397.0 |
| | | K2701-5 | 240 | 1406.4 |
| | | K2706-3 | 210 | 3165.5 |
| 650 | B-material | S0522-1 | 280 | 56.6 |
| | | S0526-8 | 210 | 364.8 |
| | | S0528-5 | 170 | 1161.0 |
| | | S0523-6 | 140 | 1851.0 |
| | | S0524-7 | 140 | 2005.2 |

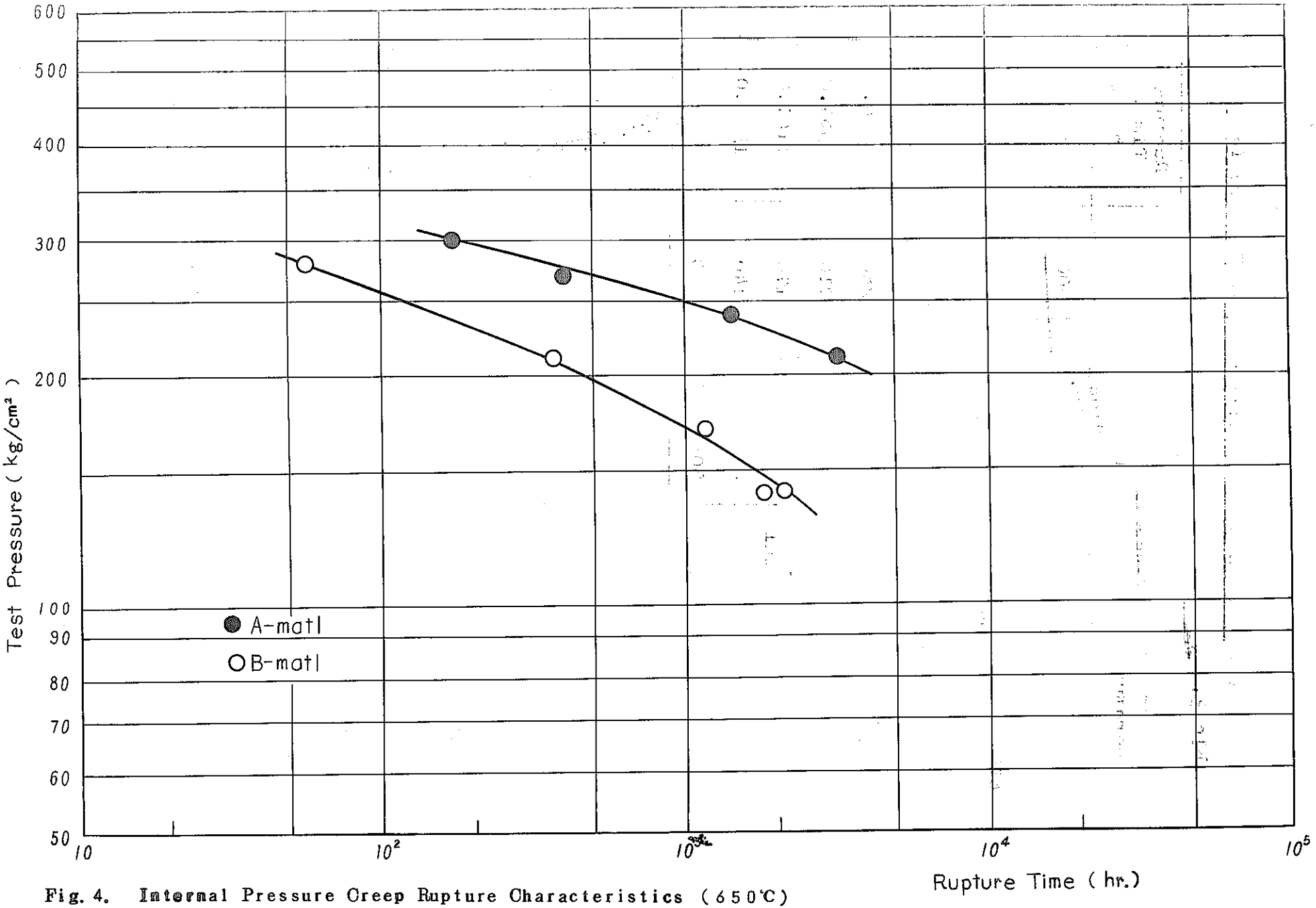



**Fig. 4. Internal Pressure Creep Rupture Characteristics (650℃)**

3. Examination of Ruptured Test Pieces

The result of the examination of test pieces after the creep rupture test is given as follows:

| Test Piece No. | Temperature °C | Internal Pressure Kg/cm² | Rupture Time h | Photographing of Appearance | Measurement of Dimension | Optical Microscopic Observation | Hardness Measurement |
|---|---|---|---|---|---|---|---|
| K2703-5 | 650 | 300 | 171.2 | ○ | ○ | | |
| K2705-6 | " | 270 | 397.0 | ○ | ○ | | |
| K2701-5 | " | 240 | 1406.4 | ○ | ○ | ○ | |
| K2706-3 | " | 210 | 3165.5 | ○ | ○ | ○ | ○ |
| S0522-1 | " | 280 | 56.6 | ○ | ○ | | |
| S0526-8 | " | 210 | 364.8 | ○ | ○ | | |
| S0528-5 | " | 170 | 1161.0 | ○ | ○ | ○ | |
| S0523-6 | " | 140 | 1851.0 | ○ | ○ | ○ | ○ |

Beside the above, the observation of optical microstructure and hardness measurement were carried out on the following two test pieces before the test:

A-material K2708-9

B-material S0532-8

The results are given as follows:

(1) Appearance of ruptured test pieces are shown in Photo-1. The arrows indicate the ruptured portions. The remarkable deformation at the ruptures was caused by the strike against the wall of the heating furnace at the time of rupture.

(2) The results of the after-test dimensional measurement of the test pieces are shown in Table 3-1 - 3-8 and Fig. 5-1 - 5-8. The measurement was performed on the outside diameters of test pieces by use of a micrometer. The measuring points were at 19 different positions at intervals of 10 mm from each other, and at 4 positions in each same cross section.

(3) The optical microstructures of the cross sections and the longitudinal sections of the test pieces prior to the tests are shown in Photo 2-1 and 2-2. Villella was used as the etching reagent.

The microstructures of the cross sections and the longitudinal sections of the test pieces after the tests are shown in Photo 3-1 - 3-4.

(4) The hardness measurement results of the cross sections and the longitudinal sections of the test pieces prior to tests are given by the following table:

| Test Piece No. | Hardness, $H_v$, 500 g | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Longitudinal Section | | | | | | Cross Section | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Aver-age | 1 | 2 | 3 | 4 | 5 | Aver-age |
| K2708-9 | 276 | 278 | 276 | 276 | 274 | 275 | 276 | 266 | 264 | 266 | 258 | 266 |
| S0532-8 | 272 | 274 | 267 | 265 | 276 | 271 | 260 | 267 | 271 | 265 | 263 | 265 |

The hardness measurement results of ruptured test pieces which had the longest rupture time and of which hardness was measured at the reverse side of the rupture in the longitudinal direction at each 10 mm interval are given in Table 4-1 and 4-2 respectively.

## VI. Conclusion

The third program of the experiment has undertaken the high temperature tensile test and the internal pressure creep rupture test of FBR's fuel cladding tube (SUS316), and has confirmed the high temperature strength characteristics of materials as well as examined the post-test structural change of the test pieces.

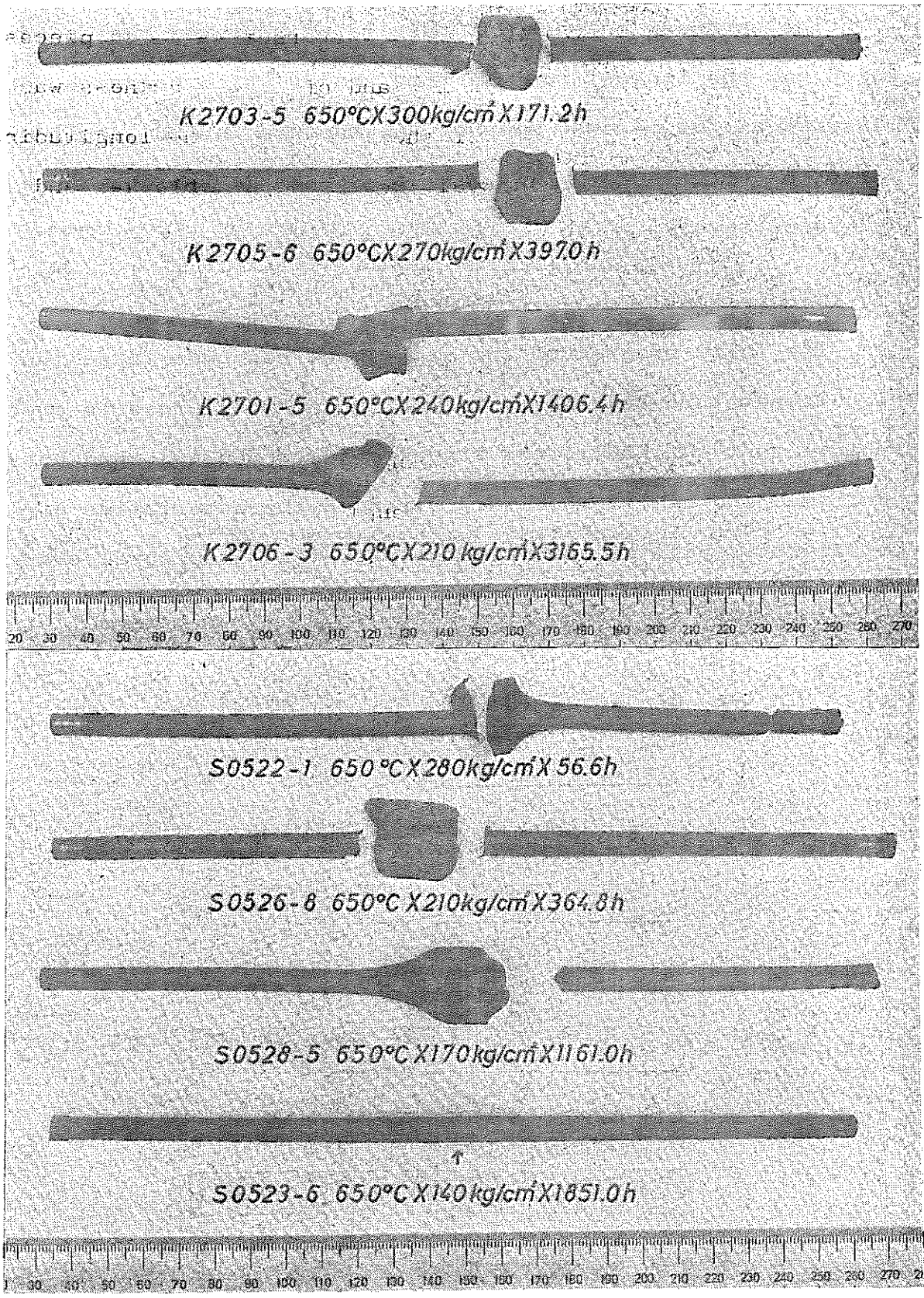



Photo 1. Appearance of Internal Pressure Creep Rupture Test Pieces.

Table 3－1　Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| K2703－5 (Temp.: 650℃ Prssr.: 300 kg/cm² Pupture Time: 1712 h) | A | 6.46 | 6.50 | 6.55 | 6.56 | 6.61 | 6.60 | 6.72 | — | — | 6.71 | 6.70 | 6.62 | 6.59 | 6.55 | 6.53 | 6.50 | 6.48 | 6.45 | 6.43 |
| | B | 6.46 | 6.50 | 6.55 | 6.56 | 6.62 | 6.67 | 6.72 | — | — | 6.73 | 6.73 | 6.61 | 6.57 | 6.55 | 6.52 | 6.50 | 6.48 | 6.45 | 6.43 |
| | C | 6.46 | 6.50 | 6.55 | 6.56 | 6.61 | 6.66 | 6.73 | — | — | 6.75 | 6.73 | 6.61 | 6.58 | 6.55 | 6.52 | 6.50 | 6.48 | 6.45 | 6.43 |
| | D | 6.46 | 6.50 | 6.55 | 6.56 | 6.61 | 6.65 | 6.77 | — | — | 6.74 | 6.73 | 6.62 | 6.59 | 6.56 | 6.52 | 6.50 | 6.48 | 6.45 | 6.43 |
| | Max. | 6.46 | 6.50 | 6.55 | 6.56 | 6.62 | 6.67 | 6.77 | — | — | 6.75 | 6.73 | 6.62 | 6.59 | 6.56 | 6.53 | 6.50 | 6.48 | 6.45 | 6.43 |
| | | (2.5) | (3.1) | (3.9) | (4.1) | (5.0) | (5.8.) | (7.4) | — | — | (7.1) | (6.8) | (5.0) | (4.6) | (4.1) | (3.6) | (3.1) | (2.8) | (2.3) | (2.0) |
| | Mean | 6.46 | 6.50 | 6.55 | 6.56 | 6.61 | 6.66 | 6.74 | — | — | 6.73 | 6.72 | 6.62 | 6.58 | 6.55 | 6.52 | 6.50 | 6.48 | 6.45 | 6.43 |
| | | (2.5) | (3.1) | (3.9) | (4.1) | (4.9) | (5.7) | (7.0) | — | — | (6.8) | (6.6) | (5.0) | (4.4) | (3.9) | (3.5) | (3.1) | (2.8) | (2.3) | (2.0) |
| | Min. | 6.46 | 6.50 | 6.55 | 6.56 | 6.61 | 6.65 | 6.72 | — | — | 6.71 | 6.70 | 6.61 | 6.57 | 6.55 | 6.52 | 6.50 | 6.48 | 6.45 | 6.43 |
| | | (2.5) | (3.1) | (3.9) | (4.1) | (4.9) | (5.5) | (6.6) | — | — | (6.5) | (6.3) | (4.9) | (4.3) | (3.9) | (3.5) | (3.1) | (2.8) | (2.3) | (2.0) |

Note 1; Figures in ( ) indicate calculated elongation(%). The pre-test outside diameter was 6.302 mm.

Note 2; ※ indicates the value at the weld-heat affected area.

Note 3; ——shows the ruptured area.

Table 3－2　Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| K2705—6 (Temp.: 650℃, Prssr.: 270 kg/cm², Rupture Time: 397.0h) | A | 6.48 | 6.49 | 6.51 | 6.51 | 6.54 | 6.62 | 6.68 | — | — | 6.74 | 6.67 | 6.72 | 6.85 | 6.70 | 6.57 | 6.52 | 6.49 | 6.48 | 6.49 |
| | B | 6.47 | 6.49 | 6.51 | 6.51 | 6.54 | 6.63 | 6.65 | — | — | 6.75 | 6.68 | 6.72 | 6.87 | 6.68 | 6.56 | 6.52 | 6.50 | 6.48 | 6.49 |
| | C | 6.47 | 8.49 | 6.51 | 6.51 | 6.54 | 6.65 | 6.65 | — | — | 6.76 | 6.67 | 6.72 | 6.88 | 6.66 | 6.56 | 6.52 | 6.49 | 6.48 | 6.48 |
| | D | 6.47 | 6.48 | 6.51 | 6.51 | 6.54 | 6.65 | 6.65 | — | — | 6.77 | 6.67 | 6.72 | 6.88 | 6.67 | 6.56 | 6.52 | 6.49 | 6.48 | 6.49 |
| | Max. | 6.48 | 6.49 | 6.51 | 6.51 | 6.54 | 6.65 | 6.68 | — | — | 6.77 | 6.68 | 6.72 | 6.88 | 6.70 | 6.57 | 6.52 | 6.50 | 6.48 | 6.49 |
| | | (2.8) | (3.0) | (3.3) | (3.3) | (3.8) | (5.5) | (6.0) | — | — | (7.4) | (6.0) | (6.6) | (9.2) | (6.3) | (4.3) | (3.5) | (3.1) | (2.8) | (3.0) |
| | Mean | 6.47 | 6.49 | 6.51 | 6.51 | 6.54 | 6.64 | 6.66 | — | — | 6.76 | 6.67 | 6.72 | 6.87 | 6.68 | 6.56 | 6.52 | 6.49 | 6.48 | 6.49 |
| | | (2.7) | (3.0) | (3.3) | (3.3) | (3.8) | (5.4) | (5.7) | — | — | (7.3) | (5.8) | (6.6) | (9.0) | (6.0) | (4.1) | (3.5) | (3.0) | (2.8) | (3.0) |
| | Min. | 6.47 | 6.48 | 6.51 | 6.51 | 6.54 | 6.62 | 6.65 | — | — | 6.74 | 6.67 | 6.72 | 6.85 | 6.60 | 6.56 | 6.52 | 6.49 | 6.48 | 6.48 |
| | | (2.7) | (2.8) | (3.3) | (3.3) | (3.8) | (5.0) | (5.5) | — | — | (7.0) | (5.8) | (6.6) | (8.7) | (5.7) | (4.1) | (3.5) | (3.0) | (2.8) | (2.8) |

Note 1: Figures in ( ) indicate calculated elongation(%). The pre-test outside diameter was 6.302 mm.

Note 2: ※ indicates the value at the weld-heat affected area.

Note 3: ——shows the ruptured area.

Table 3－3 Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| K2701－5 (Temp. : 650℃ Prssr. : 240 kg/cm² Rupture Time : 1406.4h) | A | 6.41 | 6.42 | 6.46 | 6.47 | 6.50 | 6.54 | 6.61 | 6.68 | 6.76 | 6.85 | — | — | 6.67 | 6.55 | 6.48 | 6.45 | 6.44 | 6.44 | 6.40 |
| | B | 6.41 | 6.43 | 6.46 | 6.47 | 6.49 | 6.53 | 6.63 | 6.69 | 6.78 | 6.82 | — | — | 6.68 | 6.56 | 6.48 | 6.45 | 6.44 | 6.43 | 6.40 |
| | C | 6.41 | 6.43 | 6.46 | 6.48 | 6.50 | 6.54 | 6.62 | 6.69 | 6.79 | 6.85 | — | — | 6.71 | 6.54 | 6.49 | 6.45 | 6.43 | 6.43 | 6.40 |
| | D | 6.41 | 6.43 | 6.45 | 6.48 | 6.50 | 6.54 | 6.62 | 6.68 | 6.77 | 6.89 | — | — | 6.70 | 6.54 | 6.48 | 6.46 | 6.44 | 6.43 | 6.40 |
| | Max. | 6.41 | 6.43 | 6.46 | 6.48 | 6.50 | 6.54 | 6.63 | 6.69 | 6.79 | 6.89 | — | — | 6.71 | 6.56 | 6.49 | 6.46 | 6.44 | 6.44 | 6.40 |
| | | (1.7) | (2.0) | (2.5) | (2.8) | (3.2) | (3.8) | (5.2) | (6.2) | (7.8) | (9.3) | — | — | (6.5) | (4.1) | (3.0) | (2.5) | (2.2) | (2.2) | (1.6) |
| | Mean | 6.41 | 6.43 | 6.46 | 6.48 | 6.50 | 6.54 | 6.62 | 6.69 | 6.78 | 6.85 | — | — | 6.69 | 6.55 | 6.48 | 6.45 | 6.44 | 6.43 | 6.40 |
| | | (1.7) | (2.0) | (2.5) | (2.8) | (3.2) | (3.8) | (5.1) | (6.2) | (7.6) | (8.7) | — | — | (6.2) | (4.0) | (2.8) | (2.4) | (2.2) | (2.0) | (1.6) |
| | Min. | 6.41 | 6.42 | 6.45 | 6.47 | 6.49 | 6.53 | 6.61 | 6.68 | 6.76 | 6.82 | — | — | 6.68 | 6.54 | 6.48 | 6.45 | 6.43 | 6.43 | 6.46 |
| | | (1.7) | (1.9) | (2.4) | (2.7) | (3.0) | (3.6) | (4.9) | (6.0) | (7.3) | (8.2) | — | — | (6.0) | (3.8) | (2.8) | (2.4) | (2.0) | (2.0) | (1.6) |

Note 1 : Figures in ( ) indicate calculated elongation(%). The pre—test outside diameter was 6,301 mm.

Note 2 : ※ indicates the value at the veld—heat affected area.

Note 3 : —— shows the ruptured area.

Table 3－4 Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. / (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm (End plug side) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| K2706－3 (Temp.: 650℃ Prssr.: 210 kg/cm² Rupture Time: 3165.5h) | A | 6.44 | 6.38 | 6.42 | 6.44 | 6.44 | 6.47 | 6.51 | 6.53 | 6.62 | 6.69 | — | — | — | 6.52 | 6.47 | 6.42 | 6.40 | 6.37 | 6.38 |
| | B | 6.34 | 6.42 | 6.42 | 6.43 | 6.46 | 6.48 | 6.51 | 6.53 | 6.63 | 6.59 | — | — | — | 6.48 | 6.45 | 6.43 | 6.41 | 6.38 | 6.34 |
| | C | 6.33 | 6.44 | 6.42 | 6.43 | 6.46 | 6.47 | 6.49 | 6.53 | 6.61 | 6.59 | — | — | — | 6.49 | 6.45 | 6.43 | 6.41 | 6.39 | 6.35 |
| | D | 6.37 | 6.43 | 6.43 | 6.44 | 6.47 | 6.47 | 6.51 | 6.54 | 6.61 | 6.60 | — | — | — | 6.51 | 6.45 | 6.43 | 6.41 | 6.38 | 6.37 |
| | Max. | 6.44 | 6.44 | 6.43 | 6.44 | 6.47 | 6.48 | 6.51 | 6.54 | 6.63 | 6.69 | — | — | — | 6.52 | 6.47 | 6.43 | 6.41 | 6.39 | 6.38 |
| | | (2.2) | (2.2) | (2.0) | (2.0) | (2.7) | (2.8) | (3.3) | (3.8) | (5.2) | (6.2) | — | — | — | (3.5) | (2.7) | (2.0) | (1.7) | (1.4) | (1.3) |
| | Mean | 6.37 | 6.42 | 6.42 | 6.44 | 6.46 | 6.47 | 6.51 | 6.53 | 6.62 | 6.62 | — | — | — | 6.50 | 6.46 | 6.43 | 6.41 | 6.38 | 6.36 |
| | | (1.1) | (1.9) | (1.9) | (2.2) | (2.5) | (2.7) | (3.3) | (3.6) | (5.1) | (5.1) | — | — | — | (3.2) | (2.5) | (2.0) | (1.7) | (1.3) | (1.1) |
| | Min. | 6.33 | 6.38 | 6.42 | 6.43 | 6.44 | 6.47 | 6.49 | 6.53 | 6.61 | 6.59 | — | — | — | 6.48 | 6.45 | 6.42 | 6.40 | 6.37 | 6.34 |
| | | (0.5) | (1.3) | (1.9) | (2.0) | (2.2) | (2.7) | (3.0) | (3.6) | (4.9) | (4.6) | — | — | — | (2.8) | (2.4) | (1.9) | (1.6) | (1.1) | (0.6) |

Note 1: Figures in ( ) indicate calculated elongation(%). The pre-test outside diameter was 6.301mm.

Note 2: ※ indicates the value at the weld-heat affected area.

Note 3: ——shows the ruptured area.

Table 3-5 Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| S0522-1 (Temp.: 650℃, Prssr.: 280 kg/cm², Rupture Time: 56.6 h) | A | 6.91 | 6.95 | 6.68 | 6.70 | 6.85 | 6.87 | — | — | — | 6.89 | 6.85 | 6.76 | 6.73 | 6.69 | 6.65 | 6.61 | 6.90 | 6.60 | 6.53 |
| | B | 6.92 | 6.78 | 6.71 | 6.74 | 6.80 | 6.82 | — | — | — | 6.88 | 6.85 | 6.76 | 6.73 | 6.69 | 6.65 | 6.61 | 6.80 | 6.60 | 6.53 |
| | C | 7.01 | 6.85 | 6.74 | 6.77 | 6.78 | 6.88 | — | — | — | 6.88 | 6.85 | 6.76 | 6.73 | 6.69 | 6.65 | 6.61 | 6.80 | 6.60 | 6.53 |
| | D | 6.90 | 6.85 | 6.74 | 6.77 | 6.79 | 6.87 | — | — | — | 6.92 | 6.83 | 6.75 | 6.73 | 6.69 | 6.65 | 6.63 | 6.80 | 6.60 | 6.53 |
| | Max. | 7.01 | 6.95 | 6.74 | 6.77 | 6.85 | 6.88 | — | — | — | 6.92 | 6.85 | 6.76 | 6.73 | 6.69 | 6.65 | 6.63 | 6.90 | 6.60 | 6.53 |
| | | (11.2) | (10.2) | (6.9) | (7.4) | (8.6) | (9.1) | — | — | — | (9.8) | (8.6) | (7.2) | (6.7) | (6.1) | (5.5) | (5.2) | (9.4) | (4.7) | (3.6) |
| | Mean | 6.94 | 6.86 | 6.72 | 6.75 | 6.81 | 6.86 | — | — | — | 6.89 | 6.85 | 6.76 | 6.73 | 6.96 | 6.65 | 6.61 | 6.83 | 6.60 | 6.53 |
| | | (10.1) | (8.8) | (6.6) | (7.1) | (8.0) | (8.8) | — | — | — | (9.3) | (8.6) | (7.2) | (6.7) | (6.1) | (5.5) | (4.8) | (8.3) | (4.7) | (3.6) |
| | Min. | 6.90 | 6.78 | 6.68 | 6.70 | 6.78 | 6.82 | — | — | — | 6.88 | 6.83 | 6.75 | 6.73 | 6.69 | 6.65 | 6.61 | 6.80 | 6.60 | 6.53 |
| | | (9.4) | (7.5) | (5.9) | (6.3) | (7.5) | (8.2) | — | — | — | (9.1) | (8.3) | (7.1) | (6.7) | (6.1) | (5.5) | (4.8) | (7.9) | (4.7) | (3.6) |

Note 1: Figures in ( ) indicate calculated elongation(%). The pre-test outside diameter was 6.305mm.

Note 2: ※ indicates the value at the weld-heat affected area.

Note 3: —— shows the ruptured area.

Table 3－6　Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| S0526－8 (Temp. : 650 ℃ Prssr. : 210 kg/cm² Rupture Time 3648 h) | A | 6.63 | 6.67 | 6.72 | 6.80 | 6.90 | 7.01 | 7.18 | 7.18 | 7.23 | — | — | — | 7.05 | 7.00 | 6.90 | 6.80 | 6.75 | 6.68 | 6.60 |
| | B | 6.63 | 6.67 | 6.72 | 6.80 | 6.90 | 7.02 | 7.18 | 7.19 | 7.22 | — | — | — | 7.05 | 6.98 | 6.90 | 6.81 | 6.75 | 6.68 | 6.60 |
| | C | 6.63 | 6.67 | 6.71 | 6.80 | 6.90 | 7.03 | 7.18 | 7.20 | 7.20 | — | — | — | 7.14 | 6.97 | 6.90 | 6.81 | 6.75 | 6.68 | 6.60 |
| | D | 6.63 | 6.67 | 6.72 | 6.80 | 6.90 | 7.00 | 7.19 | 7.21 | 7.20 | — | — | — | 7.15 | 6.95 | 6.91 | 6.82 | 6.75 | 6.68 | 6.60 |
| | Max. | 6.63 | 6.67 | 6.72 | 6.80 | 6.90 | 7.03 | 7.19 | 7.21 | 7.23 | — | — | — | 7.15 | 7.00 | 6.91 | 6.82 | 6.75 | 6.68 | 6.60 |
| | | (5.0) | (5.6) | (6.4) | (7.7) | (9.3) | (11.3) | (13.9) | (14.2) | (14.5) | — | — | — | (13.2) | (10.8) | (9.4) | (8.0) | (6.9) | (5.8) | (4.5) |
| | Mean | 6.63 | 6.67 | 6.72 | 6.80 | 6.90 | 7.02 | 7.18 | 7.20 | 7.21 | — | — | — | 7.10 | 6.98 | 6.90 | 6.81 | 6.75 | 6.68 | 6.60 |
| | | (5.0) | (5.6) | (6.4) | (7.7) | (9.3) | (11.2) | (13.7) | (14.0) | (14.2) | — | — | — | (12.4) | (10.5) | (9.3) | (7.8) | (6.9) | (5.8) | (4.5) |
| | Min. | 6.63 | 6.67 | 6.71 | 6.80 | 6.90 | 7.00 | 7.18 | 7.18 | 7.20 | — | — | — | 7.05 | 6.95 | 6.90 | 6.80 | 6.75 | 6.68 | 6.60 |
| | | (5.0) | (5.6) | (6.3) | (7.7) | (9.3) | (10.8) | (13.7) | (13.7) | (14.0) | — | — | — | (11.6) | (10.1) | (9.3) | (7.7) | (6.9) | (5.8) | (4.5) |

Note 1 : Figures in ( ) indicate calculated elongation(%). The pre—test outside diameter was 6.315mm.

Note 2 : ※ indicates the value at the weld—heat affected area.

Note 3 : ——— shows the ruptured area.

Table 3－7　Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. / (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm (End plug side) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| S0528—7 (Temp : 650 ℃, Prssr. : 170 kg/cm², Rupture Time 1161.0 h) | A | 6.54 | 6.58 | 6.63 | 6.66 | 6.71 | 6.80 | 6.87 | — | — | — | — | 6.84 | 6.80 | 6.71 | 6.64 | 6.59 | 6.55 | 6.50 | 6.47 |
| | B | 6.53 | 6.59 | 6.63 | 6.66 | 6.72 | 6.79 | 6.87 | — | — | — | — | 6.90 | 6.87 | 6.71 | 6.65 | 6.60 | 6.55 | 6.50 | 6.46 |
| | C | 6.54 | 6.59 | 6.63 | 6.67 | 6.72 | 6.78 | 6.88 | — | — | — | — | 6.93 | 6.77 | 6.71 | 6.65 | 6.60 | 6.56 | 6.50 | 6.47 |
| | D | 6.54 | 6.59 | 6.63 | 6.67 | 6.72 | 6.78 | 6.88 | — | — | — | — | 6.93 | 6.76 | 6.70 | 6.64 | 6.60 | 6.55 | 6.50 | 6.47 |
| | Max. | 6.54 | 6.59 | 6.63 | 6.67 | 6.72 | 6.80 | 6.88 | — | — | — | — | 6.93 | 6.80 | 6.71 | 6.65 | 6.60 | 6.56 | 6.50 | 6.47 |
| | | (3.6) | (4.4) | (5.0) | (5.6) | (6.4) | (7.7) | (9.0) | — | — | — | — | (9.8) | (7.7) | (6.3) | (5.3) | (4.5) | (3.9) | (2.9) | (2.5) |
| | Mean | 6.54 | 6.59 | 6.63 | 6.67 | 6.72 | 6.79 | 6.88 | — | — | — | — | 6.90 | 6.78 | 6.71 | 6.65 | 6.60 | 6.55 | 6.50 | 6.47 |
| | | (3.6) | (4.4) | (5.0) | (5.6) | (6.4) | (7.5) | (9.0) | — | — | — | — | (9.3) | (7.4) | (6.3) | (5.3) | (4.5) | (3.7) | (2.9) | (2.5) |
| | Min. | 6.53 | 6.58 | 6.63 | 6.66 | 6.71 | 6.78 | 6.87 | — | — | — | — | 6.84 | 6.76 | 6.70 | 6.64 | 6.59 | 6.55 | 6.50 | 6.46 |
| | | (3.6) | (4.2) | (5.0) | (5.5) | (6.3) | (7.4) | (8.8) | — | — | — | — | (8.3) | (7.1) | (6.1) | (5.2) | (4.4) | (3.7) | (2.9) | (2.6) |

Note 1 : Figures in ( ) indicate calculated elongation(%). The pre—test outside diameter was 6.314mm.

Note 2 : ※ indicates the value at the weld—heat affected area.

Note 3 : ——— shows the ruptured.

Table 3-8 Outside Diameters Measured after Internal Pressure Creep Rupture Test

| Test Piece No. (Test Condition) | Position | (Conduit tube side) Outside Diameters, mm | | | | | | | | | | | | | | | | | | (End plug side) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| S0523-6 (Temp. : 650 ℃, Prssr. : 140 kg/cm², Rupture Time 1851.0 h) | A | 6.49 | 6.54 | 6.58 | 6.66 | 6.75 | 6.85 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.18 | 7.02 | 6.91 | 6.79 | 6.68 | (6.63) | 6.58 | 6.54 |
| | B | 6.49 | 6.54 | 6.58 | 6.66 | 6.75 | 6.86 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.19 | 7.03 | 6.91 | 6.78 | 6.68 | 6.63 | 6.59 | 6.53 |
| | C | 6.49 | 6.54 | 6.59 | 6.66 | 6.75 | (6.85) | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.18 | 7.02 | 6.91 | 6.79 | 6.68 | 6.63 | 6.58 | (6.53) |
| | D | 6.49 | 6.54 | 6.58 | 6.66 | 6.75 | 6.85 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.19 | 7.03 | 6.91 | 6.79 | 6.69 | 6.63 | 6.58 | 6.53 |
| | Max. | 6.49 | 6.54 | 6.59 | 6.66 | 6.75 | 6.86 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.19 | 7.03 | 6.91 | 6.79 | 6.69 | 6.63 | 6.59 | 6.54 |
| | | (2.9) | (3.7) | (4.5) | (5.6) | (7.0) | (8.7) | (10.6) | (13.3) | (14.8) | — | (15.4) | (14.0) | (11.4) | (9.5) | (7.6) | (6.0) | (5.1) | (4.5) | (3.7) |
| | Mean | 6.49 | 6.54 | 6.58 | 6.66 | 6.75 | 6.85 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.19 | 7.03 | 6.91 | 6.79 | 6.68 | 6.63 | 6.58 | 6.53 |
| | | (2.9) | (3.7) | (4.3) | (5.6) | (7.0) | (8.6) | (10.6) | (13.3) | (14.8) | — | (15.4) | (14.0) | (11.4) | (9.5) | (7.6) | (5.9) | (5.1) | (4.3) | (3.5) |
| | Min. | 6.49 | 6.54 | 6.58 | 6.66 | 6.75 | 6.85 | 6.98 | 7.15 | 7.24 | — | 7.28 | 7.18 | 7.02 | 6.91 | 6.78 | 6.68 | 6.63 | 6.58 | 6.53 |
| | | (2.9) | (3.7) | (4.3) | (5.6) | (7.0) | (8.6) | (10.6) | (13.3) | (14.8) | — | (15.4) | (13.8) | (11.3) | (9.5) | (7.5) | (5.9) | (5.1) | (4.3) | (3.5) |

Note 1: Figures in ( ) indicate calculated elongation(%). The pre-test outside diameter was 6.309mm.

2: ※ indicates the value at the weld-heat affected area.

3: ——— shows the ruptured area.

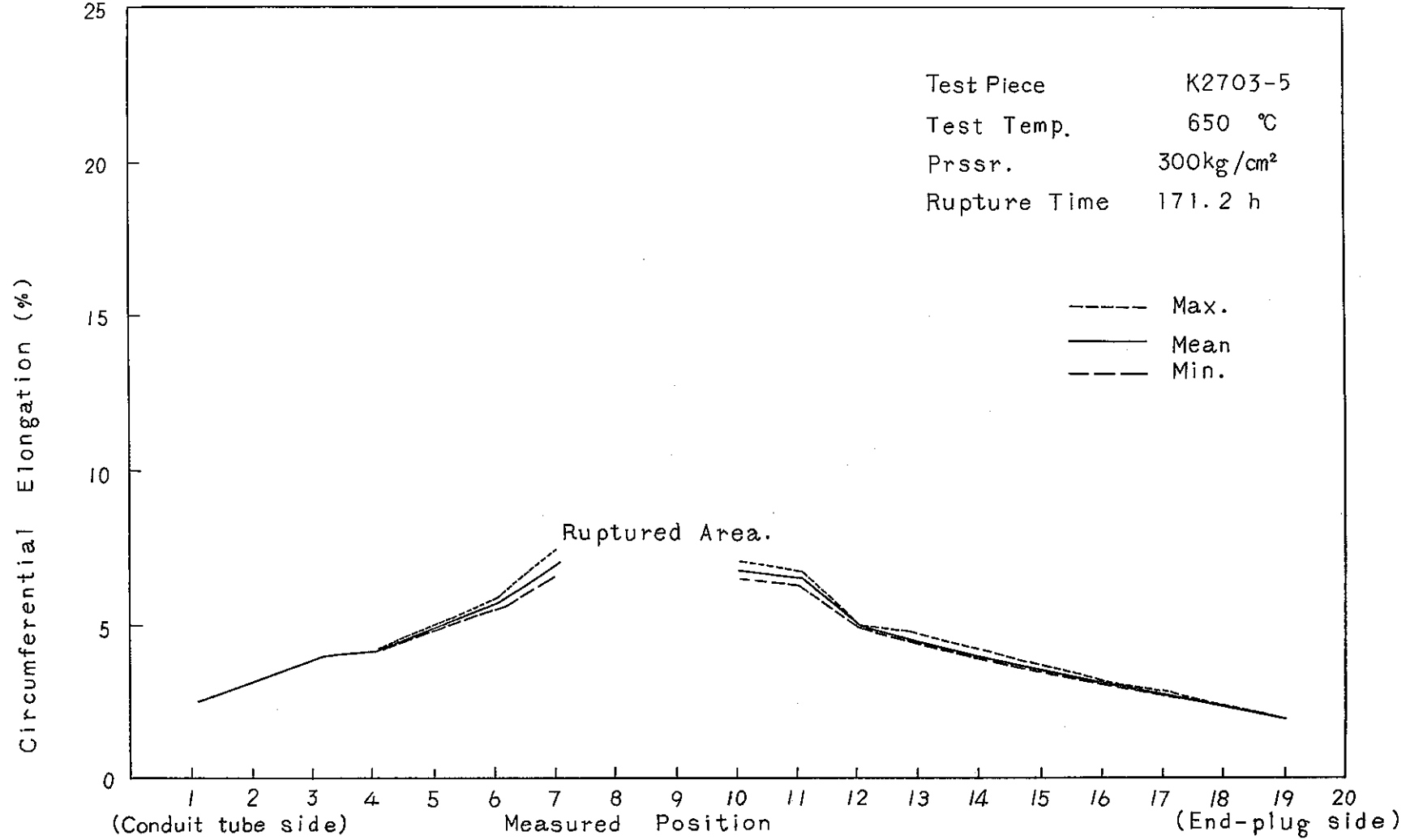



Fig. 5-1. Circumferential Elongation after Internal Pressure Creep Rupture Test

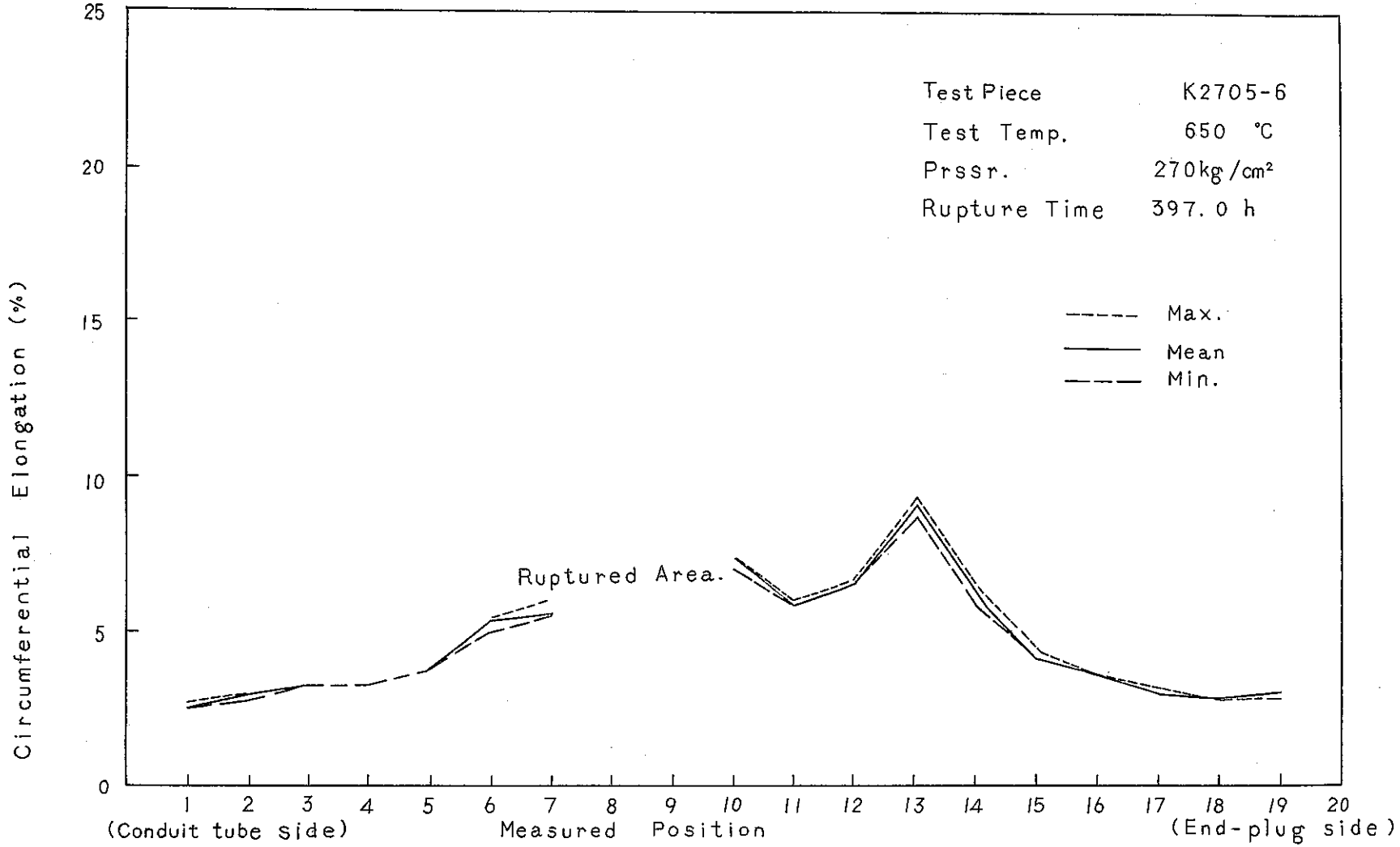



Fig. 5-2. Circumferential Elongation after Internal Pressure Creep Rupture Test

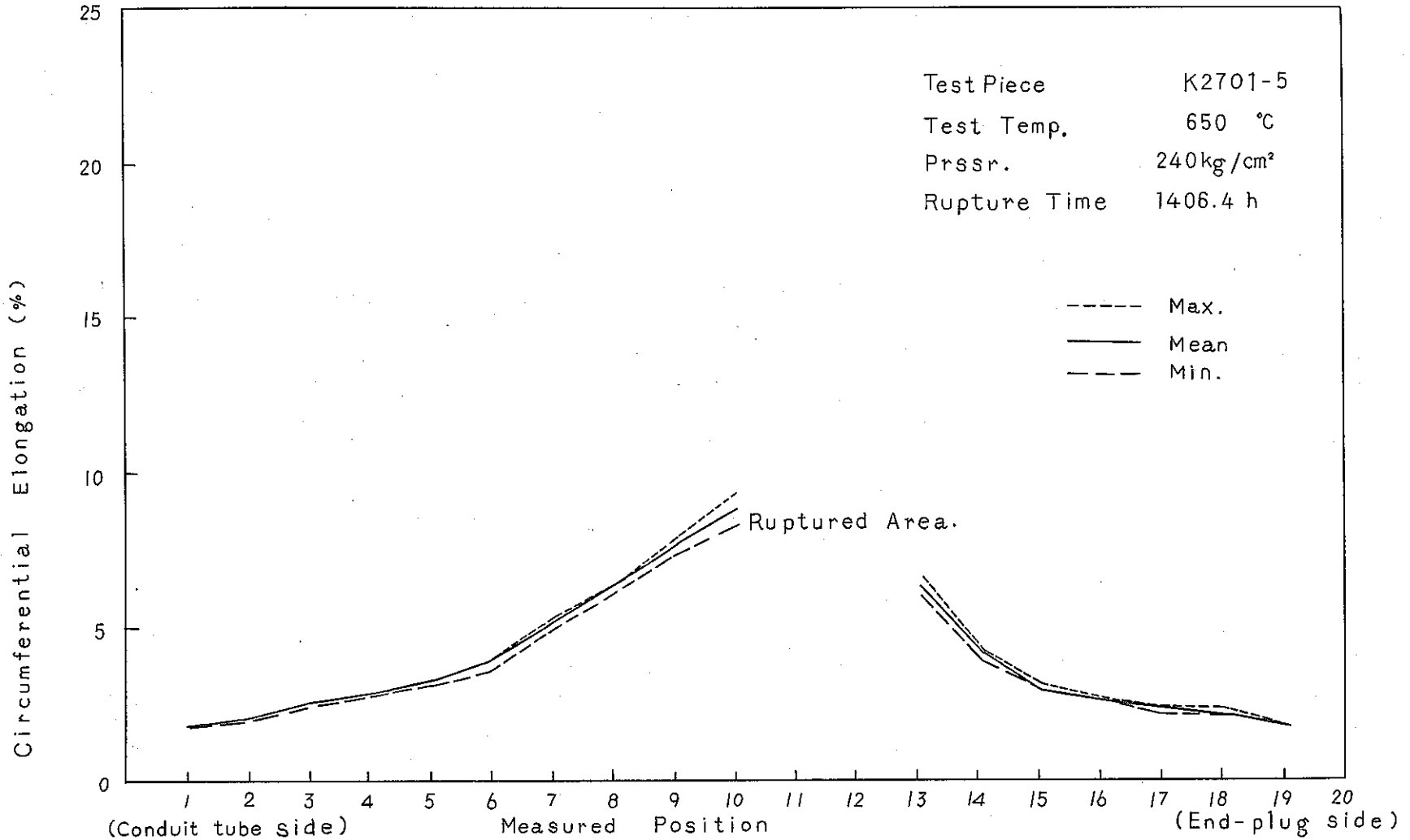



Fig. 5-3. Circumferential Elongation after Internal Pressure Creep Rupture Test

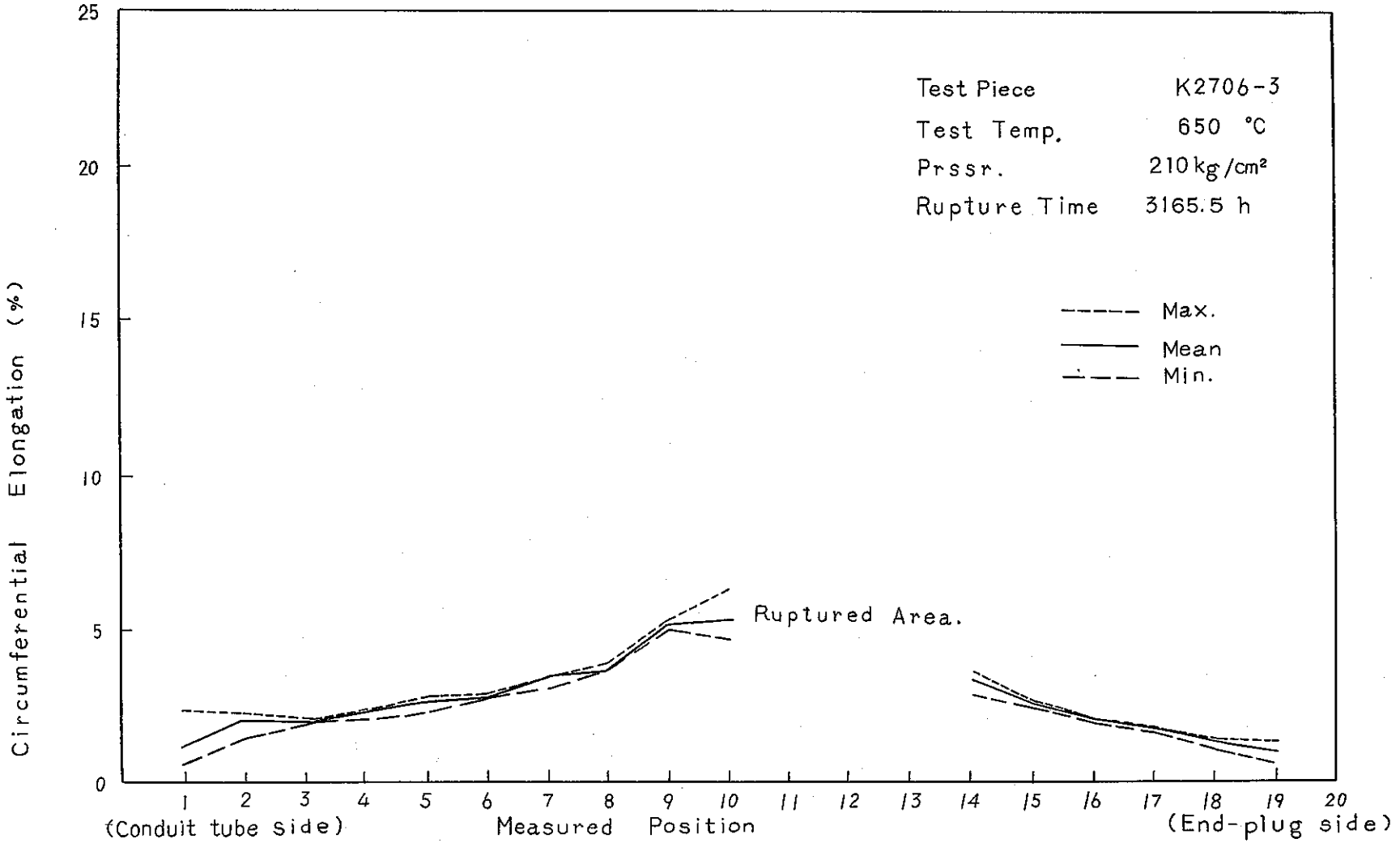



Fig. 5-4. Circumferential Elongation after Internal Pressure Creep Rupture Test

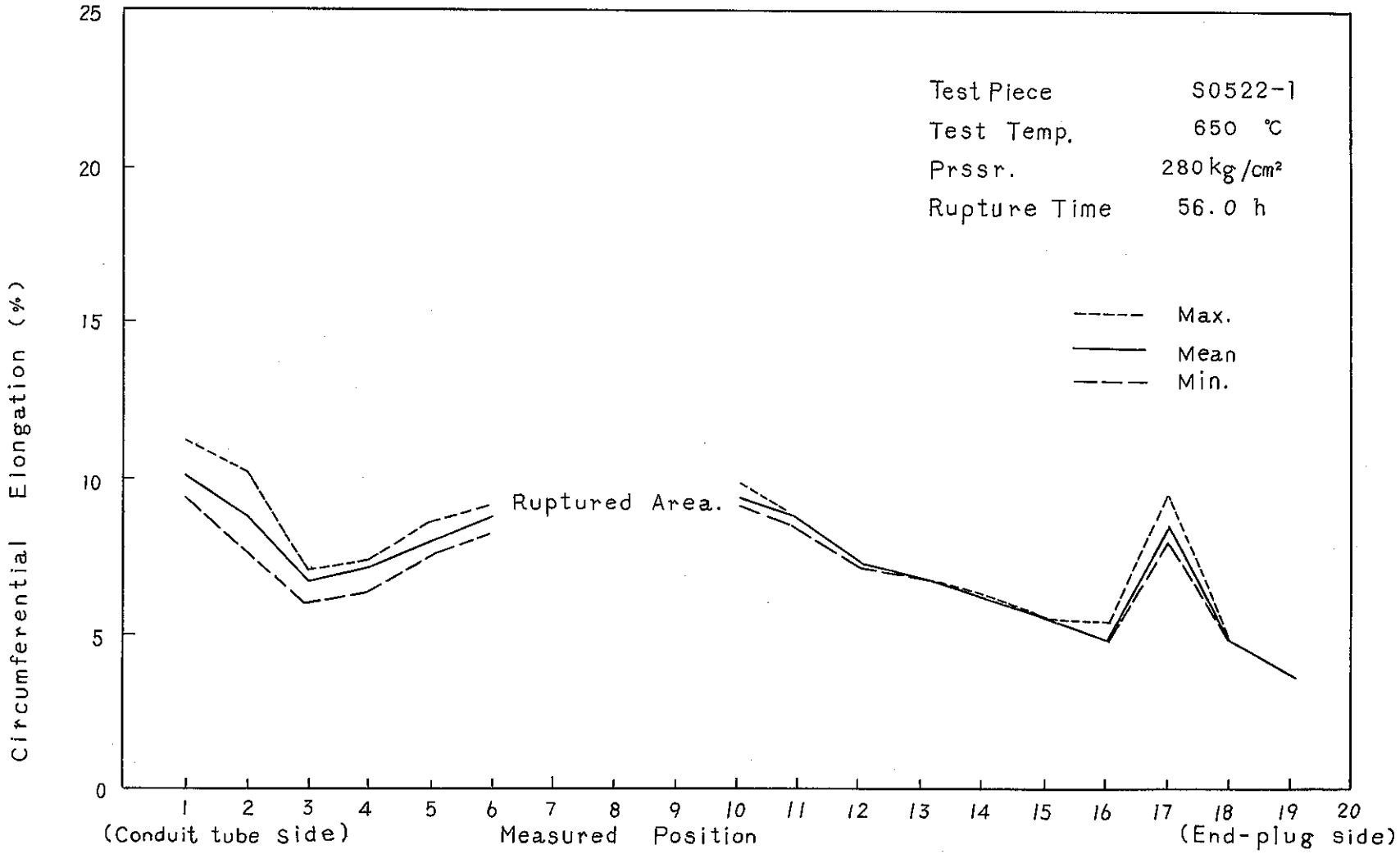



Fig. 5-5. Circumferential Elongation after Internal Pressure Creep Rupture Test

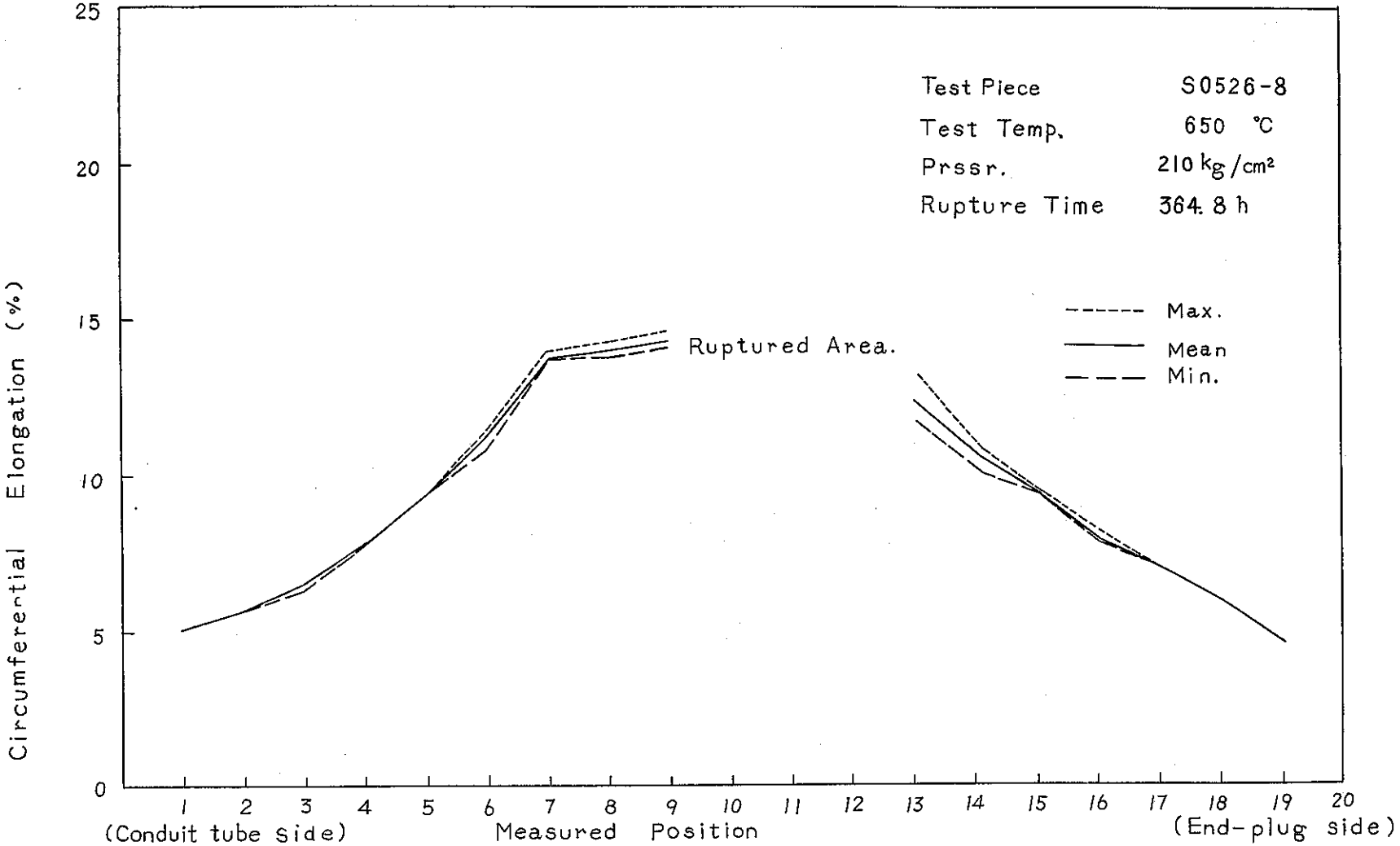



Fig. 5-6. Circumferential Elongation after Internal Pressure Creep Rupture Test

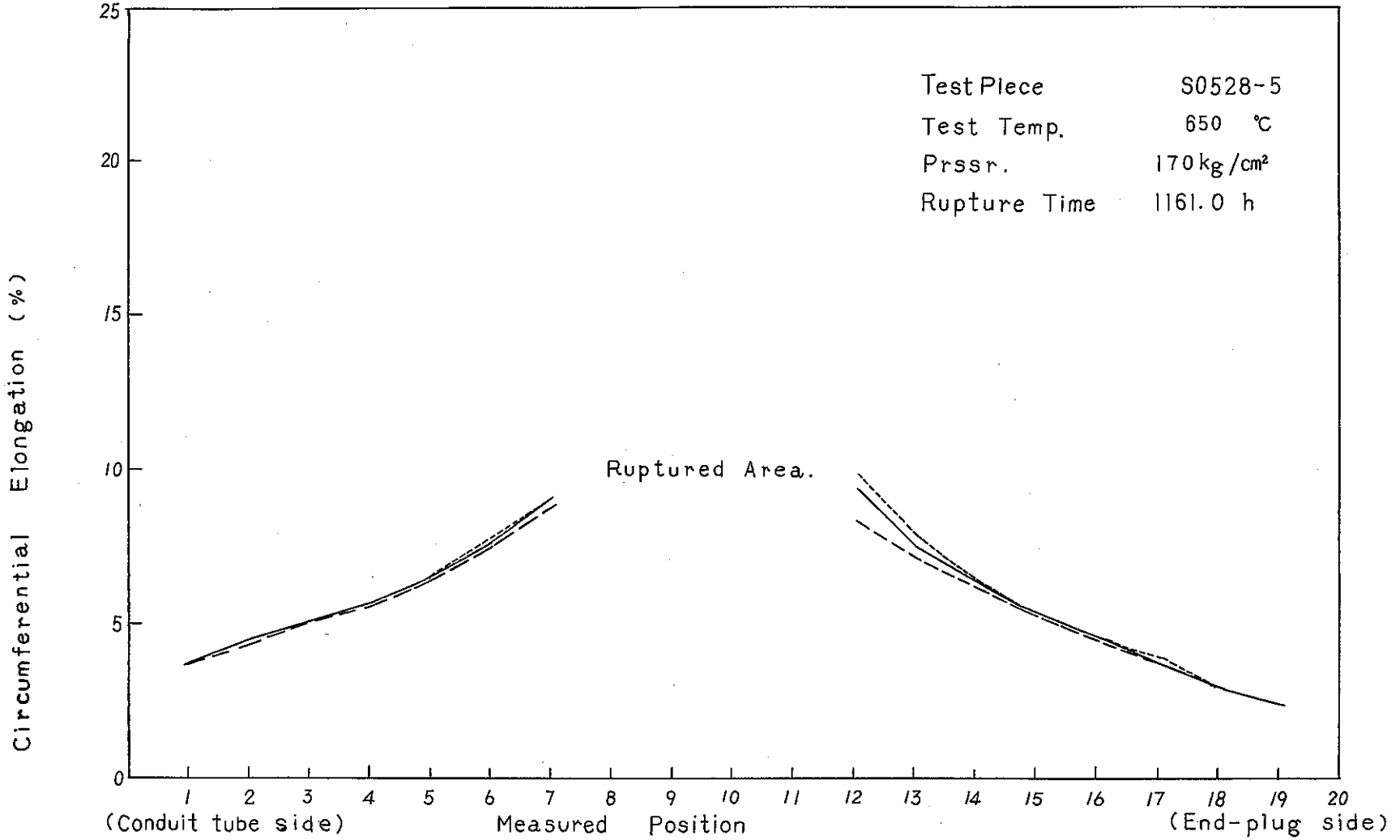



Fig. 5-7. Circumferential Elongation after Internal Pressure Creep Rupture Test

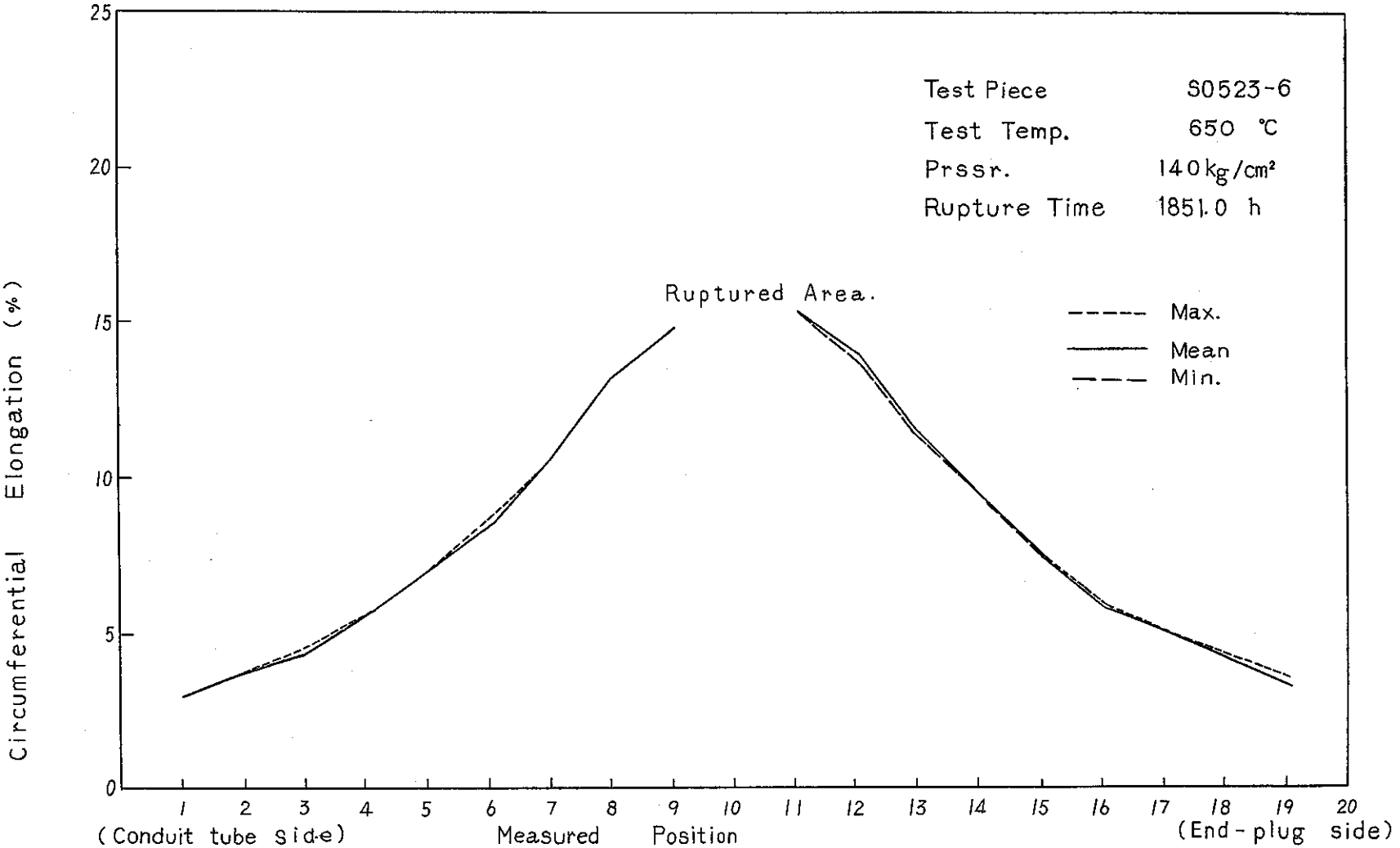
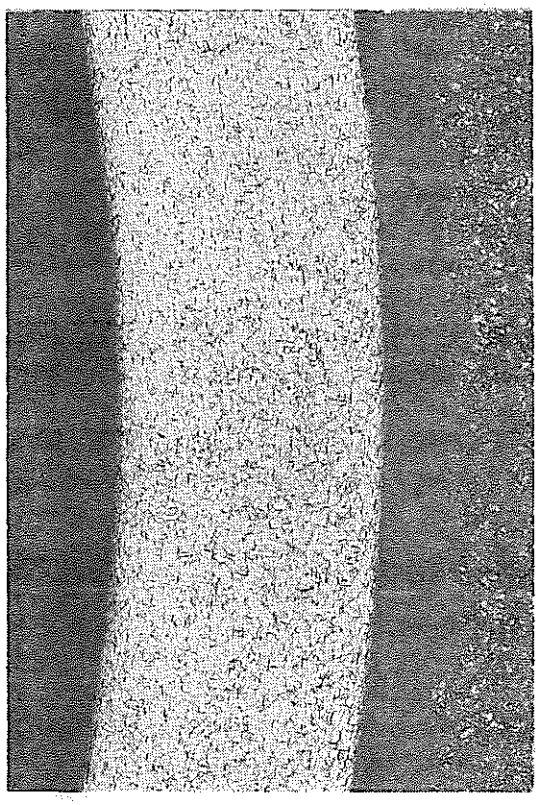
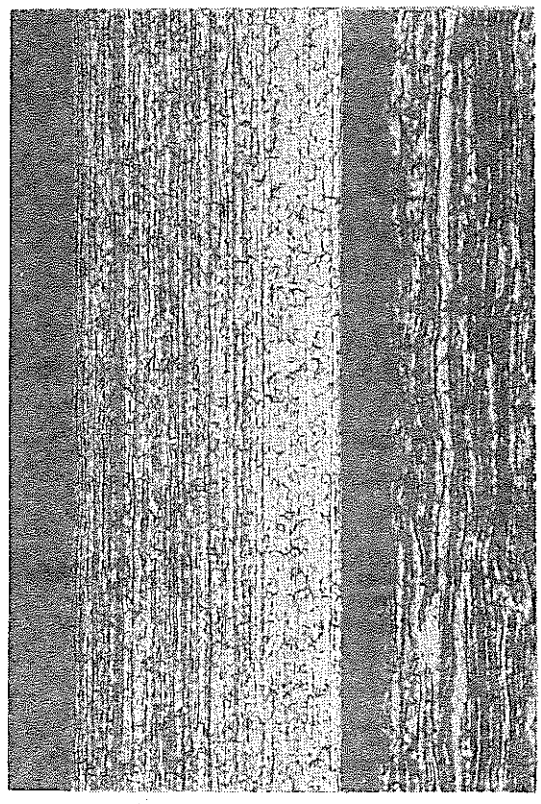


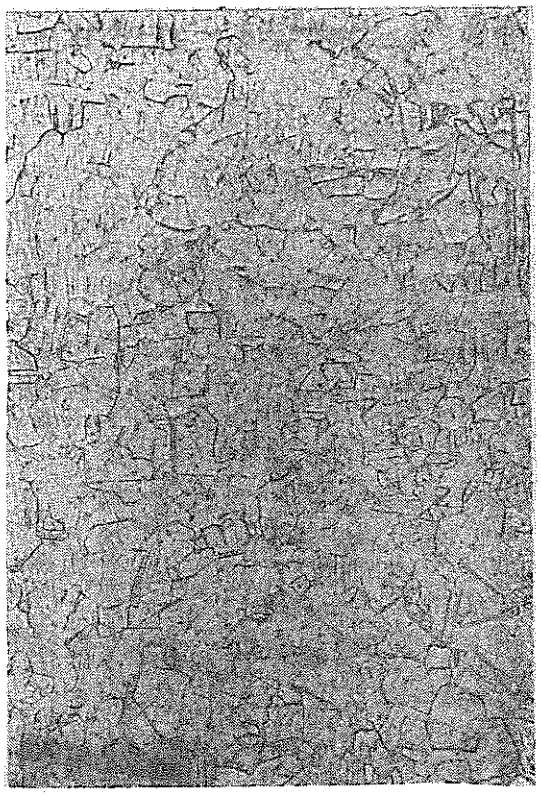

Fig. 5-8. Circumferential Elongation after Internal Pressure Creep Rupture Test



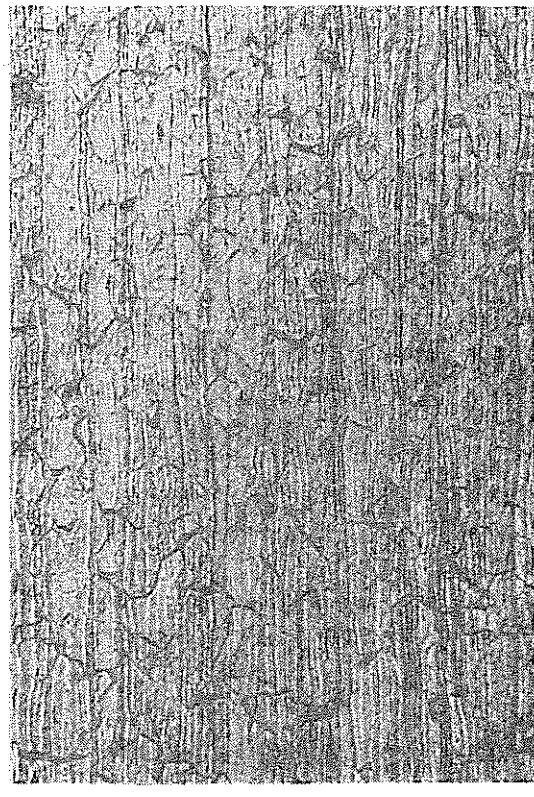
Cross section ×100



Longitudinal section ×100



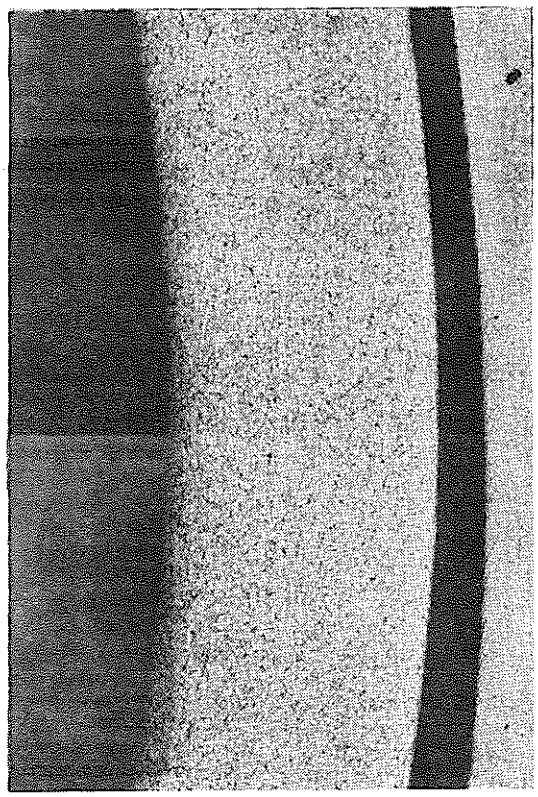
Cross section ×500



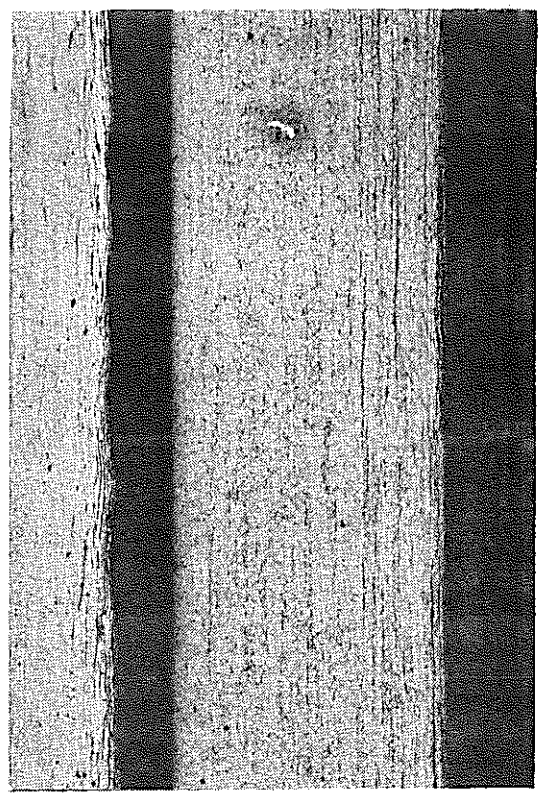
Longitudinal section ×500

Etchant : Villela reagent

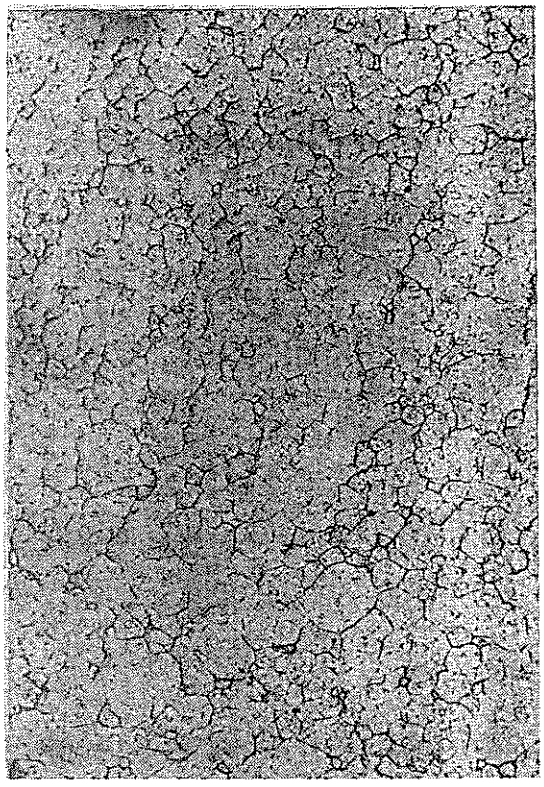
Photo. 2-1. Pre-Test Microstructure (K2708 - 9)



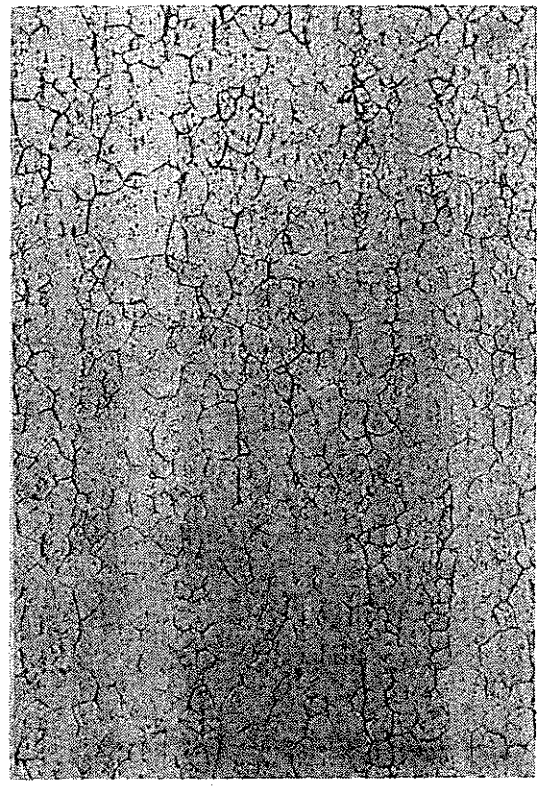
Cross section ×100



Longitudinal section ×100



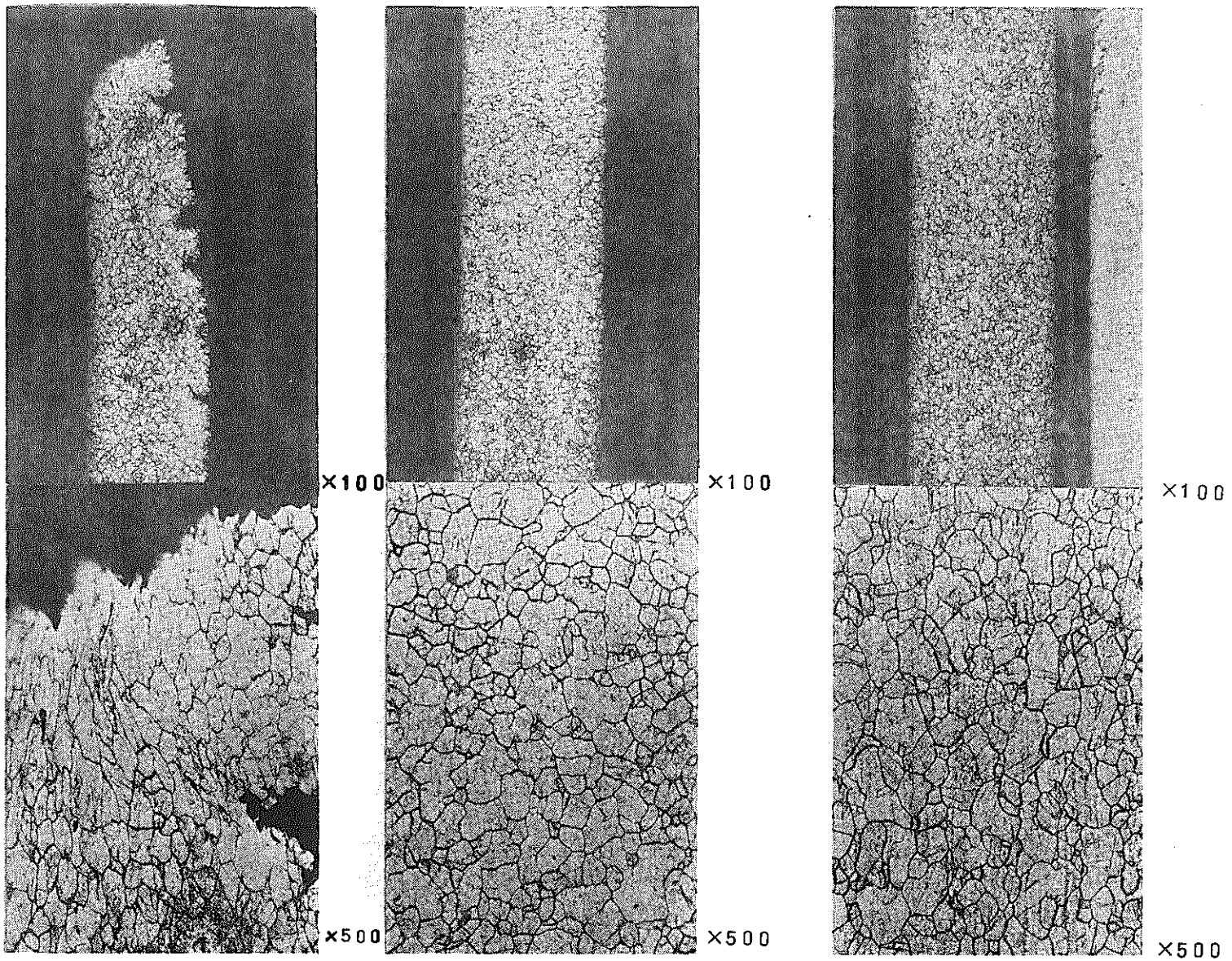
Cross section ×500



Longitudinal section ×500

Etchant : Villela reagent

Photo. 2-2. Pre-Test Microstructure (S0532 - 8)

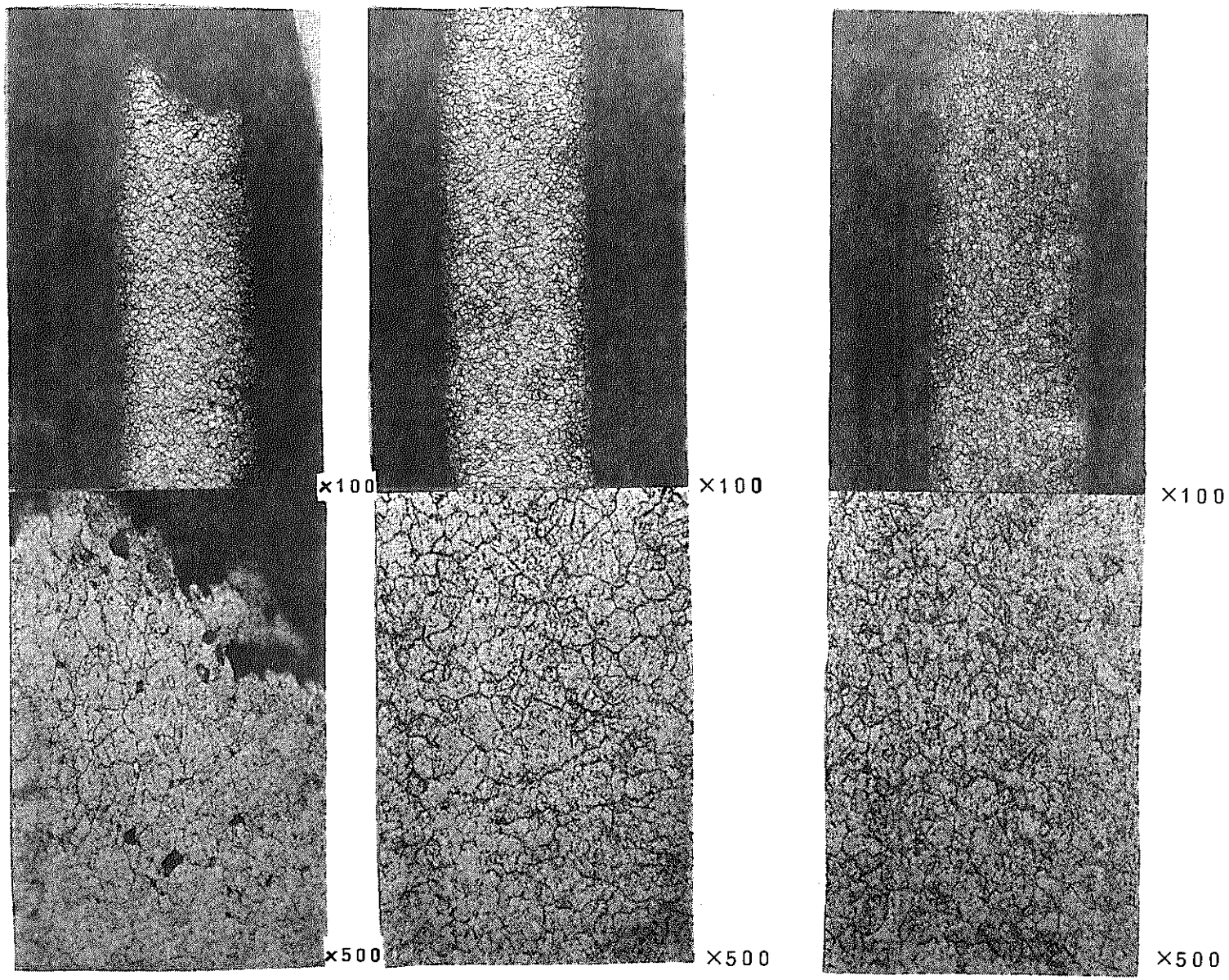



Cross section of ruptured area

Cross section on the reverse side of ruptured area

Longitudinal section of the reverse side of ruptured area

Photo 3-1. Microstructure after Internal Creep Rupture Test (K2701-5 650℃ 240Kg/cm² 1406.4h)

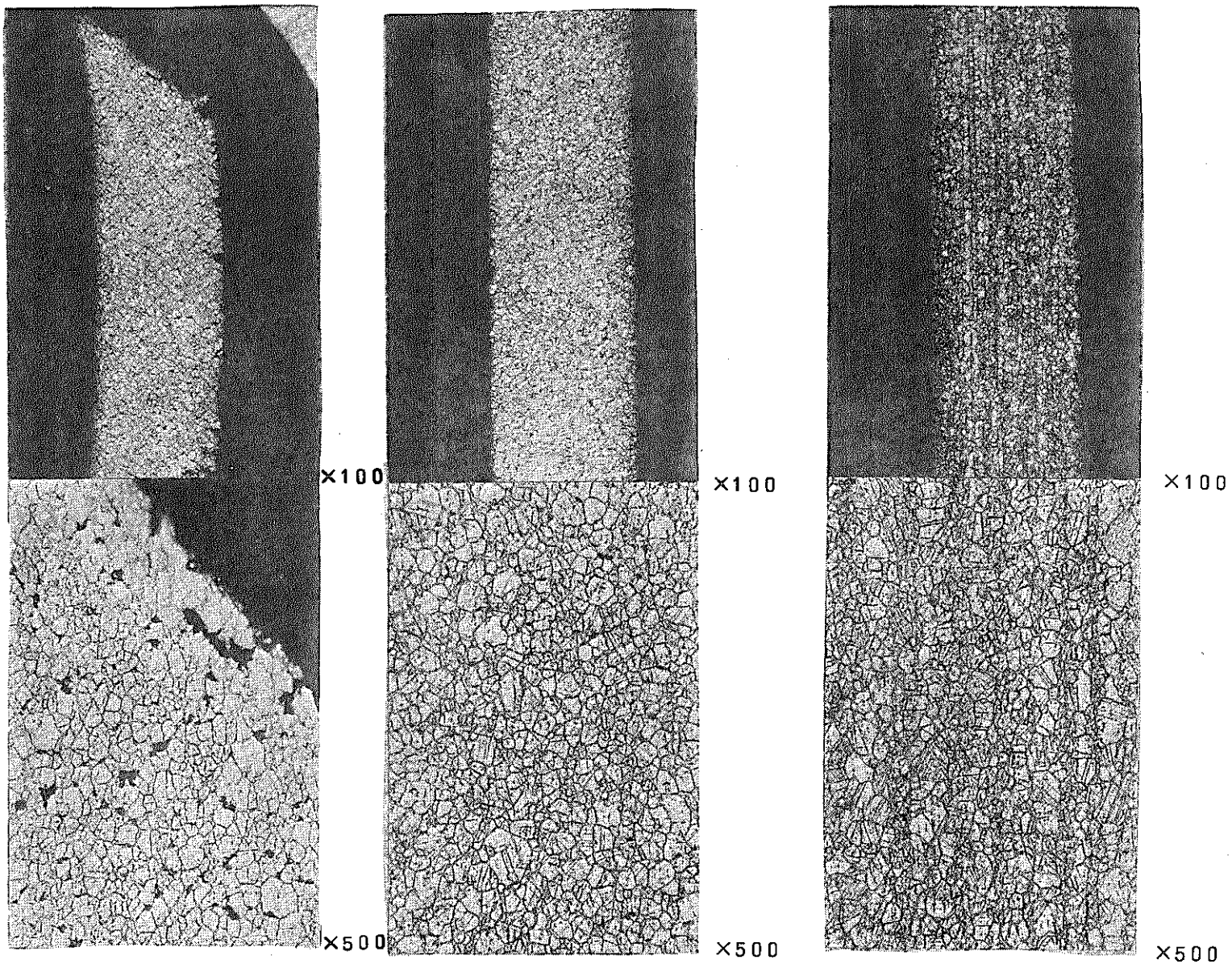



Cross section of ruptured area

Cross section on the reverse side of ruptured area

Longitudinal section of the reverse side of ruptured area

Photo 3-2. Microstructure after Internal Creep Rupture Test (K2706-3 650C 210kg/cm² 3165.5h)

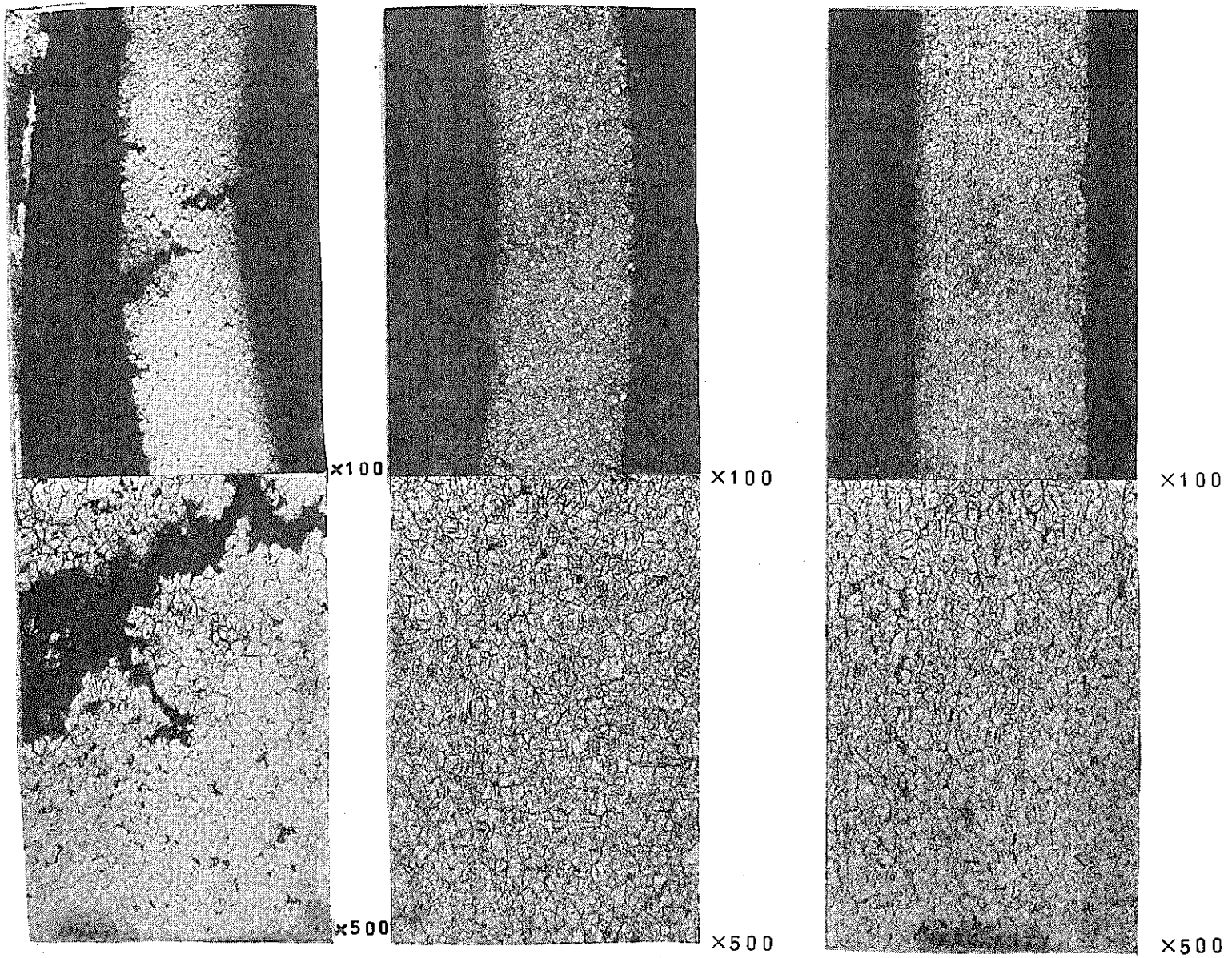



Cross section of ruptured area

Cross section on the reverse side of ruptured area

Longitudinal section of the reverse side of ruptured area

Photo 3-3. Microstructure after Internal Creep Rupture Test (SO528-5 650℃ 170Kg/cm² 1161.0h)




Cross section of ruptured area

Cross section on the reverse side of ruptured area

Longitudinal section of the reverse side of ruptured area

Photo 3-4. Microstructure after Internal Creep Rupture Test (SO523-6 650℃ 140Kg/cm² 1851.0h)

Table 4-1 Results of Hardness Measurement after Internal Pressure Creep Rupture Test.

K2706-3

| Position | Hardness, Hv, 500g | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Longitudinal section | | | | | | Transverse section | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Average | 1 | 2 | 3 | 4 | 5 | Average |
| — 1 | 256 | 256 | 256 | 256 | 253 | 255 | 258 | 249 | 250 | 249 | 256 | 252 |
| — 2 | 243 | 247 | 253 | 247 | 227 | 243 | 251 | 247 | 249 | 245 | 247 | 248 |
| — 3 | 245 | 249 | 243 | 243 | 243 | 245 | 241 | 241 | 249 | 243 | 251 | 245 |
| — 4 | 251 | 247 | 241 | 243 | 243 | 245 | 247 | 249 | 239 | 241 | 243 | 244 |
| — 5 | 238 | 245 | 247 | 251 | 254 | 247 | 241 | 252 | 247 | 243 | 241 | 245 |
| — 6 | 243 | 240 | 247 | 243 | 245 | 244 | 239 | 249 | 227 | 230 | 237 | 236 |
| — 7 | 227 | 247 | 239 | 227 | 241 | 236 | 242 | 223 | 241 | 239 | 243 | 238 |
| — 8 | 236 | 226 | 234 | 234 | 234 | 233 | 239 | 239 | 227 | 239 | 210 | 231 |
| — 9 | 234 | 236 | 243 | 228 | 232 | 235 | 241 | 241 | 242 | 237 | 241 | 240 |
| — 10 | 240 | 243 | 236 | 236 | 236 | 238 | 229 | 234 | 232 | 232 | 243 | 234 |
| — 11 | 271 | 269 | 266 | 269 | 271 | 269 | 264 | 252 | 256 | 256 | 247 | 255 |
| — 12 | 236 | 241 | 243 | 244 | 241 | 241 | 240 | 219 | 245 | 239 | 247 | 238 |
| — 13 | 245 | 245 | 247 | 251 | 245 | 247 | 251 | 238 | 241 | 245 | 243 | 244 |
| — 14 | 252 | 256 | 249 | 249 | 251 | 251 | 249 | 249 | 245 | 251 | 253 | 249 |
| — 15 | 256 | 247 | 247 | 247 | 247 | 249 | 243 | 251 | 247 | 249 | 251 | 248 |
| — 16 | 256 | 258 | 249 | 247 | 253 | 253 | 249 | 273 | 283 | 281 | 254 | 268 |
| — 17 | 254 | 256 | 267 | 256 | 260 | 259 | 270 | 269 | 264 | 266 | 271 | 268 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

Note : Hardness measurement was performed on both longitudinal and transverse sections on the reverse side of the ruptured area at intervals of 10mm in the longitudinal direction.

Table 4-2 Results of Hardness Measurement after Internal Pressure Creep Rupture Test.

S0523-6-1~18

| Position | Hardness, Hv, 500g | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Longitudinal section | | | | | | Transverse section | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Average | 1 | 2 | 3 | 4 | 5 | Average |
| — 1 | 278 | 247 | 236 | 238 | 238 | 247 | 237 | 236 | 239 | 236 | 234 | 236 |
| — 2 | 238 | 243 | 241 | 236 | 239 | 239 | 237 | 243 | 234 | 239 | 234 | 237 |
| — 3 | 239 | 236 | 230 | 232 | 236 | 235 | 236 | 239 | 234 | 239 | 234 | 236 |
| — 4 | 269 | 254 | 253 | 245 | 240 | 252 | 230 | 227 | 230 | 225 | 227 | 228 |
| — 5 | 215 | 234 | 234 | 228 | 228 | 228 | 227 | 220 | 241 | 236 | 236 | 232 |
| — 6 | 212 | 228 | 232 | 226 | 225 | 225 | 230 | 234 | 216 | 216 | 225 | 224 |
| — 7 | 232 | 225 | 223 | 218 | 225 | 225 | 206 | 223 | 220 | 213 | 212 | 215 |
| — 8 | 238 | 234 | 234 | 227 | 226 | 232 | 230 | 229 | 230 | 228 | 230 | 229 |
| — 9 | 218 | 221 | 227 | 221 | 218 | 221 | 221 | 226 | 228 | 232 | 228 | 227 |
| —10 | 232 | 234 | 230 | 234 | 236 | 233 | 239 | 240 | 241 | 234 | 230 | 237 |
| —11 | 228 | 223 | 225 | 220 | 225 | 224 | 228 | 225 | 228 | 207 | 215 | 221 |
| —12 | 227 | 220 | 228 | 229 | 230 | 227 | 228 | 225 | 230 | 227 | 232 | 228 |
| —13 | 228 | 227 | 230 | 232 | 230 | 229 | 225 | 221 | 232 | 230 | 227 | 227 |
| —14 | 254 | 238 | 237 | 232 | 234 | 239 | 225 | 236 | 236 | 220 | 237 | 231 |
| —15 | 258 | 239 | 239 | 230 | 236 | 240 | 232 | 239 | 234 | 210 | 234 | 230 |
| —16 | 232 | 230 | 232 | 228 | 236 | 232 | 241 | 232 | 236 | 228 | 232 | 234 |
| —17 | 230 | 232 | 231 | 236 | 234 | 233 | 234 | 234 | 236 | 240 | 234 | 236 |
| —18 | 239 | 239 | 240 | 240 | 210 | 234 | 236 | 238 | 247 | 240 | 241 | 240 |
| —19 | 240 | 239 | 241 | 249 | 243 | 242 | 247 | 241 | 241 | 237 | 234 | 240 |

Note : Hardness measurement was performed on both longitudinal and transverse sections on the reverse side of the ruptured area at intervals of 10 mm in the longitudinal direction.