PNC TN9410 89-001

SUMMARY OF
STRUCTURAL COMPONENT TEST FOR FBR

January 1989

Power Reactor and Nuclear Fuel Development Corporation

PNC TN9410 89-001

January 1989

SUMMARY OF STRUCTURAL COMPONENT TEST FOR FBR

Katsumi WATASHI*

Akira IMAZU*

ABSTRACT

Many sorts of structural component tests were conducted for the prototype fast breeder reactor "MONJU" with an objective of development of structural design guide for high temperature application, structural integrity assessment method, fabrication-testing guide and in-service inspection guide. This report is composed of many short descriptions of selected structural tests, the test objective, the test method, the test condition and the test result. Structural tests for future large FBRs are also included in this report.

* Oarai Engineering Center , Structural Engineering Section

PNC TN9410 89-001
１９８９年１月

高速炉用構造物試験の概要

渡士　克己*，今津　彰*

要　旨

本資料は高速原型炉“もんじゅ”の高温構造設計基準の開発、構造物の健全性評価手法の開発、製作検査基準の開発および供用期間中検査基準の開発に関連して実施された構造物試験のうち、今後の高速大型炉の開発上有用であると考えられるものについてその試験内容をまとめたものである。また本書には高速大型炉の開発のために現在実施している構造物試験の内容も含まれている。

本書は、時間的な制約から調査範囲を絞らざるを得なかった。今後、継続的な見直しを実施して、構造物試験の集大成版を作成していくつもりである。

＊大洗工学センター、構造工学室

CONTENTS

1. SUMMARY DOCUMENTS

—— List & brief description of available test data and analysis/evaluation results ——

NICKNAME OF TEST FACILITY

TTS ; Thermal Transient test facility for Structures

STST : Small Thermal Shock Test loop

SPTT : Sodium Piping Thermal transient Test loop

SITR : Structural Integrity Test loop for Reactor vessel

TST : Thermal Shock Test loop

ATTF : Air cooled Thermal transient Test Facility

MLT : Multi-Luading Test rig

BCT : Bi-axial Creep test rig

SBT : Structural Buckling Test rig

ATTACHMENT 1

E L B O W

1. ABSTRACT

Elbow is one of the most important structures in FBR plants, not only in safety but also in reliability of plants. Elbow tests have three objectives. The first is to verify computer codes by investigating whether they manage to predict stress and strain behaviors with reasonable accuracy from the view point of protection of associated failures. Secondly, the design criteria can be established based on elbows test data, with aid of associated theoretical analyses and basic material data. Thirdly, safety margin inherent in the design rule can be confirmed in an overall sense for particular failure modes, and the conservatism of the rule can be demonstrated by elbows data.

2. ARTICLE OF ELBOWS TEST

A. LOW-CYCLE FATIGUE
B. CREEP-FATIGUE
C. PLASTIC INSTABILITY
D. CREEP BUCKLING
E. FATIGUE CRACK GROWTH
F. THERMAL AND CREEP RATCHETING

3. SIMPLE DESCRIPTION

A. Low-cycle Fatigue and B. Creep-Fatigue

AB.1 Objective

(1) To confirm conservatism of the design rule for fatigue and creep-fatigue evaluation

(2) To investigate cyclic relaxation behavior and crack pattern

(3) To observe situation of sodium leakage from actual crack and to demonstrate the excellent performance of sodium leakage detectors.

AB.2 Test description

(1) Test equipment and testing procedure

Piping Components Test Rig and Creep-Fatigue Test Rig for Piping Componen ts were used for the test. One end of a specimen was connected to an elec tro-hydraulic actuator and forced displacement with triangular or trapezo idal waveform is applied until crack penetrates through the wall thickness of specimens.

(2) Instrumentation

Measured were load and stroke of an actuator, strain and temperature.

AB.3 Result

Measured (total) strain was split into elastic, plastic and creep components and stresses were calculated by use of constitutive equation. FEM code was used to compute the cyclic elastic-plastic-creep deformation of an elbow. Using components of stresses and strains derived in this way, available criteria for creep-fatigue failure, such as Campbell's method , Manson's method and ASME Code were applied to evaluate the life of piping components. Generally, actual life of elbows is shorter than the estimated by Campbell's and Manson's method, and this implied the life of components is shorter than life of simple small specimens. ASME Code Case gave a reasonably conservative estimation of life of piping components. The ETSDG* provides considerably different approach from ASME Code for creep-fatigue evaluation. The criteria of the ETSDG was also justified by these tests.

* ETSDG : Elevated Temperature Structurol Design Guide for Prototype Fast Breeder Reactor

Similar evaluation to the case of creep-fatigue test in air was made for the life of the specimen tested in sodium. Slightly shorter life was observed in sodium test than that in air test. Excellent performance of the sodium leakage detector developed by PNC has been demonstrated through the application to two tests. Slight corrosion of material was observed because of leaked sodium.

Ref. (1.AB.1) Imazu, A., Miura, R., Nakamura, K., Nagata, T. and Okabayashi, K., Elevated temperature elastic plastic creep test of an elbow subjected to in-plane moment loadings, J. of Pressure Vessel Technology, ASME, 1977, pp. 291-297

Ref. (1.AB.2) Yamasato, K. and Imazu, A. Simplified creep analyses of elbows subjected to three directional moment loadings, Proc. Japan Society of Mechanical Engineers, 1979, No. 790-13, pp. 15-18

Ref. (1.AB.3) Nakanura, K., Ngata, T., Imazu, A., Miura, R. and Okabayashi, K. Creep fatigue test of an elbow subjected to cyclic in-plane moment loading, Proc. 3rd Int. Con. Pressure Vessel Technology, 1977, pp. 787-794

C. PLASTIC INSTABILITY

C.1 OBJECTIVE

(1) To investigate elastic-plastic large deformation and plastic instability

behavior and to compare with creep deformation and creep buckling

(2) To examine the adequacy of limit for primary stresses

C.2 TEST DESCRIPTION

Test specimens are elbows of 12 inches in diameter which were classfied into thick elbows(sch.20s) and thin elbows(sch.10s). Four tests were performed under in-plane bending and one test under out-of-plane bending. Test temperature was 600 ℃.

An electro-hydraulic actuator was conected to one end of a specimen, with the other end fixed to the frame structure, and load(shear force) was applied slowly by contolling the stroke of the actuator which has the maximum stroke of 500 mm. An electric heater was inserted inside the specimens.

C.3 RESULT

The test clarified that the limit for primary stresses provided in ASME Code could not prevent plastic instability in these specific case. Details is shown in Ref.1.4.

Ref.(1.C.1) Imazu,A., Hashimoto,T., Nagata,T. and Sakakibara,Y., Plastic instability test of elbows under in-plane and out-of-plane bending, 6th SMIRT, 1981, E-6/5

Ref.(1.C.2) Imazu,A. and Nakamura,K., Simplified creep buckling analisis of elbows under in-plane bending, 5th SMIRT, 1979,

D. CREEP BUCKLING

D.1 OBJECTIVE

(1) To investigate creep buckling phenomena

(2) To establish the design criteria for creep buckling

D.2 TEST DESCRIPTION

An elbow specimen is with 12 inches outer diameter with sch.10s. Load is kept constant for a long period at 600 ℃ by use of deadweight. After steady state deformation is reached, load level is increased in some cases. Three tests on elbows and one test on a straight pipe were completed.

D.3 RESULT

Two kinds of simplified inelastic analysis program were developed for predicting creep buckling behavior of elbows subject to in-plane closing moment. The validity of these programs for design purpose was demonstrated by comparing with experimental data. The effects of various parameters were evaluated.

E. FATIGUE CRACK GROWTH TEST

E.1 OBJECTIVE

Objective is to demonstrate experimentally that downcomer elbow of the piping system used in Japanese prototype FBR will be subjected to no significant low-cycle fatigue damage during design life, even if it is posturated that this component has several flaws at the unfavorable locations with respect to stress condition and material property prior to operation.

E.2 TEST DESCRIPTION

Four test specimens made of SUS 304 were fabricated. Two specimens have the same configuration of 24 inches in outer diameter and 9.5 mm in thickness, and the other two specimens 15.1 mm in thickness. In-plane fatigue loading corresponding to 3 S_m was applied to the specimen at room temperature and 400 ℃. The tests were continued to penetration.

E.3 RESULT

The test result showed that stable crack growth caused finally moderate penetration. An analytically predicted results based on elastic fracture mechanics agreed well with experimentally observed results from beach marks.

1.2 Sakakibara,Y.,Okabayashi,K.,Imazu,A.and Nagata,T.,Fatyigue crack propagation from surface flaw of elbow,6th SMIRT,1981,E-7/3

F. THERMAL AND CREEP RATCHETING

F.1 OBJECTIVE

(1) To evaluate experimentally thermal and creep ratcheting behavior

F.2 TEST DESCRIPTION

A thermal ratcheting tests , in which specimens made of SUS 304 and 2.25Cr-1.0Mo steel elbows were subjected to constant axial loads and cyclic thermal transient caused by sodium temperature change, was carried out in SPTT. Specimens configurations are shown in Fig.1.F.1. In SUS 304 elbows tests, combined loads of nine levels of axial force and one thermal transient condition of the maximum temperature 550 ℃ and the minimum temperature 350℃ were applied to the specimen. In 2.25Cr-1.0Mo steel elbow tests, combined loads of thirteen levels of axial force and one thermal transient condition of the maximum temperature 550℃ and the minimum temperature 250℃ were applied to the specimen. The measured were temperatures of sodium and specimen and progressive deformation of elbow cross section.

Creep ratcheting tests were conducted using tube shaped specimens with 86 mm in outer diameter and 10 mm in thickness as shown in Fig. 1. F. 2. Test conditions were such that two axial forces, namely 6 kgf/mm ^{2} and 8 kgf/mm ^{2}, and three thermal transient conditions of 300 ℃, 400 ℃ and 400℃ in the minimum temperature under constant maximum temperature of 600℃ during one week.

F. 3 RESULT

Thermal ratcheting occured in the elbow model under the conbination of constant in-plane load and cyclic thermal transient load. Deformation increments per one cycle became smaller with cycles and they saturated to constant values. Instantaneous plastic and transient ratcheting deformations were increased greatly with external loads but steady state ratcheting rates were not so much. In-plane bending deformations progressed in the regions of elbow side, and longitudinal deformation progressed in±30° region from elbow sides. These deformations causes incremental deformation of whole elbow. Ratchetting conditions, estimated by ASME Code Case N-47, were very conservative in comparison with experimental results. Using x parameter, which defined from equivalent stress at middle surface at ±30° from elbow sides caused by in-plane load, and y parameter, which defined from the maximum thermal stress calculated by moment equivalent linear temperature distribution, it is presumed fairly well by Bree's diagram whether ratcheting occurs or not in a elbow. The initiation condition for ratcheting is determined conservatively, if X and Y parameter are used in accordance with the 'ETSDG'.

The results of creep ratcheting test showed that ratcheting deformation due to cyclic thermal transient and creep deformation under high temperature holding time appeared in all tests. The results of thermal elastic-plastic-creep analyses by FEM agreed with the test results quite well. It was found that 'Strain Limit' in 'ETSDG' was conservative.

Ref. (1. F. 1) Ueda, M., Kanou, T. and Yoshitoshi, S., Thermal ratchetting criteria and behavior of pipingelbows, Proc. 5th ICPVT Part-1, pp. 16-26

DATA LIST OF PIPING ELBOW

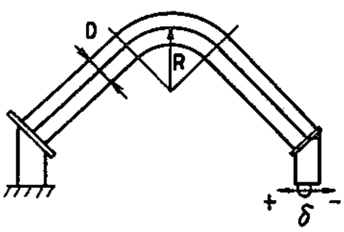
1. Test Item and Number of Test Models

Test Item		Number of Test Models				
		3[B] ELBOW	6[B] ELBOW	12[B] ELBOW	24[B] ELBOW	Total
A	Low-cycle Fatigue		15	17		32
B	Creep-Fatigue		11	10		21
C	Plastic Instability			6		6
D	Creep Buckling			6		6
E	Fatigue Crack Growth			2	4	6
F	Thermal Ratchetting	3			1	4

2. Test Condition and Test Specimen

Table 1-A-1 Test Specimen and Condition for Low-cycle Fatigue

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
C-1-1	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	Room Tem-perature	In-Plane Bending	Displacement $\delta = \pm 30$mm TH = 10 sec
C-1-2	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement $\delta = \pm 30$mm TH = 10 sec
C-1-3	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	Room Tem-perature	In-Plane Bending	Displacement $\delta = \pm 30$mm TH = 10 sec
C-2-1	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	Room Tem-perature	In-Plane Bending	Displacement $\varepsilon = 0 \sim -47$ mm TH = 10 sec
C-2-2	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement $\delta = 0 \sim -48$ mm TH = 10 sec
C-3-1	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	Room Tem-perature	In-Plane Bending	Displacement $\delta = 0 \sim -46$ mm TH = 10 sec
C-3-2	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement $\delta = 0 \sim -46$ mm TH = 10 sec
D-1-1	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	650	In-Plane Bending	Displacement $\delta = \pm 35$mm TH = 10 sec
D-1-2	SUS 304	165.2^{D}, 3.4^{t} 228.6^{R}	650	In-Plane Bending	Displacement $\delta = \pm 21$mm TH = 10 sec



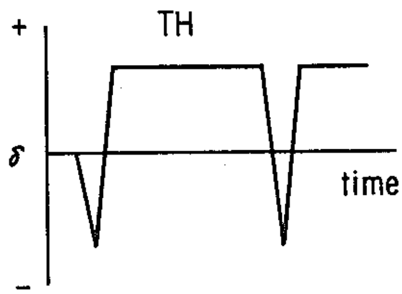
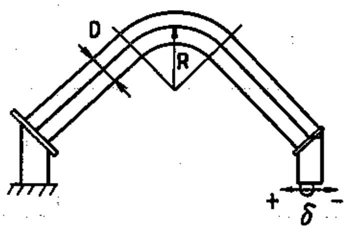


Table 1-A-2 Test Specimen and Condition for Low-cycle Fatigue

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
D-1-3	SUS 304	165.2 D, 3.4 t 228.6 R	650	In-Plane Bending	Displacement δ =±14mm TH = 10 sec
C-1-4	SUS 304	165.2 D, 3.4 t 228.6 R	650	In-Plane Bending	Displacement δ =±20mm TH = 10 sec
E-1-2	SUS 304	165.2 D, 3.4 t 228.6 R	600	In-Plane Bending	Displacement δ =±35mm TH = 10 sec
E-1-3	SUS 304	165.2 D, 3.4 t 228.6 R	600	In-Plane Bending	Displacement δ =±13mm TH = 10 sec
F-1-2	SUS 304	165.2 D, 3.4 t 228.6 R	550	In-Plane Bending	Displacement δ =±20mm TH = 10 sec
F-1-3	SUS 304	165.2 D, 3.4 t 228.6 R	550	In-Plane Bending	Displacement δ =± 8mm TH = 10 sec



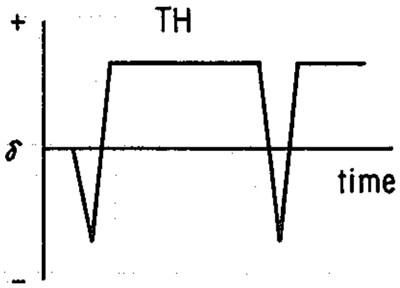
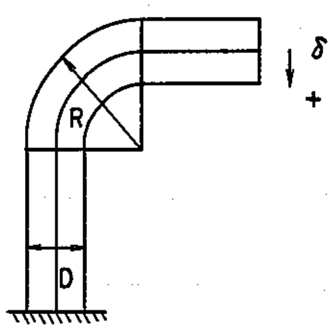


Table 1-A-3 Test Specimen and Condition for Low-cycle Fatigue

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
BE-3	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	550	In-Plane Bending	Load M = 2.5 t-m TH = 0 sec
BE-4	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	Room Temperature	In-Plane Bending	Load M = 4.65t-m TH = 0 sec
BE-5	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	Room Temperature	In-Plane Bending	Displacement δ = ±40mm TH = 0 sec
BE-7	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	Room Temperature	In-Plane Bending	Displacement δ = ±60mm TH = 0 sec
BE-9	SUS 304	318.5 ^{D}, 10.3 ^{t} 457.2 ^{R}	Room Temperature	In-Plane Bending	Displacement δ = ±30mm TH = 0 sec
BE-10	SUS 304	318.5 ^{D}, 10.3 ^{t} 457.2 ^{R}	Room Temperature	In-Plane Bending	Displacement δ = ±25mm TH = 0 sec
BE-11	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	550	In-Plane Bending	Displacement δ = ±30mm TH = 0 sec
BE-12	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	550	In-Plane Bending	Displacement δ = ±23mm TH = 0 sec



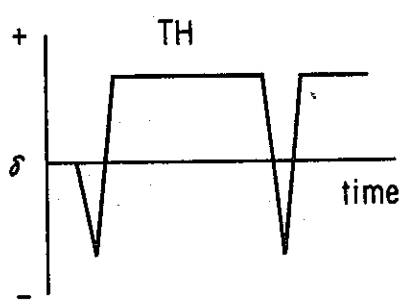
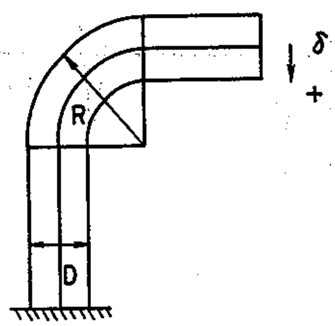


Table 1-A-4 Test Specimen and Condition for Low-cycle Fatigue

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper- ature(℃)	Loading Mode	Control
BE-13	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	Room Tem- perature	Out of Plane Bending	Displacement δ =±30mm TH = 0 sec
BE-14	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	Room Tem- perature	Out of Plane Bending	Displacement δ =±30mm TH = 0 sec
BE-16	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	Room Tem- perature	In-Plane Bending	Displacement δ =0～54 mm TH = 0 sec
BE-101	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±28mm TH = 0 sec
BE-102	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±39mm TH = 0 sec
BE-203	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±30mm TH = 0 sec
BE-206	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±30mm TH = 0 sec
BE-207	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	650	In-Plane Bending	Displacement δ =±30mm TH = 0 sec
BE-208	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±35mm TH = 0 sec



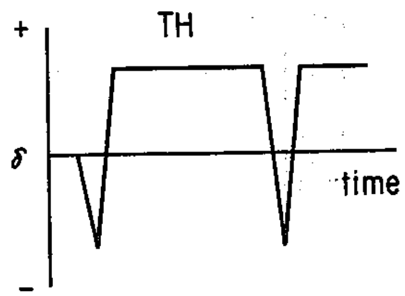
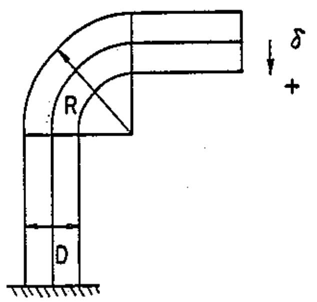


Table 1-B-1 Test Specimen and Condition for Creep Fatigue

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
D-2-2	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	650	In-Plane Bending	Displacement δ = ±25mm TH = 10 min
D-3-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	650	In-Plane Bending	Displacement δ = ±35mm TH = 100 min
D-4-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	650	In-Plane Bending	Displacement δ = ±35mm TH = 24 hr
E-2-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±25mm TH = 10 min
E-2-2	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±15mm TH = 10 min
E-2-3	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±10mm TH = 10 min
E-3-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±35mm TH = 100 min
E-3-2	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±34mm TH = 100 min
E-3-3	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±15mm TH = 100 min
E-4-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	600	In-Plane Bending	Displacement δ = ±35mm TH = 24 hr
F-4-1	SUS 304	165.2^{D} , 3.4^{t} 228.6^{R}	550	In-Plane Bending	Displacement δ = ±35mm TH = 24 hr



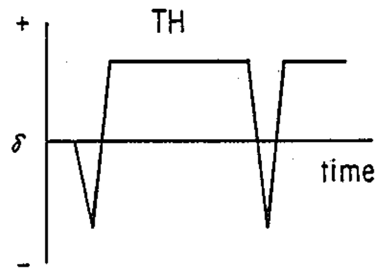
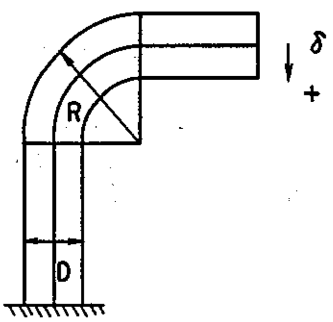


Table 1-B-2 Test Specimen and Condition for Creep Fatigue

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temperature (℃)	Loading Mode	Control
BE-103	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±37mm TH=1000 sec
BE-104	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±37mm TH=1000 sec
BE-105	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±47mm TH=1000 sec
BE-106	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±53mm TH=3600 sec
BE-201	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±30mm TH= 100 sec
BE-202	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±30mm TH= 100 sec
BE-204	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±30mm TH=1000 sec
BE-205	SUS 304	318.5^{D} , 6.5^{t} 457.2^{R}	650	In-Plane Bending	Displacement δ =±30mm TH=3600 sec
BE-209	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	600	In-Plane Bending	Displacement δ =±35mm TH=3600 sec
BE-210	SUS 304	318.5^{D} , 4.5^{t} 457.2^{R}	650	In-Plane Bending	Displacement δ =±35mm TH=3600 sec



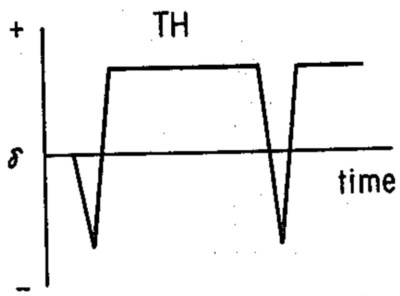


Table 1-C Test Specimen and Condition for Plastic Instability

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
BE-301	Carbon Steel	318.5 D, 6.5 t 457.2 R	Room Tem-perature	In-Plane Bending	Displacement Rate 0.1 mm/sec
BE-305	SUS 304	318.5 D, 6.5 t 457.2 R	600	In-Plane Bending	Displacement Rate 0.1 mm/sec
BE-306	SUS 304	318.5 D, 6.5 t 457.2 R	600	In-Plane Bending	Displacement Rate 0.1 mm/sec
BE-308 A	SUS 304	318.5 D, 4.5 t 457.2 R	600	In-Plane Bending	Displacement Rate 0.1 mm/sec
BE-308 B	SUS 304	318.5 D, 4.5 t 457.2 R	600	In-Plane Bending	Displacement Rate 0.1 mm/sec
BE-309	SUS 304	318.5 D, 4.5 t 457.2 R	600	Out of plane Bending	Displacement Rate 0.1 mm/sec

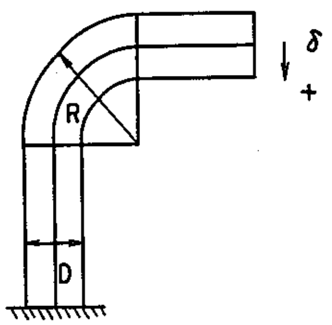


Table 1-D Test Specimen and Condition for Creep Buckling

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
BE-302	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 615～1382kg
BE-303	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 700～3170kg
BE-304	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 1497～1738kg
BE-307	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 1500kg
BE-310	SUS 304	318.5 ^{D}, 4.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 448～767kg
BE-311	SUS 304	318.5 ^{D}, 4.5 ^{t} 457.2 ^{R}	600	In-Plane Bending	Load dead weight 448～767kg

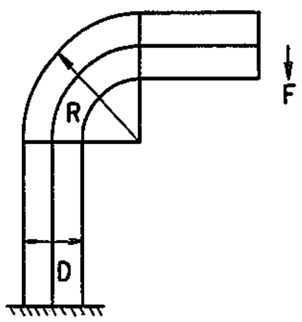
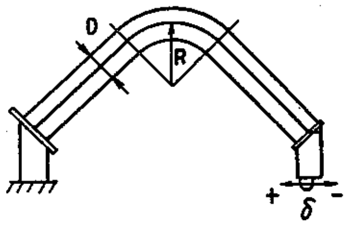


Table 1-E Test Specimen and Condition for Fatigue Crack Growth

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
BE-6	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R} (1.5 ^{a}, 45.0^{b})	550	In-Plane Bending	Displacement δ =± 40mm TH=1000 sec
BE-8	SUS 304	318.5 ^{D}, 6.5 ^{t} 457.2 ^{R} (1.5 ^{a}, 35.0^{b})	Room Tem-perature	In-Plane Bending	Displacement δ =± 13mm TH=1000 sec
BE-501	SUS 304	615.0 ^{D}, 10.1 ^{t} 914.4 ^{R} (3.4 ^{a}, 25.6^{b})	Room Tem-perature	In-Plane Bending	Displacement δ = 0 ～44mm 3Sm, TH=0sec
BE-502	SUS 304	615.0 ^{D}, 10.1 ^{t} 914.4 ^{R} (3.3 ^{a}, 27.0^{b})	400	In-Plane Bending	Displacement δ = 0 ～40mm 3Sm, TH=0sec
BE-503	SUS 304	612.4 ^{D}, 15.1 ^{t} 915.5 ^{R} (3.2 ^{a}, 44.0^{b})	Room Tem-perature	In-Plane Bending	Displacement δ = 0 ～40mm 3Sm, TH=0sec
BE-504	SUS 304	612.4 ^{D}, 15.1 ^{t} 915.5 ^{R} (3.3 ^{a}, 41.4^{b})	400	In-Plane Bending	Displacement δ = 0 ～35mm 3Sm, TH=0sec



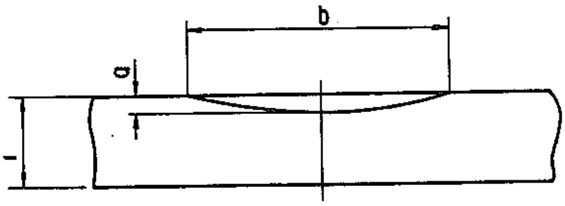
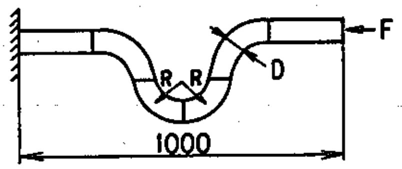


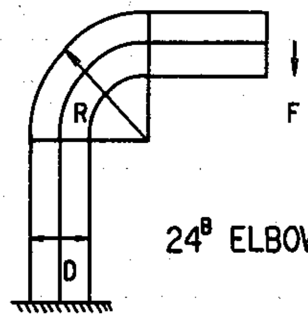
Table 1-F Test Specimen and Condition for Thermal Ratchetting

(PIPING ELBOW)

Test Number	Specification of Test Specimen		Test Condition		
	Material	Dimension (mm)	Temperature (℃)	Dead Load (kg)	Loading Cycle
ETR-1	SUS 304	89.0 ^{D} , 4.5 ^{t} 115.0 ^{R}	550 / 350 ΔT=200	0 ~1800 (13step)	100cycle ×13 steps
TRE-1	STPA24 (2.25Cr-1Mo)	89.0 ^{D} , 5.0 ^{t} 115.0 ^{R}	550 / 350 ΔT=200	0 ~3200 (13step)	100cycle ×13 steps
TRE-3	STPA24 (2.25Cr-1Mo)	89.0 ^{D} , 5.0 ^{t} 115.0 ^{R}	550 / 350 ΔT=200	0 ~3200 (13step)	100cycle ×13 steps
ETC-1	SUS 304	609.6 ^{D} , 14.3 ^{t} 914.4 ^{R}	500 / 260 ΔT=240	~27000 (8step)	5 ~20cycle × 8 steps



6^B ELBOW



24^B ELBOW

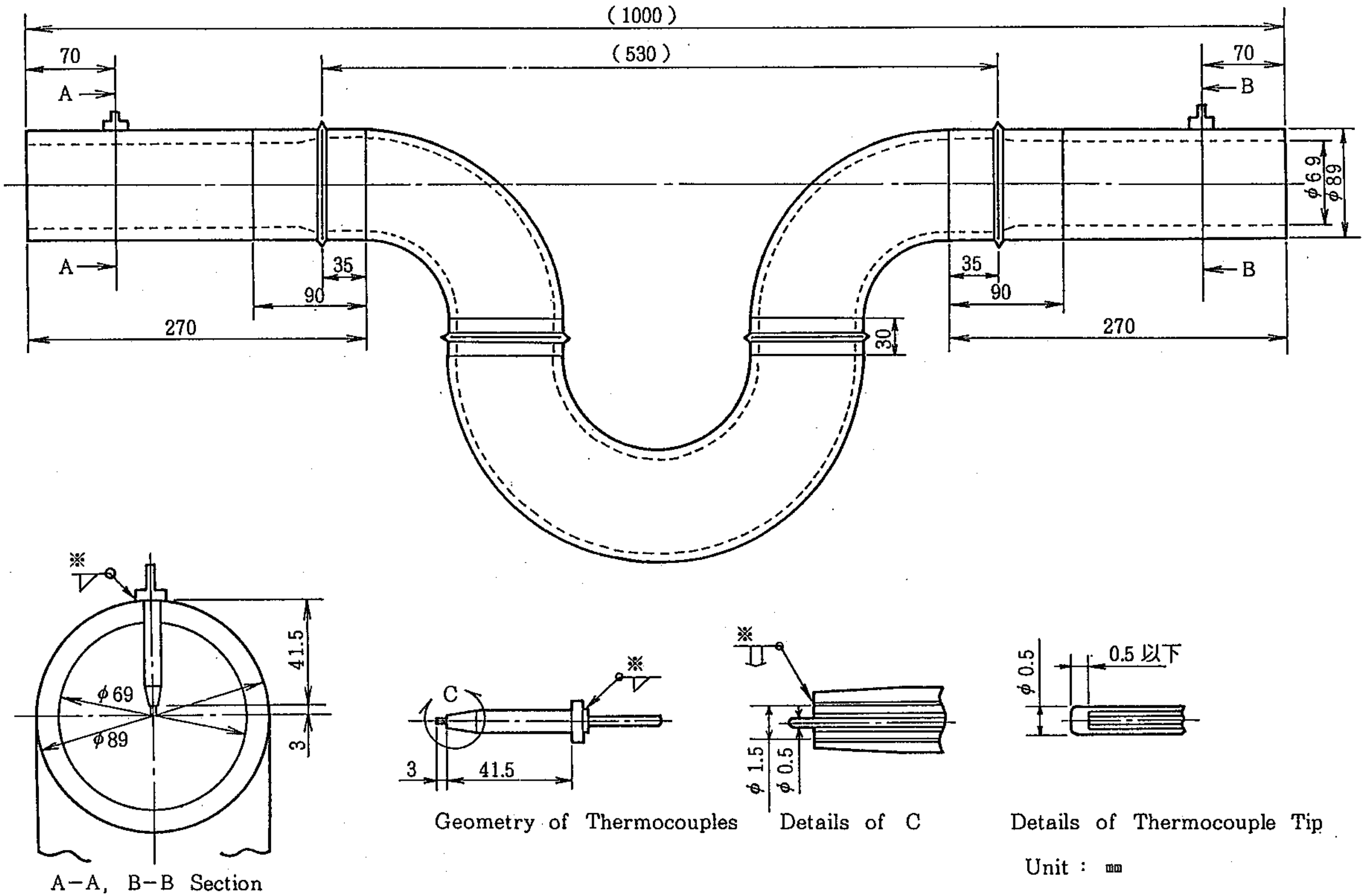


Fig1.F.1 Configuration of Test Specimen and Thermocouples

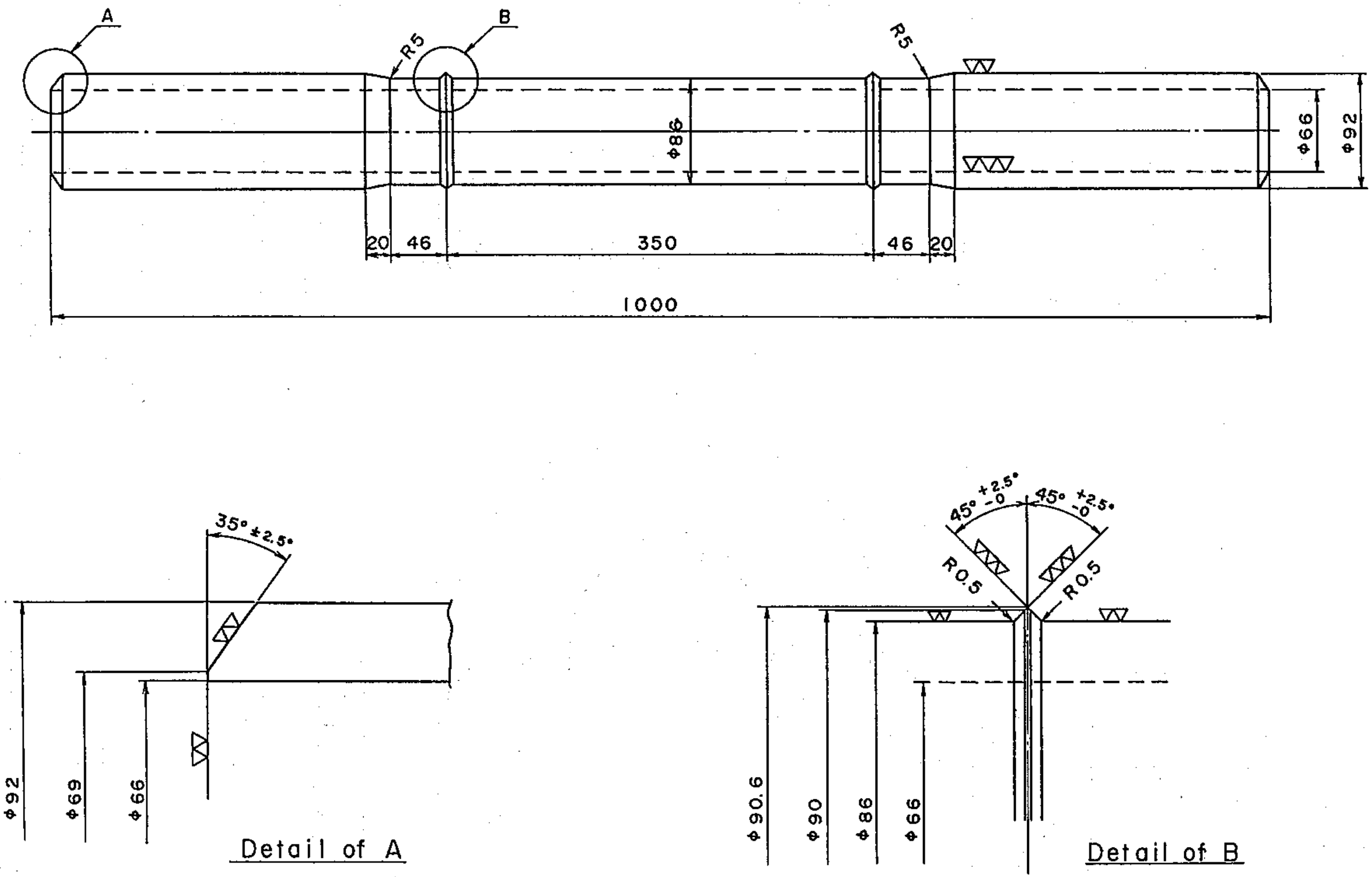


Fig 1.F.2　Configuration of Test Specimen

ATTACHMENT 2

TEES

1. ABSTRACT

Design method and design evaluation method of tees were developed based on a series of tees test outlined here. Elastic deformations test, fatigue terst at high temperature and plastic collapse test clarified adequate flexibility, stress indeces such as C_2, K_2 and B_2, and stress concentration factorK_e'.

Tees with small diameter branch were tested about the same items described above. Adequate flexibility, stress indeces and strain concentration factor were also developed.

2. ARTICLES OF TEES TEST

A. ELASTIC BEHAVIOR
B. LOW-CYCLE FATIGUE
C. PLASTIC INSTABILITY
D. CREEP BUCKLING
E. TEES WITH SMALL DIAMETER BRANCH

3. SIMPLE DESCRIPTION

Test models and conditions are listed in Table 2.A.1 ~2.E.2.

3.A ELASTIC BEHAVIOR

A.1 OBJECTIVE

The objectives of the tests are to validate the stresses indeces and other factors of the simplified design analysis methods for pipings provided in the design codes such as ASME Boiler and Pressure Vessel Code Sec.Ⅲ and MITI Notice No.501, and to investiugate the basic deformation behavior of tees.

A.2 TEST DESCRIPTION

The test specimens are a 22^B - 22^B -22 ^{B} tee and a 22^B - 22^B -12 ^{B} tees. Five types of loadings were applied to the former, and seven to the later. Furthermore, stress analysis were performed for the test conditions by finite element method.

A.3 RESULT

It turned out that C_2 index is conservative for all loading conditions if they were evaluated based on nominal values of the configuration of the tees. K_2 index determined by calculation is nearly 1.0, which is provided in the design code. Flexibility factor is more than zero for all cases. This means tees are more flexible than the expected modelling by the ASME Sec. III.

Moreover the deformation mechanism of tees were made clear by the experiments and analyses. Cares must be directed to their locations near welded joints between tees and joining branch pipes for the stress riser due to structural discontinuity, in case of in-plane bending to branch pipes.

B LOW-CYCLE FATIGUE

B.1 OBJECTIVE

The tests have the objectives of observing the fatigue failure modes, fatigue life and strain behavior of tees at high temperature, and of verifiing the creep-fatigue evaluation method by elastic analysis in the ETSDG.

B.2 TEST DESCRIPTION

Two sorts of tees, 22^B run pipe-12^B branch pipe and 22^B run pipe-22^B branch pipe, made of SUS 304, were tested at 600℃. A cyclic out-of-plane bending was continued until fatigue crack penetrated the wall.

B.3 RESULT

Fatigue cracks appeared at the intersection of the run pipe and the branch pipe, and grew from the outer surface to the inner surface in the thickness. The crack length on the outer surface was 5.4 to 7.3 times of the wall thickness at the cycle of the penetration through the wall. Fatigue lives of the present tests were nearly equal to those of uniaxial test data under tension-compression loading of the same material as the tees.

A large safety margin was incorporated in the ETSDG for fatigue. The stress index C_2 and the strain concentration factor defined in ETSDG were found to be copnservative values.

C PLASTIC COLLAPSE

C.1 OBJECTIVE

The objective of the tests is to demonstrate experimentary that the adequate design margin is incorporated for the limits for primary stresses of the ETSDG.

C.2 TEST DESCRIPTION

Out-of-plane bending to branch pipe was applied to 22^B run-12 ^{B} branch and 22^B run -22 ^{B} branch tee at 600 ℃.

C.3 RESULT

It was confirmed that the B_2 index was conservative. As for the methods for determining the collapse load experimentally, it was made clear that the mathod in ASME Code was the most appropriate one among the four methods considered here.

D CREEP BUCKLING

D.1 OBJECTIVE

In piping design of the ETSDG, design engineers need not to evaluate about creep buckling if long range primary stress is low. The objective of this test is to validate it about tees.

D.2 TEST DESCRIPTION

A tested model was a 22^B run-12 ^{B} branch tee. The branch was subjected to step up out-of plane bending with hold time of 1,000 ~1,500 hrs in each stepat 600℃. Out-of plane buckling was occured at 7,341 hrs of the sum of creep time.

D.3 RESULT

E TEES WITH SMALL DIAMETER BRANCH

E.1 OBJECTIVE

Tees with small branch pipe are used for the secondary pipings of the prototype FBR in Japan. Objectives are the same as mentioned above. Experimental works and theoretical analyses were conducted to investigate elastic stress distribution of the tees.

E.2 TEST DESCRIPTION

Test specimens with dimensions of 22^B - 22^B -6^B, 22^B - 22^B -3^B and 22^B - 22^B -2^B were adopted for elastic deformation test. In-plane and out-of-plane moments were applied to branch pipes of the specimens at room temperature. The analyses were conducted for the 22^B - 22^B -3^B model subject to out-of-plane moment for the branch pipe.

The test models are the same as adopted in elastic deformation tests. The tests were performed under displacement controlled condition ,subject to out-of-plane moment loadings at room temperature and 600℃. The tests were continued until cracks penetrate through the wall- thickness.

The test model is a 22 ^{B} - 22 ^{B} -3^{B} tees and is subjected to out0of-plane moment at the branch at room temperature.

E.3 RESULT

It was turned out from elastic deformation tests and analyses that C_2 index gave two or five times larger values than those obtained from the tests and analyses, K_2 index derived from the analyses was 1.04 , which valid K_2 = 1.0 provided in the ETSDG. Flexibility factor obtained by the tests was one half of that given in the ETSDG. It was clarified that strain concentration is large for smaller branch pipes and in-plane moment loadings rather than out-of plane loadings.

The fatigue test results revealed that strain concentration factor provided by ETSDG had 1.5 to 3 times larger than the experimental values. It was clarified that the ETSDG gave the safety margin of 100 or more for low cycle fatigue failure, if C_2 indeces derived from the experiments were used,and much more safety margin if C_2 index provided by the ETSDG were adopted. The lives of tees were nearly the same as those of the materials. Cracks appeared at the intersection where strain concentration occurs. Cracks initiated on outer surfaces, grew through the walls only from outer surfaces,and penetrated. No crack initiated on inner surfaces and weld joints.

In the collapse test, the deformation concentrated at the intersection of the tees and plastic instability were not observed under the present test condition, though local yielding phenomina occured. The limit for primary stresses were conservative , when b_{2B} was used both butt welding tees and for branch conections.This is true for b_{2B} based on both nominal and measured values of the dimensions of the pipes. Furthermore, the limits for primary stresses based on buckling load were compared with the experimental results. It was found that the method described in ASME Sec. Ⅲ was the most appropriate.

Table 2-A-1 Test Specimen and Condition for Elastic Behavior Test

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temperature(℃)	Loading Mode	Control
TE-002	SUS 304	Run pipe $558.5^{OD} - 9.5^{t}$ Branch pipe $318.5^{OD} - 6.5^{t}$ (2 Seams)	Room Temperature	In-Plane, Out-of-Plane & Torsional Moment	Displacement applied at Run & Branch Pipe
TE-202	SUS 304	Run pipe $558.5^{OD} - 9.5^{t}$ Branch pipe $318.5^{OD} - 6.5^{t}$ (1 Seam)	Room Temperature	In-Plane, Out-of-Plane & Torsional Moment	Displacement applied at Run & Branch Pipe
TE-011	SUS 304	Run pipe $558.5^{OD} - 9.5^{t}$ Branch pipe $558.5^{OD} - 9.5^{t}$ (1 Seam)	Room Temperature	In-Plane, Out-of-Plane & Torsional Moment	Displacement applied at Run & Branch Pipe

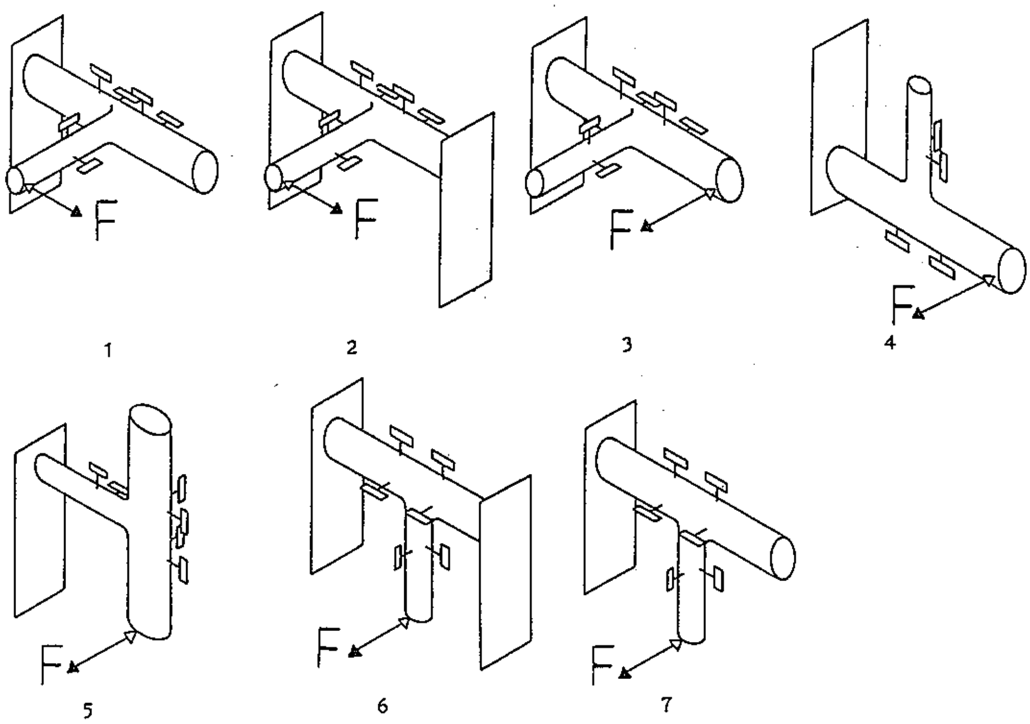


Table 2-B-1 Test Specimen and Condition for Low-cycle Fatigue

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
TE-002	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 318.5 ^{OD} - 6.5 ^{t} (2 Seams)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 28.0$mm applied at Branch Pipe
TE-003	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 318.5 ^{OD} - 6.5 ^{t} (2 Seams)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 23.8$mm applied at Branch Pipe
TB-005	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 318.5 ^{OD} - 6.5 ^{t} (2 Seams)	Room Tem-perature	In-Plane Bending Moment	Displacement $\delta = \pm 33.5$mm applied at Branch Pipe
TB-011	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 558.5 ^{OD} - 9.5 ^{t} (1 Seam)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 19.0$mm applied at Branch Pipe

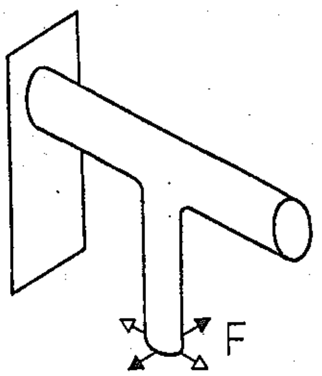


Table 2-B-2 Test Specimen and Condition for Low-cycle Fatigue

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
TE-201	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 318.5 ^{OD} - 6.5 ^{t} (2 Seams)	600	Out-of-Plane Bending Moment	Displacement $\delta = \pm 32.0$mm applied at Branch Pipe
TE-202	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 318.5 ^{OD} - 6.5 ^{t} (1 Seam)	600	Out-of-Plane Bending Moment	Displacement $\delta = \pm 23.5$mm applied at Branch Pipe
TE-211	SUS 304	Run pipe 558.5 ^{OD} - 9.5 ^{t} Branch pipe 558.5 ^{OD} - 9.5 ^{t} (1 Seam)	600	Out-of-Plane Bending Moment	Displacement $\delta = \pm 19.0$mm applied at Branch Pipe

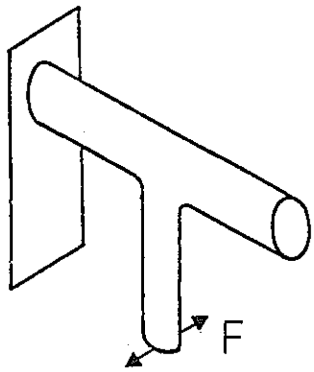


Table 2-B-3 Test Specimen and Condition for Low-cycle Fatigue

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
BR-003	SUS 304	Run pipe 318.5 ^{OD} -10.3 ^{t} Branch pipe 165.2 ^{OD} - 7.1 ^{t}	Room Tem-perature	In-Plane Bending Moment	Force F= ±1.0ton applied at Branch Pipe
BR-004	SUS 304	Run pipe 318.5 ^{OD} -10.3 ^{t} Branch pipe 165.2 ^{OD} - 7.1 ^{t}	Room Tem-perature	In-Plane Bending Moment	Force F=0～1.0ton applied at Branch Pipe
BR-005	SUS 304	Run pipe 318.5 ^{OD} -10.3 ^{t} Branch pipe 216.3 ^{OD} - 8.2 ^{t}	Room Tem-perature	In-Plane Bending Moment	Force F= ±2.0ton applied at Branch Pipe
BR-006	SUS 304	Run pipe 318.5 ^{OD} -10.3 ^{t} Branch pipe 216.3 ^{OD} - 8.2 ^{t}	550	In-Plane Bending Moment	Displacement δ = ±4.5 ～ ±7.5 mm applied at Branch Pipe

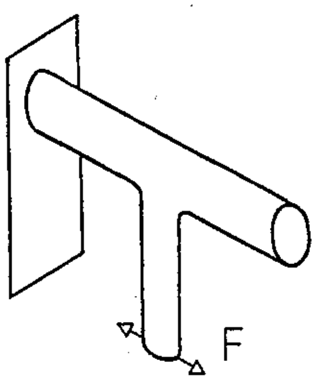


Table 2-C-1 Test Specimen and Condition for Plastic Instability

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
TE-301	SUS 304	Run pipe 558.5 ^{OD} , 9.5 ^{t} Branch pipe 318.5 ^{OD} , 6.5 ^{t} (2 Seams)	600	Out-of-Plane Bending Moment	Displacement Rate 0.28mm/sec at Branch Pipe
TE-311	SUS 304	Run pipe 558.5 ^{OD} , 9.5 ^{t} Branch pipe 558.5 ^{OD} , 9.5 ^{t} (1 Seam)	600	Out-of-Plane Bending Moment	Displacement Rate 0.28mm/sec at Branch Pipe

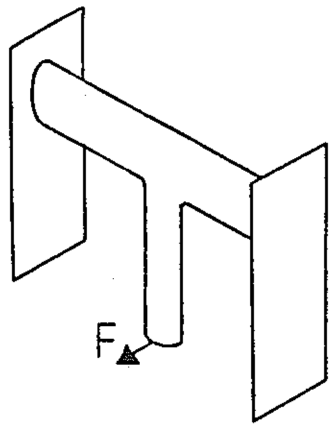


Table 2-D-1 Test Specimen and Condition for Creep Buckling

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temperature(℃)	Loading Mode	Control
TE-302	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 318.5 ^{OD}, 6.5 ^{t} (2 Seams)	600	Out-of-Plane Bending Moment (4 step)	Dead Weight W=2000~ 5800 kgf at Branch Pipe
TE-312	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 558.5 ^{OD}, 9.5 ^{t} (1 Seam)	600	Out-of-Plane Bending Moment (6 step)	Dead Weight W=6200~ 16100 kgf at Branch Pipe

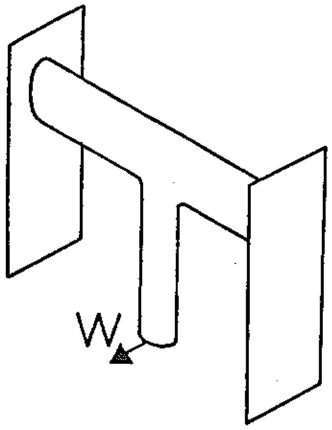


Table 2-E-1 Test Specimen and Condition for Tees With Small Diameter Branch

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
TE-31A (Elastic Behabior)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 165.2 ^{OD}, 7.1 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane & In-Plane Bend-ing Moment	Force (in-elastic Range) at Branch Pipe
BR-31B (Elastic Behabior)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 60.5 ^{OD}, 3.9 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane & In-Plane Bend-ing Moment	Force (in-elastic Range) at Branch Pipe
TE-32 (Elastic Behabior)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane & In-Plane Bend-ing Moment	Force (in-elastic Range) at Branch Pipe
TE-33 (Elastic Behabior)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane & In-Plane Bend-ing Moment	Force (in-elastic Range) at Branch Pipe
TE-34 (Elastic Behabior)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane & In-Plane Bend-ing Moment	Force (in-elastic Range) at Branch Pipe

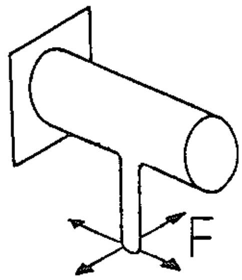
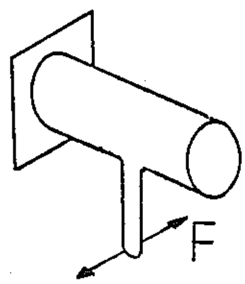


Table 2-E-2 Test Specimen and Condition for Tees With Small Diameter Branch

Test Number	Specification of Test Specimen		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
TE-31A (Low-cycle Fatigue)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 165.2 ^{OD}, 7.1 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 12.5$mm at Branch Pipe
TE-31B (Low-cycle Fatigue)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 60.5 ^{OD}, 3.9 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 18.0$mm at Branch Pipe
TE-32 (Low-cycle Fatigue)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement $\delta = \pm 15.0$mm at Branch Pipe
TE-33 (Plastic Instability)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	Room Tem-perature	Out-of-Plane Bending Moment	Displacement Rate 0.1mm/sec at Branch Pipe
TE-34 (Low-cycle Fatigue)	SUS 304	Run pipe 558.5 ^{OD}, 9.5 ^{t} Branch pipe 89.1 ^{OD}, 5.5 ^{t} (Seamless)	600	Out-of-Plane Bending Moment	Displacement $\delta = \pm 12.0$mm at Branch Pipe



ATTACHMENT 3

PIPING SYSTEM MODEL TEST

1. ABSTRACT

In piping systems operated at high temperature, a strain is accumulated at a relatively weak portion in the piping due to stress redistribution though thermal expansion caused the stresses. So stress classfication criterion and strain increment evaluation method are needed for high temperature structural design evaluation. These method , which describes in the ETSDG, were developed based on the piping system model test.

2. ARTICLES OF PIPING SYSTEM MODEL TEST

A. SIMPLE SYSTEM TEST

B. SCALE DOWN MODEL TEST OF HOT LEG PIPING OF 'MONJU'

3. SHORT DESCRIPTION

A. SIMPLE SYSTEM TEST

A.1 OBJECTIVE

(1) To investigate elastic follow-up behavior of simple piping system

(2) To develop simplified inelastic evaluation method of elastic follow-up

A.2 TEST DESCRIPTION

A test model consists of an elbow of 12 ^{B} sch 20 and a long straight pipe with small diameter as shown in Fig.3.A.1. This test is named EF-301. The prescribed displacement was applied to one end of the assembly by screw mechanism and it was maintained constant throughout the test. An elecrtric heater was installed inside the model. Table 3.A.1 shows the test condition of EF-301.The initially forced displacement was kept for 4,100 hrs. Test temperature was 600℃.

A.3 RESULT

The test result were compared with numerical computation by the simplified elastic creep analysis program 'PISAC' as shown in Ref.3.A.1. Analytical values differed very greatly depending upon the material constants which constituted the Norton's law for creep equation. This type of analysis can not predict the abrupt drop of load immediately after loading, because the simple Norton's law is used for creep analysis which can fit only the average deformation behavior and the possible time dependency of plastic deformation can not be incorporated into the program. Generally, the program using Norton's law predicts larger accumulation of deformation of the soft member(elbow) than that observed in the test. So applicability of k* analysis, which proposed by Clark and Reisner(Ref. 3.A.2) and adopted in the ETSDG, was performed by PISAC program.

Ref.3.A.1 Yamasato,K.,Imazu,A.,Simplified creep analysis of elbows subjected to three directional moment loadings,Proc.of Japan Society of Mechanical Engineering,Oct.1979,No.790-13,pp15-18(in Japanese)
Ref.3.A.2 Clark,R.A.,Reisner,E.,Bending of curved tubes,Advances in Applied Mechanics,Vol.2, 1951

B. SCALE DOWN MODEL TEST OF HOT LEG PIPING OF 'MONJU'

B.1 OBJECTIVE

(1) To demonstrate that elastic follow-up of hot-leg piping of the primary coolant system of 'MONJU' is not significant

(2) To justify the criteria for evaluating elastic follow-up provided in the ETSDG

B.2 TEST DESCRIPTION

A scale down model of hot leg piping of 'MONJU' was placed on a large test bed as shown in 3.B.1. Both ends of the pipings were fixed by two fixtures simulating the reactor vessel outlet nozzle and intermediate heat exchanger inlet nozzle. The piping was heated up by electric heaters attached outside the pipe, with a special consideration not to restrain the deformation of the piping. The end fixtures are capable of providing the nozzle deformation with three dimensional end displacements were given at the begining of the test.

B.3 RESULT

Strain accumulation of the 'MONJU' primary hot leg piping system due to thermal expansion was small. The ETSDG is conservative to evaluate stresses induced by thermal expansion. The PISAC program is applicable to evaluating elastic follow-up behaviors of high temperature piping systems.

Table 3-A-1 Test Model and Condition for Elastic Follow-up Test

Test Model	Specification of Test Model		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
Elbow - Straight Pipe (EF-301)	Elbow Pipe SUS 316 Straight Pipe (A-53"B")	Elbow Pipe 318.5 ^{OD}- 4.5 ^{t} - 457.2 ^{R} Straight Pipe 76.3 ^{OD}- 7.0 ^{t}	600	In-plane Bending Displacement at Top of Model	δ = 347.24mm Constant (σ_{Max} =16 kg/cm ^{2}) 4123 hour

Table 3-A-2 Test Model and Condition for Elastic Follow-up Test

Test Model	Specification of Test Model		Test Condition		
	Meterial	Dimension (mm)	Temper-ature(℃)	Loading Mode	Control
Hot Leg Piping System	SUS 316	216.3 ^{OD} - 2.8 ^{t}	600	Three Dimensional Displacement at End of Model	δ_X =-3.49mm δ_Y =-8.06mm δ_Z =36.64mm Constant 5000 hour

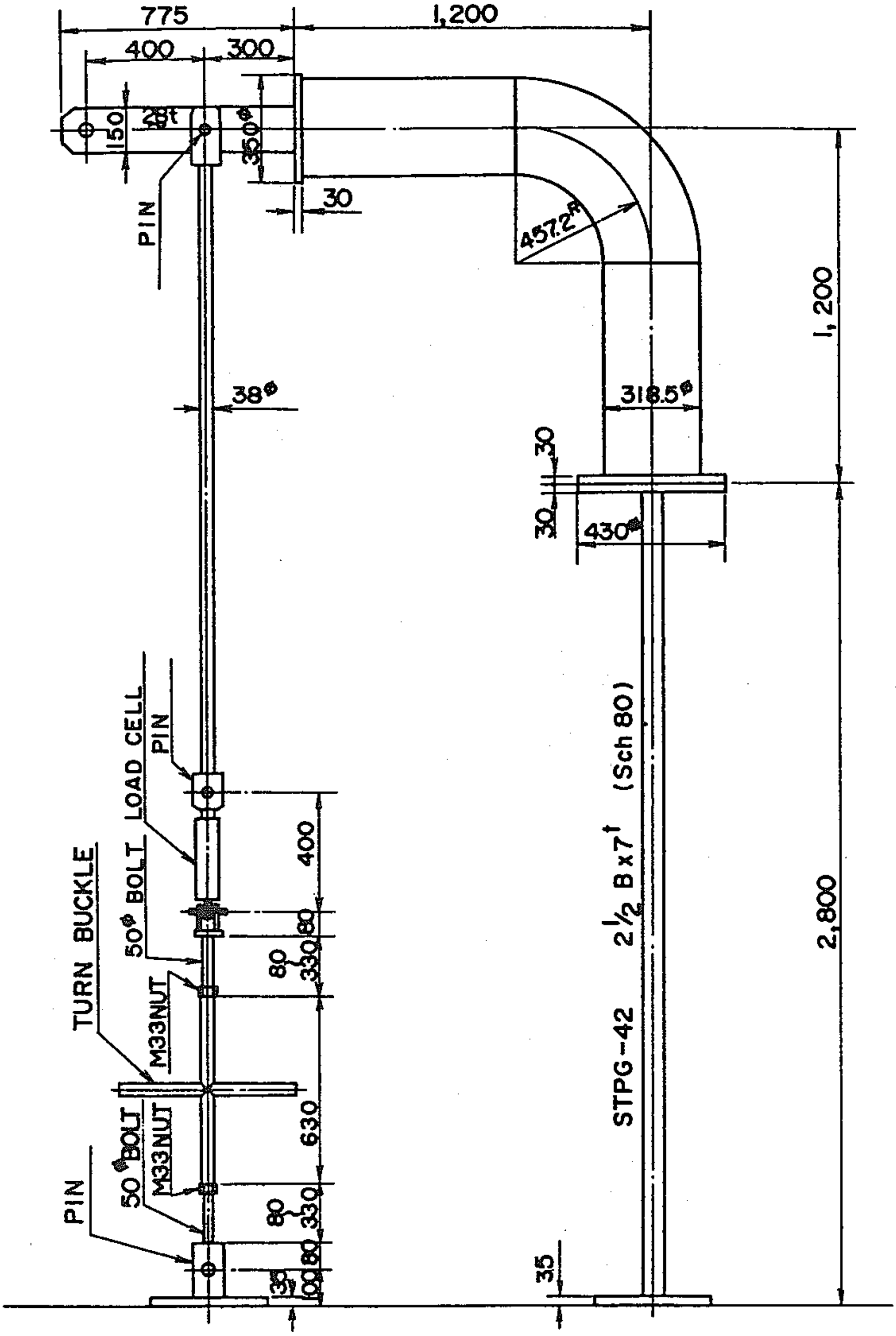


Fig.3.A.1 Simple system test

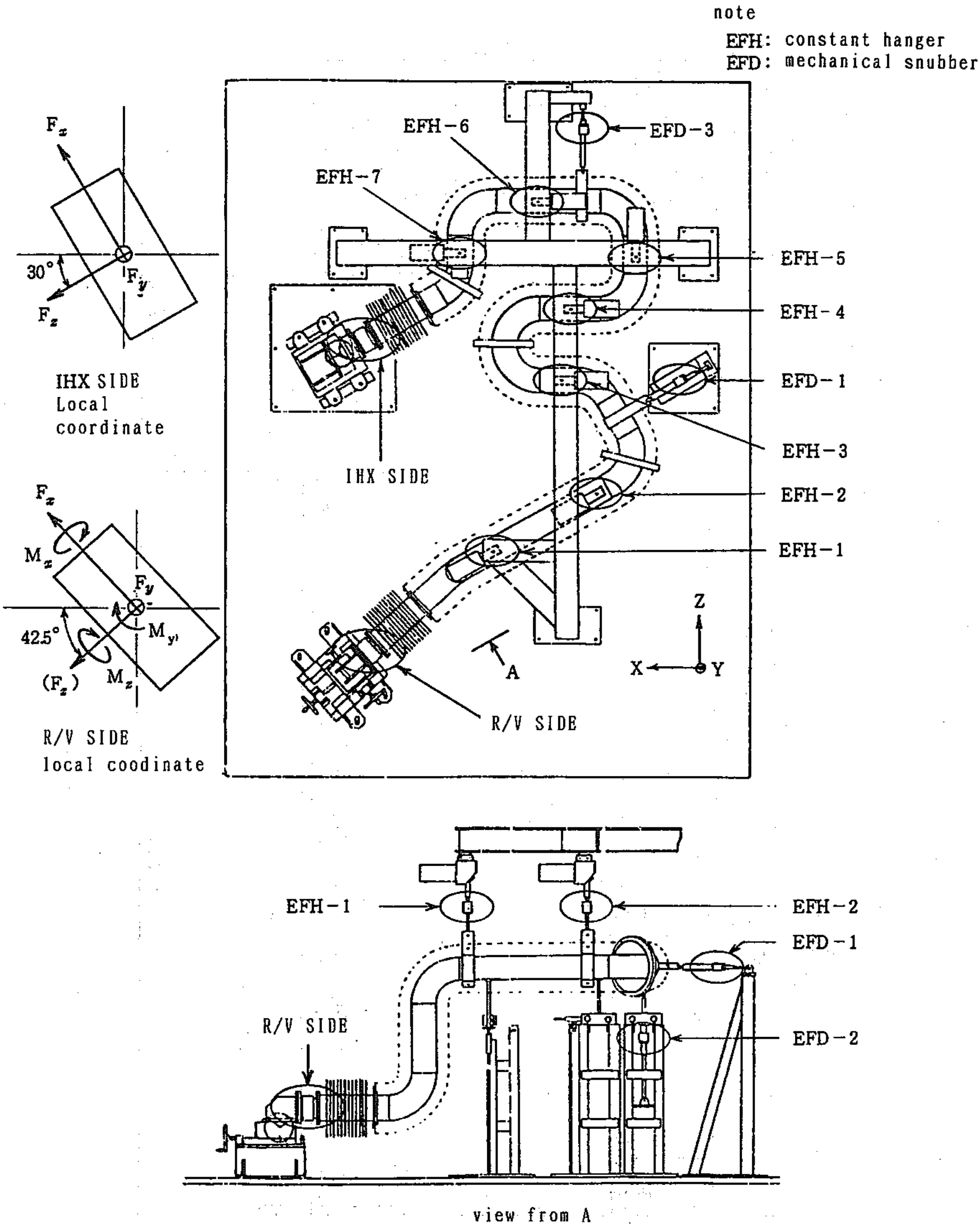


Fig. 3. B. 1　　Scale down model test of hot leg piping of "MONJU"
(position of load cell)

ATTACHMENT 4

BUCKLING TEST

1. ABSTRUCT

Experimental buckling study were performed for special structures considered in a design of prototype fast breeder reactor, and the results were reflected to 'Limit to Buckling Failure' described in ETSDG. Recently simple buckling test program is going on for development of basic computational method.

2. ARTICLES OF BUCKLING TEST

A. HEAT TRANSFER TUBE TEST

B. CONTAINMENT VESSEL MODEL TEST

C. BASIC TEST

3. SHORT DESCRIPTION

A. HEAT TRANSFER TUBE TEST

A.1 OBJECTIVE

IHX adopted in prototype fast breeder reactor has straight heat transfer tubes with both sides welded on to upper and lower tube sheets. Due to the heterogeneous flow distribution through the tube bundle, probable temperature difference will occur among each tube. If the temperature of a certain tube is highter than that of average, axial compressive stress can be found in this tube. The objectives are to study the buckling behavior and to develop adequate design guide.

A.2 TEST DESCRIPTION

Full size model buckling tests were conducted at room temperature and high temperature up to 550 ℃. The models completely simulated the actual structures except tube was heated up by electric heater in it instead of hot sodium in actual IHX. Testing parameters were axial displacement, initial imperfection, temperature and length of holding time up to 1,000 hrs.

A.3 RESULT

The test results showed that the effects of temperature and initial imperfection were rather small, and temperature differnce corresponding to the axial deformation, at which buckling started, were 27℃. Multi-span model predicted well buckling behavior. Safety margin against displacement controlled loading provided by ASME was applicable to prevent buckling of heat transfer tubes.

Ref. 5. A. 1 Nakagawa, Y., Ueno, T., Fukuda, Y. and Shimoyashiki, Y., Research and development of intermediate heat exchanger for ' MONJU', 5th, ICPVT, 1984. 9
Abstract of R & D about IHX is presented in this reference.
Ref. 5. A. 2 Nakagawa, Y., Ueno, T., Fukuda, Y. and Sumikawa, M., Elastic plastic creep buckling of straight type heat transfer tube, Proc. of HITACHI Meeting, JSME, 1985, pp. 28-30 (in Japanese)

B. CONTAINMENT VESSEL MODEL TEST

B. 1 OBJECTIVE

(1) To confirm that buckling load tested in the mock up model is higher than that caused by design earthquake
(2) To study an effect of ring-stiffner
(3) To confirm design evaluation method provided in MITI standard
(4) To show surplus of energy absorption in contain vessel against earthquake

B. 2 TEST DESCRIPTION

A series of buckling tests were made on 15 steel fabricated, ring-stiffened cylinders. Loading conditions were axial compression or transverse shear, and test temperature was at room temperature. Test methods and configuration of the models are shown in Fig. 5. B. 1. The radius of the model is 1303.6 mm and thickness is 2.0 mm, which is reduced to a scale of one-nineteenth the actual containment vessel. The material is carbon steel SAPH45 in JIS. Prior to the yest, initial shape measurement of all models and tensile tests of materials were carried out. 6 axially compressed buckling tests and 7 transverse shear and bending buckling tests were performed by using three different types of models with ring-stiffener spacing of 0.14, 0.27 and 0.40.

The transverse shear and bending buckling tests were carried out by using the 2 models with similar configuration to the lower part of actual containment vessel.

B. 3 RESULT

Buckling occured in the shell plates between two ring stiffners. Buckling strength increases when the ring-stiffner spacing becomes shorter. And such effect of ring-stiffner spacings on the buckling strngth are more remarkable in the case of transverse shear and bending buckling than that of axially loaded buckling.

The tests using similar configuration models shows that buckling load are about three times as much as the S_2 seismic loads.

C. BASIC TEST

C.1 OBJECTIVE

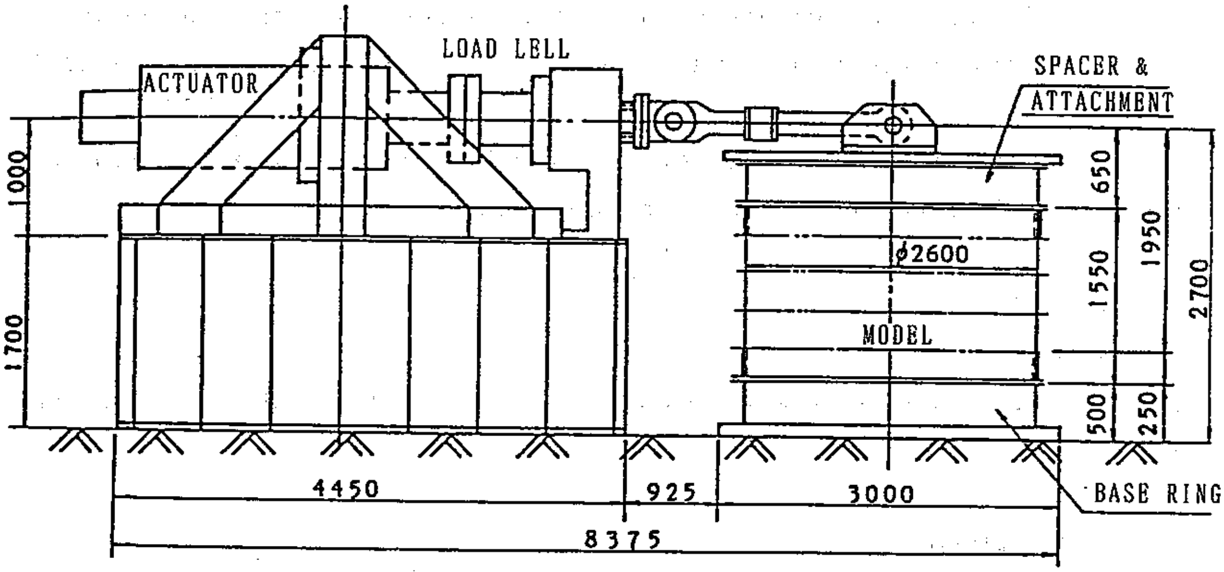
To develop more precisely computational prediction method of buckling behavior.

C.2 TEST DESCRIPTION

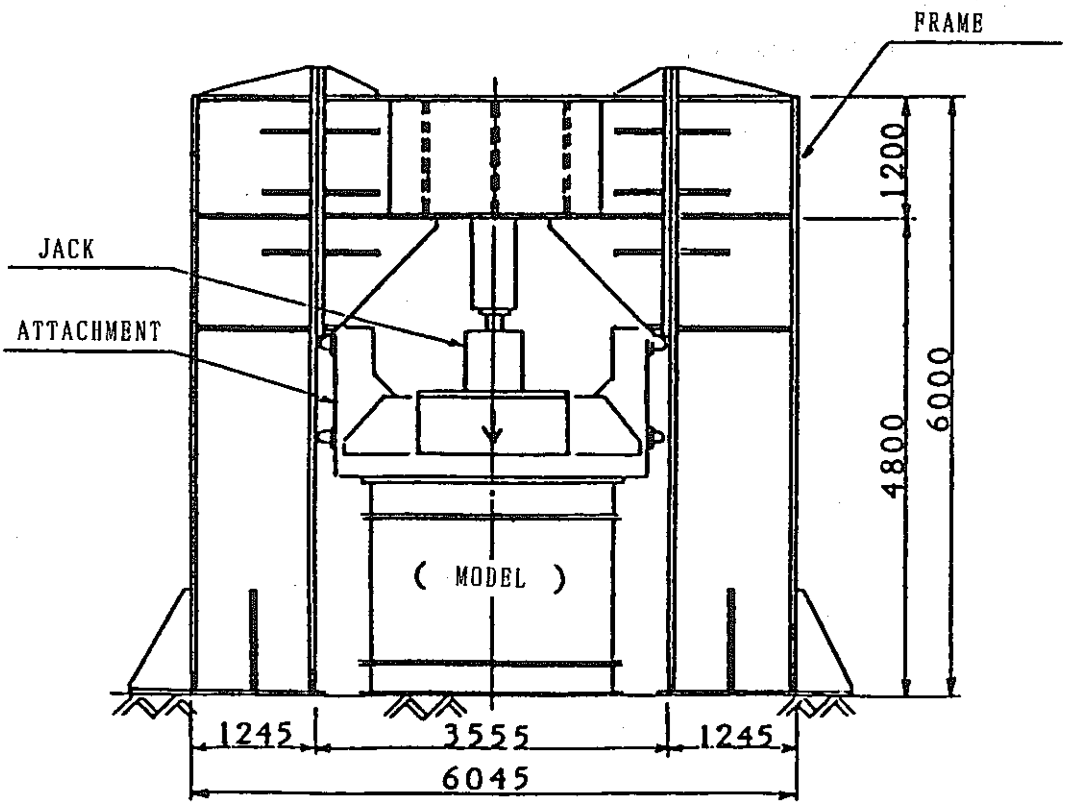
Test models are simple Cylinder without stiffner, and shearing force is applied to them in Bellows Creep Fatigue Test Rig at room temperature and 600℃. All models were made of SUS 304. Testing appratus is shown in Fig.4.C.1. Configuration of the model and test conditions are shown in Table 4.C.

C.3 RESULT

Test is now underway.



SHEARING TEST



AXIALLY COMPRESSION TEST

Fig. 5. B. 1　Test method and the model

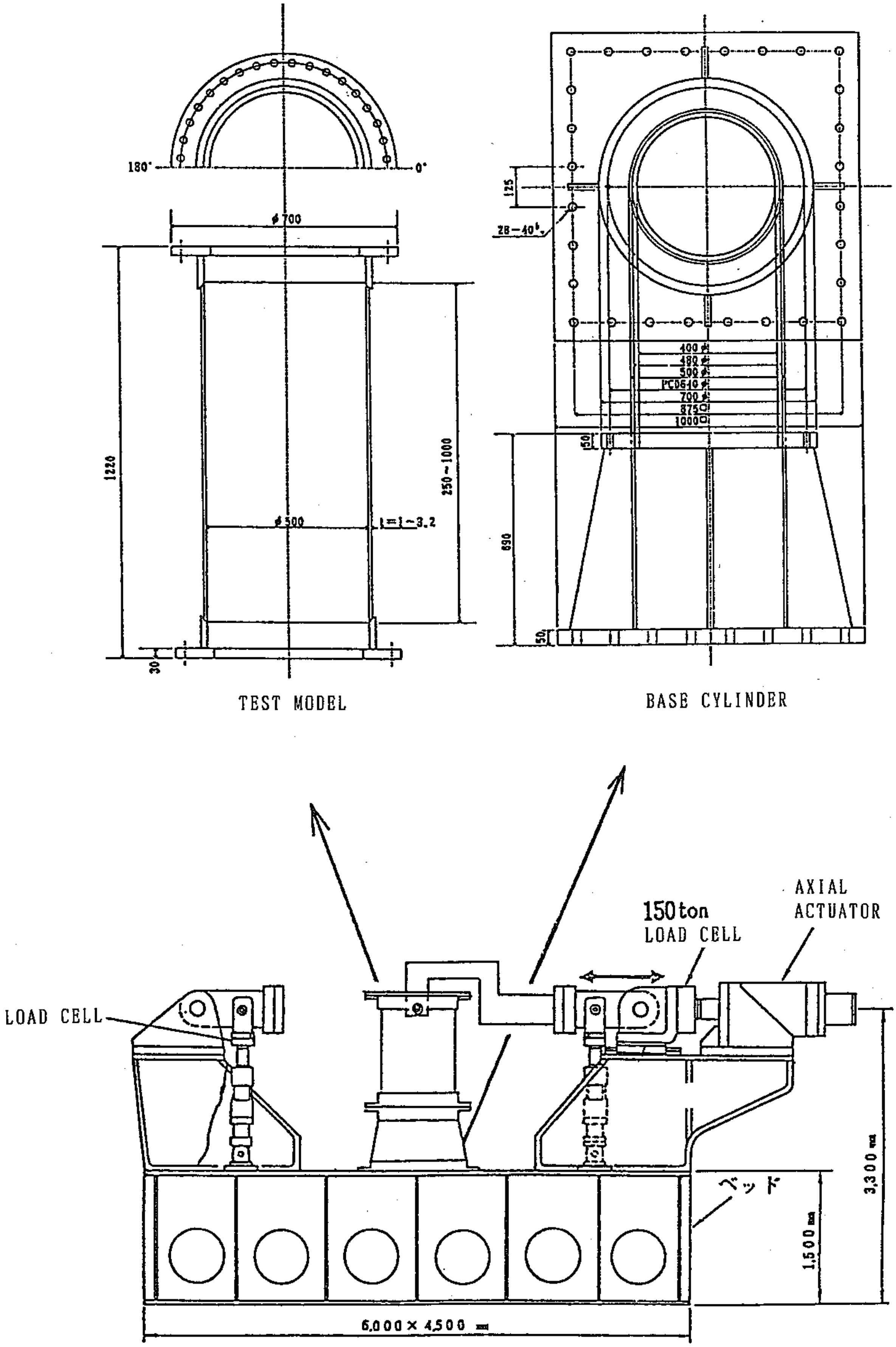
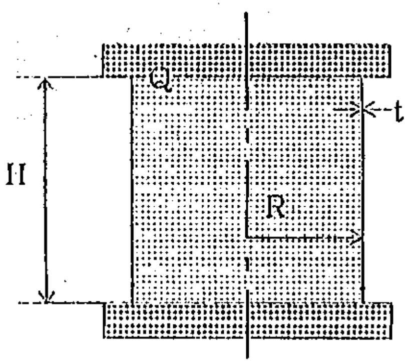
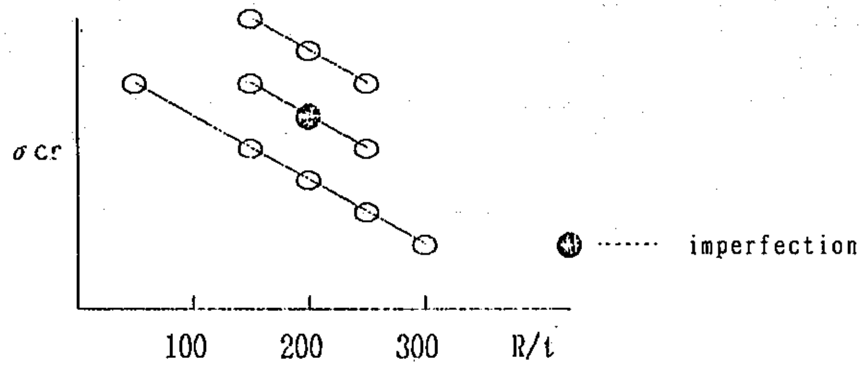


Fig. 4. C. 1　Test apparatus for basic buckling test

Table 4.C Testing parameter and test condition

model No.	parameter R／t	parameter Temp	parameter H／R	R (mm)	t (mm)	L (mm)	material	Remark 備考 (試験体No.)
CB 501	8 0	Room Temperature	4. 0	2 5 0	3. 1 2 5	1 0 0 0	SUS 304	
CB 502	1 6 0		1. 0		1. 5 6 3	2 5 0		
CB 503			2. 0			5 0 0		
CB 504			4. 0			1 0 0 0		
CB 505	2 0 0		1. 0		1. 2 5	2 5 0		
CB 506			4. 0			1 0 0 0		
CB 507	2 5 0		1. 0		1. 0	2 5 0		
CB 508			2. 0			5 0 0		
CB 509			4. 0			1 0 0 0		
CB 510	3 0 0		4. 0		0. 8 3	1 0 0 0		
CB 511	2 0 0		2. 0		1. 2 5	5 0 0		imperfection
CB 512			2. 0			5 0 0		imperfection





ATTACHMENT 5

BELLOWS EXPANSION JOINT

1. ABSTRACT

One of the measures to reduce the construction cost of large FBR plants is the shortening of the coolant piping systems by using bellows expansion joints. The use of bellows expansion joints enables to simplify piping roots, to shorten piping rength, and to reduce the number of components for supports, and the electric installation, air conditioning system etc., which the additional reduction of the construction cost, will be attained. Under the full recognition of such merits acquired through the use of the bellows type joints, PNC has devoted its utmost efforts to the development of bellows expansion joints from 1983.

The standards for the design, fabrication and inspection of bellows type joints have been developed to assure high reliability sufficient for the component to be used in nuclear plants.

2. ARTICLES OF BELLOWS EXPANSION JOINTS TEST

A. MATERIAL STRENGTH TEST
B. CREEP-FATIGUE TEST OF BELLOWS
C. FAILURE BEHAVIOR TEST OF BELLOWS
D. BUCKLING BEHAVIOR TEST OF BELLOWS
E. THERMAL TRANSIENT TEST OF BELLOWS EXPANSION JOINTS MODELS
F. SEISMIC VIBRATION TEST OF BELLOWS EXPANSION JOINTS MODELS
G. IMPULSIVE PRESSURE TEST OF BELLOWS
H. FABRICATION AND APPLICATION TEST OF 42^B BELLOWS EXPANSION JOINTS

3. SHORT DESCRIPTION

A. MATERIAL STRENGTH TEST

A.1 OBJECTIVE

Objectives are to obtain fundamental material data of bellows, and to review whether it is possible or not to apply the present material strength standard for structural design of general compontnts to the material of the thin plate for bellows.

A. 2 TEST DESCRIPTION

Tensile test, creep test and sodium environmental test were carried out.

A. 3 RESULT

The present material strength standard for SUS 316 is applicable to the bellows materials. Even in sodium, no reduction of material strength bellows is observed.

B. CREEP-FATIGUE TEST OF BELLOWS

B. 1 OBJECTIVE

The objectives is to develop the evaluation method of creep-fatigue strength of bellows based on elastic analysis.

B. 2 TEST DESCRIPTION

Configuration of the test specimen made of SUS 316 is seven crown model of 42 inches in nominal diameter with 2 mm thickness. Fatigue and creep-fatigue tests were conducted at room temperature and 600℃ in air under tension-compression loading or cyclic bending loading with 2.0 kg/mm^2 in internal pressure. Testing condition is summaried in Table 5. B. 1.

B. 3 RESULT

The rule for prevention of creep-fatigue failure was developed.

C. FAILURE BEHAVIOR TEST OF BELLOWS

C. 1 OBJECTIVE

An objective is to investigate the possible failure behaviors of bellows from the view point of structural safety evaluation.

C. 2 TEST DESCRIPTION

Two sorts of tests were conducted. One is fatigue crack growth test of part-through surface crack, and the other is instable crack test of through crack. Testing condition et al. are shown in Table 5. C. 1～5. C. 3. In fatigue crack growth test one pitch models and bellows models were used.

C. 3 RESULT

Predicted results based on elastic fracture mechanics using ΔK agreed well with experimental fatigue crack growth behavior. As the next step creep-fatigue crack growth test is underway.

Instability test clarified that the bellows are very hard to be broken unstably and LBB condition is easily fulfilled.

D. BUCKLING BEHAVIOR TEST OF BELLOWS

D.1 OBJECTIVE

Bellows exhibits unique buckling modes because of its peculiar shape. Depending on its dimensions and the number of convolutions, two differnt modes, namely column squirm (simmilar mode observed in column) and in-plane sqirm (bellows pitches change in a wave pattern around the circumference) can occur. In oder to develop the evaluation method of buckling including the influence of initial deformation and high temperature, buckling test of bellows with various configurations and sizes were carried out .

D.2 TEST DESCRIPTION

Buckling test were conducted using models of 12 inches, 21 inches or 42 inches in nominal diameter at room temperature and 600 ℃ under internal or external pressures in the Structural Buckling Test Rig. The test condition is summaried in Table 5.D.1.

D.3 RESULT

A rule for buckling prevension of bellows was developed.

E. THERMAL TRANSIENT TEST OF BELLOWS EXPANSION JOINTS

E.1 OBJECTIVE

Objective is to study structural integrity and applicability of monitering systems of deformation.

E.2 TEST DESCRIPTION

Six bellows type expansion joints were installed in the pipings subject to moderate thermal transient of sodium loop named TTS. One set consisted of two hinge type junctions and one gimbal type junction used in the hot sodium loop in which steady state temperature is 600 ℃～650 ℃, the other set installed in cold sodium loop used at 250 ℃. Connecting piping diameter is 10 inches. and thermal transient of ΔT = 160℃ and cyclic thermal bending due to piping expansion are applied to these bellows type junctions in every thermal transient cycles conducted in TTS.

The piping with bellows type junction and thermal load conditions are shown in Fig.5.E.1.

E.3 RESULT

Presently the bellows type junctions subjected about 2,700 cycles of thermal transient, but no trouble happened. One junction, which subjected to most severe thermal loading, was dismantled to investigate its integrity after 1,900 cycles of thermal transient loading. The result showed full integrity.

F. SEISMIC VIBRATION TEST OF BELLOWS EXPANSION JOINTS MODELS

F.1 OBJECTIVE

Objectives are to obtain natural frequencies of bellows itself and piping with bellows type expansion joint, and develop a simplified analysis method to evaluate the seismic response characteristic of bellows.

F.2 TEST DESCRIPTION

Vibration test using bellows with 22 inches in nominal diameters and 0.6 mm in wall thickness were conducted for four test models. The models with three different number of convolution, namely 15, 20 and 30 convolutions, were tested to study the effects of vibration direction and included fluid. The remained model with 20 convolutions was tested to study an effect of flow sleeve included in the junction. The all were teted at room temperature.

Piping vibration tests were peformed by using a straight pipe model with two gimbal type bellows junctions as shown in Fig.5.F.1 and a three dimensional piping model shown in Fig.5.F.2. In these tests the models filled with water were installed in the rigid flame wark on the acceralating bed. The modela were fixed about special direction at ends of the models and both ends of bellows expansion joints were supported by mechanical snubbers. Seismic wave in horizontal and vertical direction were applied to the models. The maximum acceralation of seismic wave forms used in the tests was 433 gal which continued during 25 sec.

F.3 RESULT

Detail analysis method and simplified evaluation method of bellows type junctions were developed to applicable for axial type vibration mode and beam type vibration mode which were important in sesmic design.

An application method to piping systems is studing now.

G. IMPULSIVE PRESSURE TEST OF BELLOWS

G.1 OBJECTIVE

Impulsive pressure test have been performed in order to comprehend the fundamental response and dynamic buckling strength of bellows against inpulsive pressure wave simulating sodium-water reaction accident.

G.2 TEST DESCRIPTION

The bellows , set up in an open air loop, were subjected to impulsive shock waves with a wide range of peak values and time durations, which were generated by slow explosive, and the deformation behavior of the bellows was observed. Consequently a prospect for functional capability of bellows against impulsive waves was observed.

G.3 RESULT

In general, the bellows would not exhibit significant deformation up to several times as high as static buckling pressure, but as time durations become longer, the dynamic buckling strength tend to reach the static buckling pressure.

H. DEMONSTRATION TEST OF PROTYPE PIPING BELLOWS EXPANSION JOINT

H.1 OBJECTIVE

(1) To establish manufacturing and inspection technique of the 42 inches bellows type expansion joints

(2) To demonstrate the function as a mpiping joint for FBR plant

(3) To confirm excellent performance of sodium leak detector system

H.2 TEST DESCRIPTION

Test models are hinge type bellows junction and gimbal type bellows junction with 42 inches in nominal diameters as shown in Fig.6.H.1. Those models installed in large sodium loop named Sodium Pump Testing Loop. The test will be contimued to continuous four years, and in which period rotational displacements will be applied to the models.

H.3 RESULT

Presently the test is continuing.

Table 5.B.1. Testing condition of creep-fatigue test

SPECIMEN NUMBER	TEMP ℃	LOAD MODE	INT. PRESS. kgf/cm²	HOLD TIME min
BF.4201 BF.4202 BF.4210 BF.4211	R.T.	TEN.-COMP.	2	0
BF.4203 BF.4204 BF.4209 BF.4212 BF.4207 BF.4205 BF.4206 BF.4208	600	TEN.-COMP.	2	0 0 0 0 10 30 30 120
BF.4222 BF.4222 BF.4223 BF.4224	600	BEND.	2	0 30 30 120

Table 5.E.1 Test condition of one pitch model

T.P. No	CONFIGURATION HEIGHT mm	PITCH mm	THICKNESS mm	INITIAL NOTCH DEPTH mm	WIDTH mm	LENGTH mm	APPLIED SECONDARY STRESS $S_n/3S_m$ #	TEMP. ℃
FS102	60	50	2.0	0.5	0.1	3.0	2.49	R.T.
FS103	〃	〃	〃	〃	〃	〃	2.26	〃
FS113	〃	〃	〃	〃	〃	〃	2.00	〃
FS104	〃	〃	〃	〃	〃	6.0	2.49	〃
FS105	〃	〃	〃	〃	〃	〃	2.25	〃
FS106	〃	〃	〃	〃	〃	〃	2.00	〃
FS107	〃	〃	〃	〃	〃	12.0	2.49	〃
FS108	〃	〃	〃	〃	〃	〃	2.25	〃
FS109	〃	〃	〃	〃	〃	〃	2.00	〃
FS110	〃	〃	〃	〃	〃	3.0	2.50	600
FS111	〃	〃	〃	〃	〃	〃	2.25	〃
FS112	〃	〃	〃	〃	〃	〃	2.00	〃
FS1191	〃	〃	〃	〃	〃	〃	2.63 ##	〃
FS1192	〃	〃	〃	〃	〃	〃	3.10 ##	〃
FS124	〃	〃	〃	〃	〃	〃	5.00 ##	〃
FS122	〃	〃	〃	〃	〃	12.0	5.00 ##	〃
FS123	〃	〃	〃	〃	〃	〃	4.00 ##	〃
FS125	〃	〃	〃	〃	〃	3.0	4.00 ##	〃
FS126	〃	〃	〃	〃	〃	〃	4.00	〃
FS127	〃	〃	〃	〃	〃	12.0	4.00	〃
FS202	60	50	3.0	0.75	0.1	4.5	2.50	R.T.
FS203	〃	〃	〃	〃	〃	〃	2.25	〃
FS201	〃	〃	〃	〃	〃	〃	2.00	〃
FS205	〃	〃	〃	〃	〃	9.0	2.50	〃
FS208	〃	〃	〃	〃	〃	〃	2.25	〃
FS207	〃	〃	〃	〃	〃	〃	2.00	〃
FS210	〃	〃	〃	〃	〃	4.5	5.00 ##	600
FS211	〃	〃	〃	〃	〃	〃	5.00	〃
FS212	〃	〃	〃	〃	〃	18.0	5.00 ##	〃
FS213	〃	〃	〃	〃	〃	〃	5.00	〃
LS101	300	250	10	2.5	0.1	15.0	2.50	R.T.
LS102	〃	〃	〃	〃	〃	〃	2.25	〃
LS103	〃	〃	〃	〃	〃	〃	2.00	〃

: S_m = 14.0 kgf/mm² at R.T. 10.0 kgf/mm² at 600℃

: with hold time of 10 min.

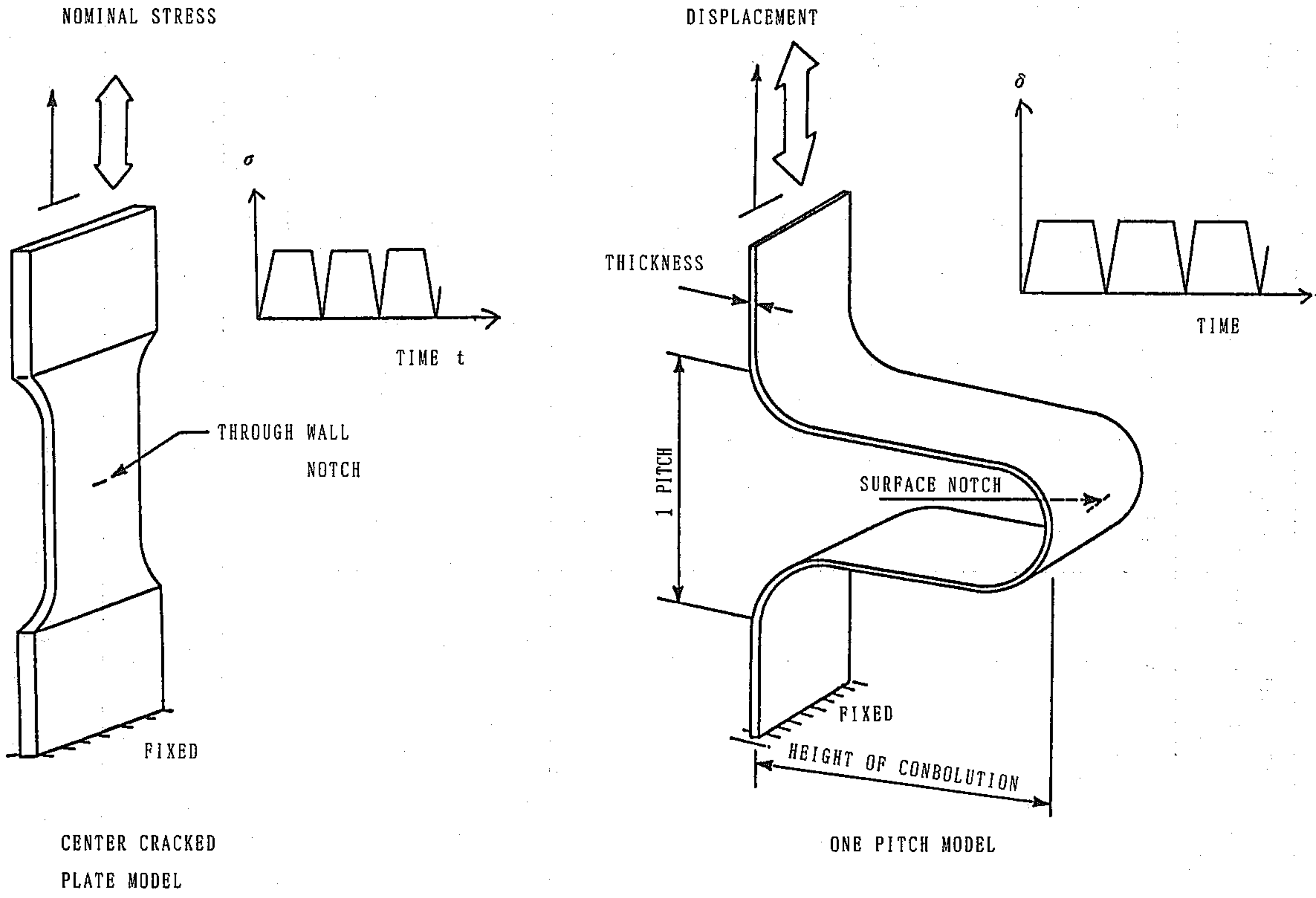
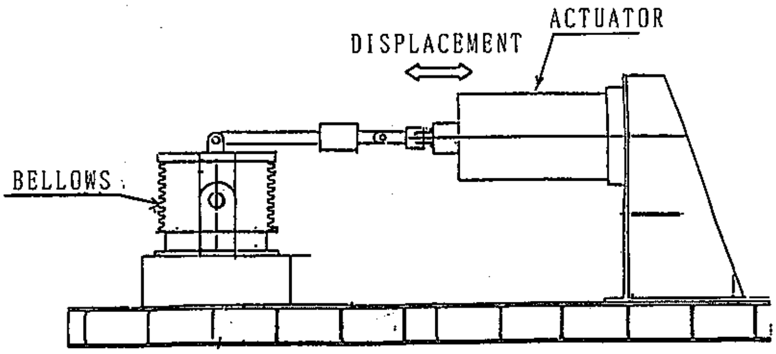


Figure5.C Creep-Fatigue Crack Growth Tests

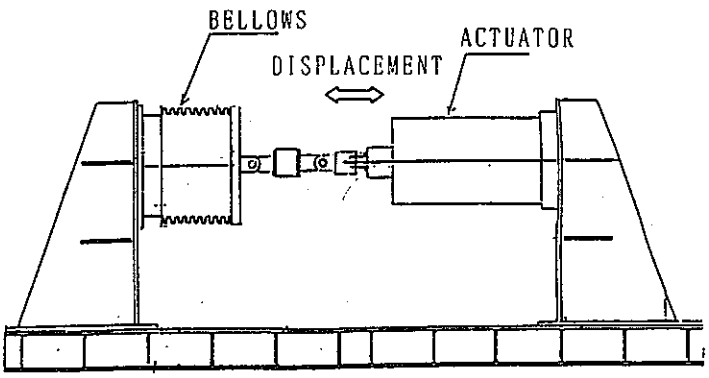
Table 5.C.2 Fatigue crack growth test condition

T.P. Mo.	CRACK SHAPE (mm) DEPTH	PITCH	THICKNESS	TEST CONDITION TYPE	TEMP. ℃	IN.PRESS. kgf/cm²	APPLIED SECONDARY STRESS $S_n/3S_m$ #
No1	30	25	1	AXIAL	R.T.	1.5	1.45
No2	30	25	1	HINGE	R.T.	1.5	1.41

All tests used the model with same dimensions : 30 mm in height, 25 mm in pitch, 1 mm in thickness and 548 mm in nominal diameter.



Fatigue Crack growth test of hinge type bellows

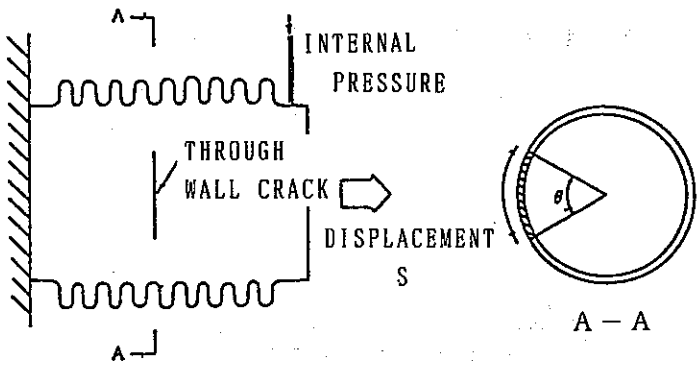


Fatigue Crack growth test of axial type bellows

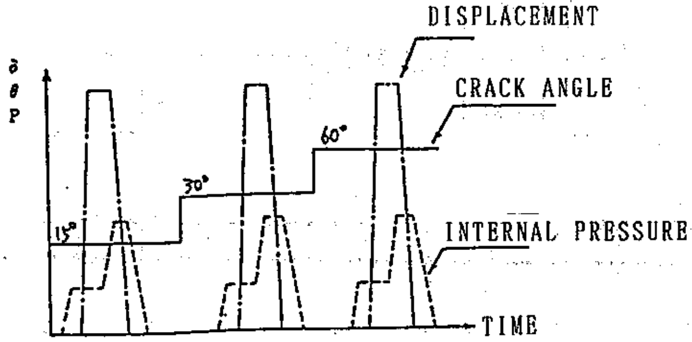
Table 5.C.3 Instable fracture test condition of bellows

T.P. No.	NUMBER OF CONVOLUTION	CRACK SHAPE DEPTH mm	WIDTH mm	ANGLE deg	TEST CONDITION TEMP. ℃	IN.PRES. kgf/cm²	DISPLACEMENT $S_n/3S_m$ #	LOAD TYPE
IF101	17	1.0	0.1	15	R.T.	1.5	2.25	AXIAL
				30	〃	2.0	2.25	
				60	〃	5.0	1.13	
IF102	17	1.0	0.1	15	〃	1.5	2.25	HINGE
				30	〃	2.0	1.13	
				60	〃	5.0	3.17	
IP101	17	1.0	0.1	60	R.T.	9.2	0	HINGE
IP102	17	1.0	0.1	60	〃	9.1	0	HINGE
IP103	7	1.0	0.1	60	〃	11.8	0	AXIAL
IP104	3	1.0	0.1	60	〃	13.4	0	AXIAL

All tests used the model with same dimensions : 30 mm in height, 25 mm in pitch, 1 mm in thickness and 548 mm in nominal diameter.



TEST MODEL



Loading patterns

Loading patterns

Table 5.D.1 Testing condition of buckling test

	SPECIMEN CONFIGURATION NOMINAL DIA.	WALL THICKNESS	NUMBER OF CONVOLUTION	TEST TEMP. ℃	SORT OF TEST	REMARK
BF.1201	12 in	0.5 mm	7		TYPE 1	
BF.1202	〃	〃	7		〃	PRE-DEFORMATION
BF.1203	〃	〃	10		〃	
BF.1204	〃	〃	10		〃	PRE-DEFORMATION
BF.1205	〃	〃	15		〃	
BF.1206	〃	〃	15		〃	REPEATABILITY
BF.1207	〃	〃	20		〃	
BF.1208	〃	〃	20		〃	REPEATABILITY
BF.1209	〃	〃	20		〃	PRE-DEFORMATION
BF.1210	〃	〃	25	ROOM	〃	
BF.1211	〃	〃	30		〃	
BF.1212	〃	〃	30	TEMP.	〃	PRE-DEFORMATION
BF.1213	〃	1.0	7		〃	
BF.1214	〃	0.8	7		〃	
BF.1215	〃	〃	20		〃	
BF.1216	〃	〃	20		〃	PRE-DEFORMATION
BE.1217	〃	〃	30		〃	
BE.2101	21 in	1.0	12		〃	
BE.2102	〃	〃	12		TYPE 2	
BE.2103	〃	〃	20		TYPE 1	
BE.2104	〃	〃	20		TYPE 2	
BE.4201	42 in	2.0	7		TYPE 1	
BE.4202	〃	〃	7		〃	
BE.4203	〃	〃	7		〃	PRE-DEFORMATION
BE.4204	〃	〃	7		〃	PRE-DEFORMATION
BE.4205	42 in	2.0	7		〃	
BE.4206	〃	〃	7		〃	
BE.4207	〃	〃	14		〃	
BE.4208	〃	〃	7	600	TYPE 3	
BE.4209	〃	〃	7		〃	
BE.4210	〃	〃	14		〃	

TYPE 1 : Plastic buckling due to internal pressure
TYPE 2 : Plastic buckling due to external pressure
TYPE 3 : Creep buckling due to internal pressure

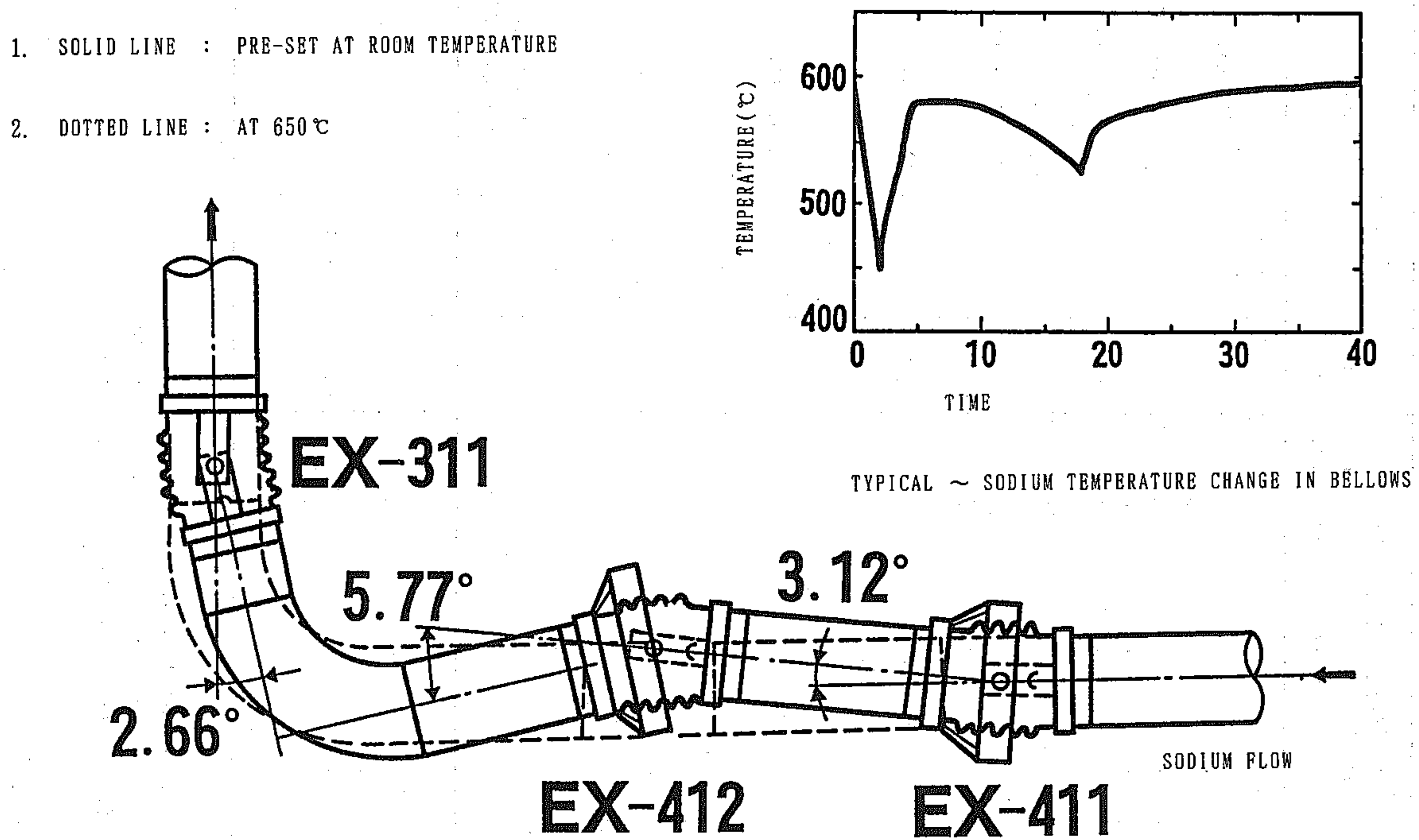


Fig5.E.1 Thermal transient test of bellows type junction in TTS outlet piping

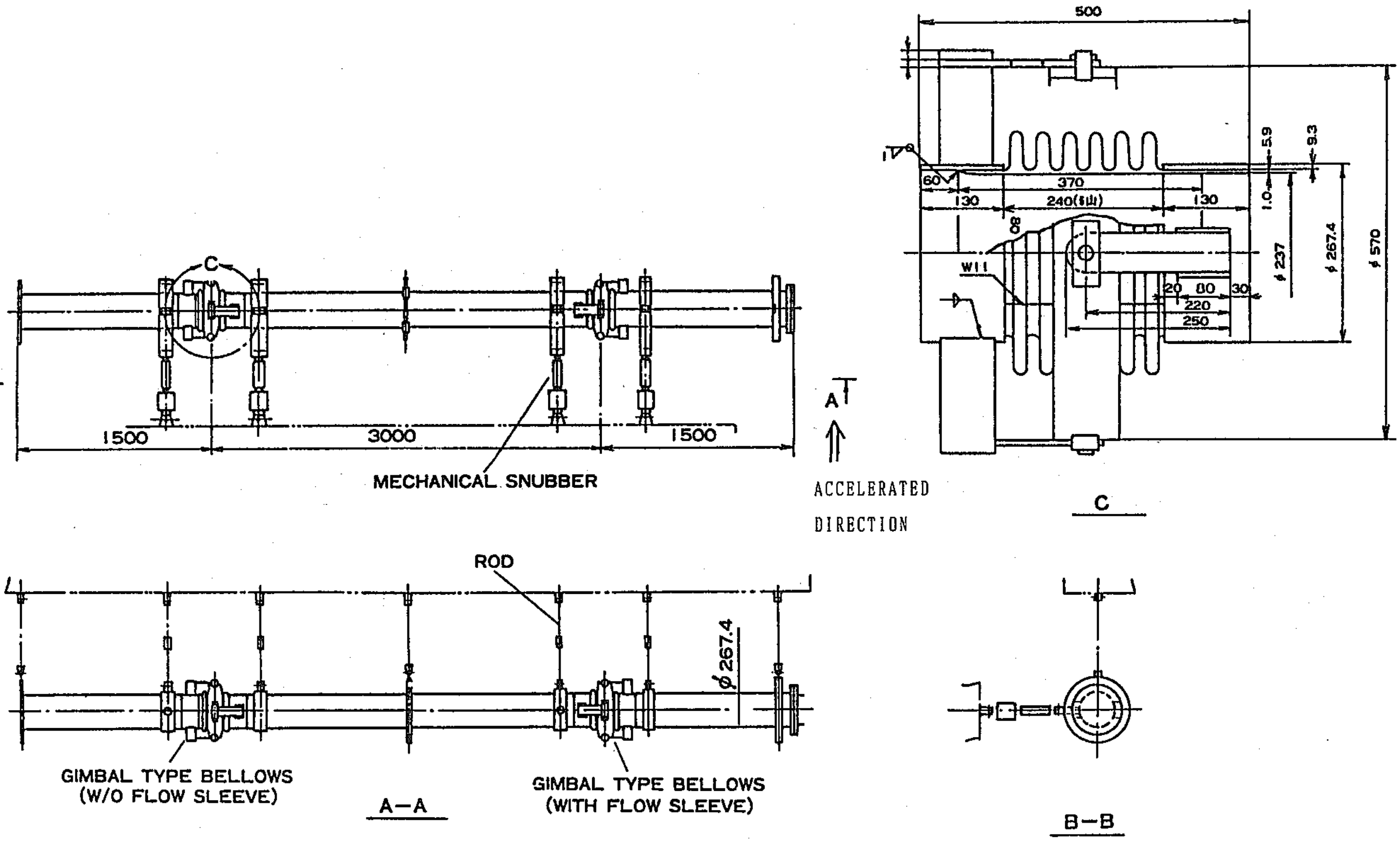


Fig. 5. F. 1　　Bellows vibration test using straight piping model

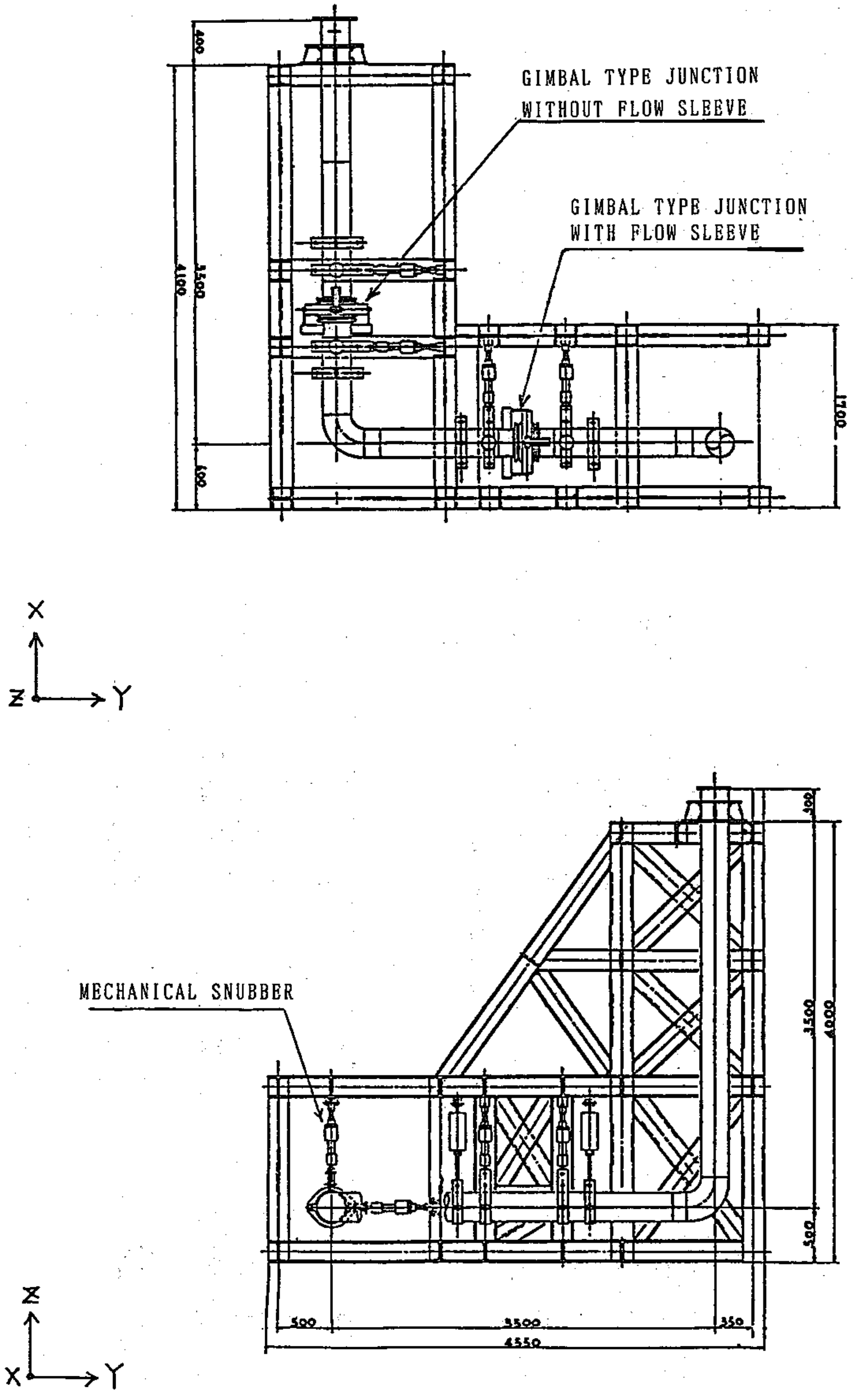
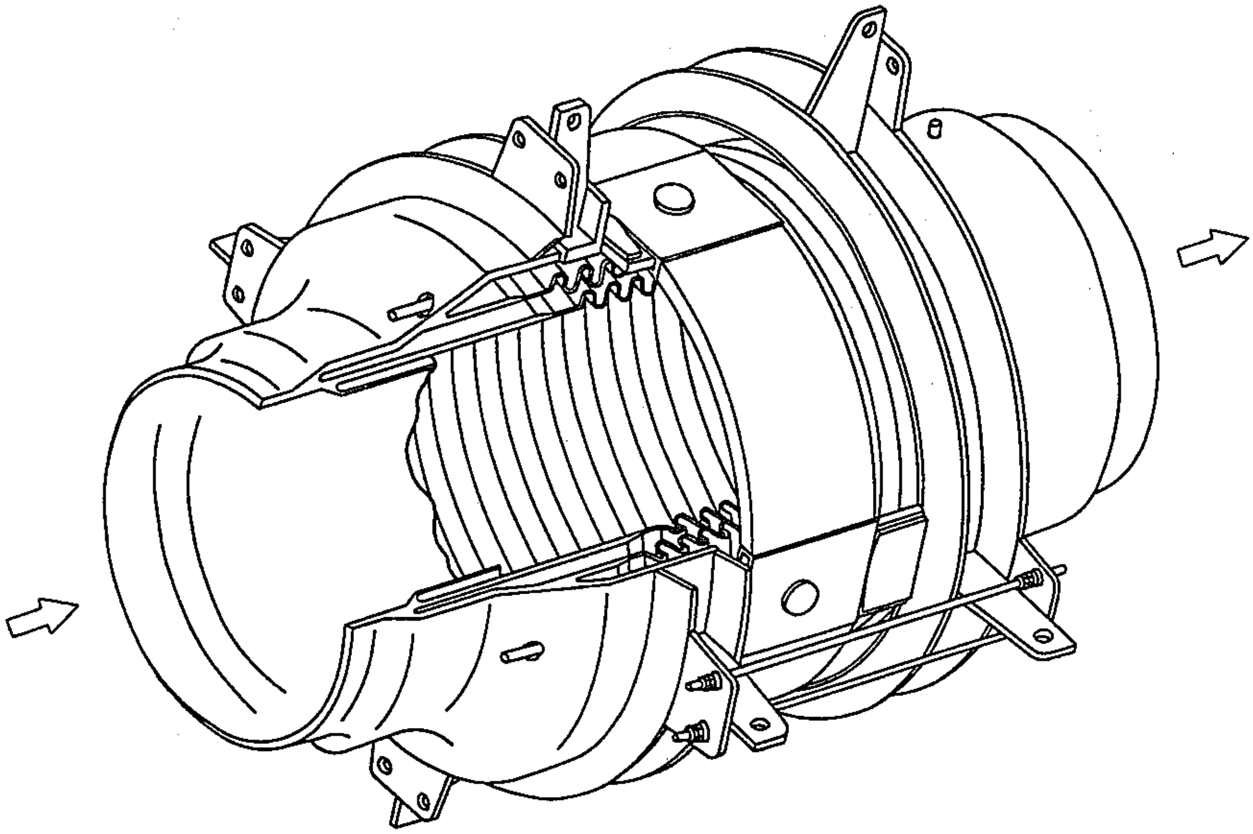
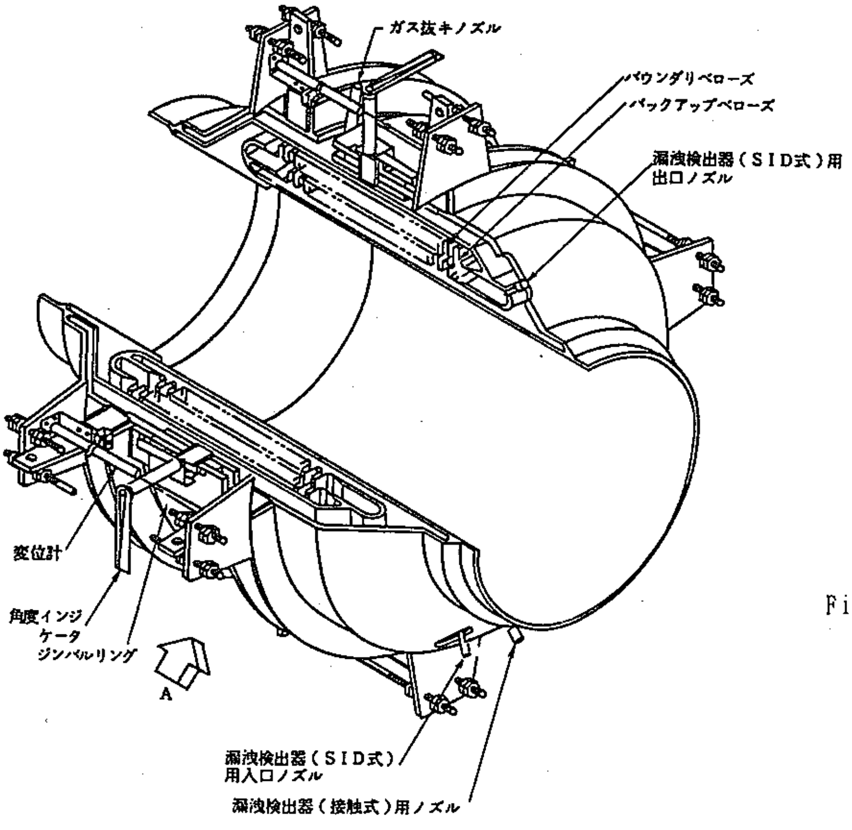


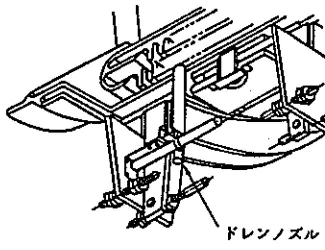
Fig. 5. F. 2　　3-dimensional vibration test



内圧型配管用ベローズ継手

Internal Pressure Type Bellows Joint





A矢視部詳細

Fig. 5. H. 1　LONG RANGE TEST

外圧型配管用ベローズ継手

External Pressure Type Bellows Joint

ATTACHMENT 6

BEAM MODEL TEST

1. ABSTRACT

Beam is one simple test model for cyclic relaxation test and creep-fatigue test. Three types of test and many analyses were conducted for development of strain multiplier and the method of creep damage evaluation. A main objective of this article is to develop the method of creep damage calculation for high temperature structural design evaluation by analysis under displacement controlled bending load with elastic follow-up.

2. ARTICLE OF BEAM MODEL TEST

A. FOUR POINTS BENDING TEST

B. CONTROLLED ELASTIC FOLLOW-UP TEST

C. RELAXATION TEST OF BEAM WITH UNUNIFORM CROSS SECTION UNDER BENDING

D. CYCLIC RELAXATION TEST OF BEAM WITH UNUNIFORM CROSS SECTION UNDER TENSION-COMPRESSION LOADING

E. RELAXATION TEST OF CURVED BEAM UNDER PRIMARY PLUS SECONDARY STRESSES

3. SIMPLE DESCRIPTION

A. FOUR POINTS BENDING TEST

A.1 OBJECTIVE

(1) To investigate cyclic inelastic behavior of SUS 304

(2) To develop inelastic analysis method

A.2 TEST DESCRIPTION

The beams used in the test were made of SUS 304, of which dimensions are 900 mm in length, 40 mm in height and 37 mm in width. The models subjected to four points bending at room temperature and 600 ℃. The tests are classfied into four groups as shown in Fig.6.A.1, namely cyclic plastic behavior test at room temperature and 600℃, cyclic creep test at 600℃, relaxation test at 600℃ and creep-plasticity interaction test at 600℃.

A.3 RESULT

The comparison of the test and the analysis brought the following results:

(1) Initial elasto-plastic behavior of a beam can be simulated accurately by in

elastic computation using bilinear representation of a stress-strain curve. (2) Inelastic computation using kinematic hardening rule can predict accurately the re-yield load of a beam after load reversal, but overestimates the deflection increment after re-yielding. (3) Creep strain is overestimated slightly in the inelastic analysis of beams if $\alpha_R = 5$ is used in the uniaxial creep law, while the results of uniaxial creep test agrees with the calculated results using $\alpha_R = 5$. But $\alpha_R = 5$ would be unsuitable for low stress region of beams subjected to four points bending. (4) The creep analysis using the auxialiary rules suggested by C.E.Pugh et al. for stress reversal conditions under estimates the quantity of decrease of creep strain during no loading after creation of much creep strain. The reason for this is that the creep strain recovery was not considered in this analysis.

B. CONTROLLED ELASTIC FOLLOW-UP TEST

B.1 OBJECTIVE

Objectives are to understand stress relaxation behavior of SUS 304 under primary plus secondary stresses, to supply experimental data to the creep damage evaluation in the ETSDG and to assess the predictability of the current inelastic analysis methods.

B.2 TEST DESCRIPTION

The flat plate made of SUS 304 was subjected to five cycles of repeated secondary bending moment accompanied with elastic follow-up of 168 hrs at 600℃. Test specimen and test rig (MLT) are shown in Fig.6.B.1. The elastic follow-up parameter q in the ETSDG was kept constant '3 'during the holding time by the MLT.

B.3 RESULT

Cyclic elastic follow-up behavior was stabilized in the early cycles sussequent to the second cycle, and elastic follow-up strain per cycle decreased with that of the first cycle. The results of inelastic analyses showed good agreement with the experimental data in a qualitative sense.The use of average material properties of SUS 304 in the analysis gave a little greater stress compared with the experimental data. Accumulated creep damage per cycle evaluated according to the ETSDG was conservative compared with the experimental one.

C. RELAXATION TEST OF BEAM WITH UNUNIFORM CROSS SECTION UNDER BENDING

C.1 OBJECTIVE

C.2 TEST DESCRIPTION

Table6.C Fig.6.C Fig.6.D OMISSION

C.3 RESULT

D. CYCLIC RELAXATION TEST OF BEAM WITH UNUNIFORM CROSS SECTION UNDER TENSION-COMPRESSION LOADING

D.1 OBJECTIVE

D.2 TEST DESCRIPTION

Table6.D Fig.6.C Fig.6.D OMISSION

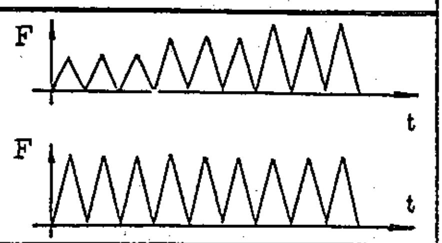
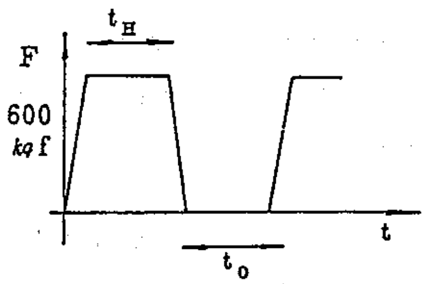
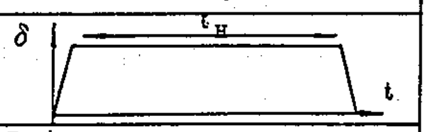
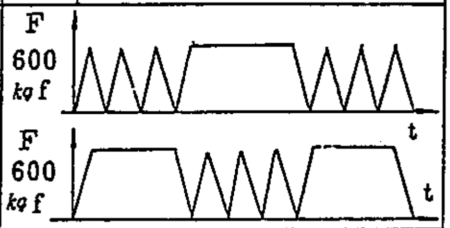
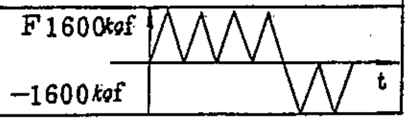
D.3 RESULT

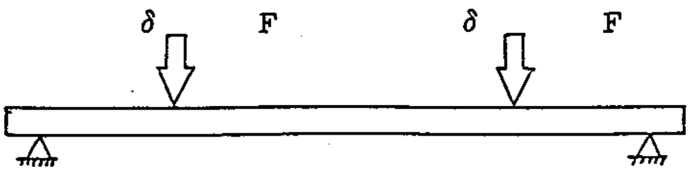
E. RELAXATION TEST OF CURVED BEAM UNDER PRIMARY PLUS SECONDARY STRESSES

E.1 OBJECTIVE

E.2 TEST DESCRIPTION Table6.C Fig.6.E OMISSION

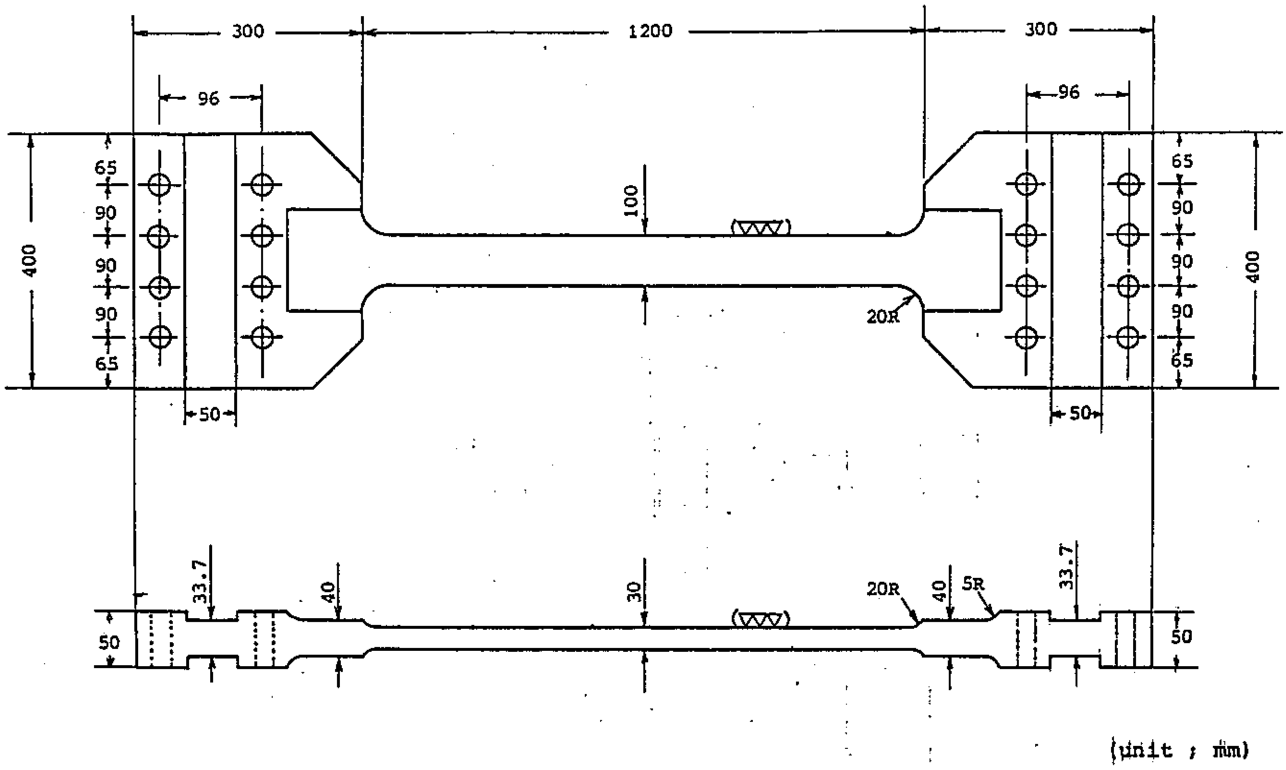
E.3 RESULT

	No.	TEMP	LOAD LEVEL	LOAD PATTERN
CYCLIC PLASTICITY	1	RT	F=245, 716, 1075, 1684kgf 10 cycles	
	2	RT	F=1680kgf, 160 cycles	
	3	600℃	F=240, 416, 605, 915, 1060kgf 10 cycles	
	4	600℃	F=600kgf, 100 cycles	
CYCLIC CREEP	5	600℃	t_H=1min, t_0=0min, 100 cycles	
	6	600℃	t_H=1min t_0=1min, 100 cycles	
	7	600℃	t_H=1h, t_0=0h, 50 cycles	
	8	600℃	t_H=1h, t_0=1h, 50 cycles	
	9	600℃	t_H=50h, t_0=0h., 5 cycles	
	10	600℃	t_H=50h, t_0=50h, 5 cycles	
RELAXATION	11	600℃	δ=4mm, t_H=300h	
	12	600℃	δ=6mm, t_H=300h	
PLASTICITY-CREEP INTERACTION	13	600℃	10 cycles · 100h 10cycles	
	14	600℃	100 cycles · 100h · 100cycles	
	15	600℃	100h · . 10cycles · 100h	
	16	600℃	100h. · 100cycles · 100h	
REVERSED PLASTICITY	17	RT	F=1600kgf, 20 cycles F=−1600kgf, 10 cycles	

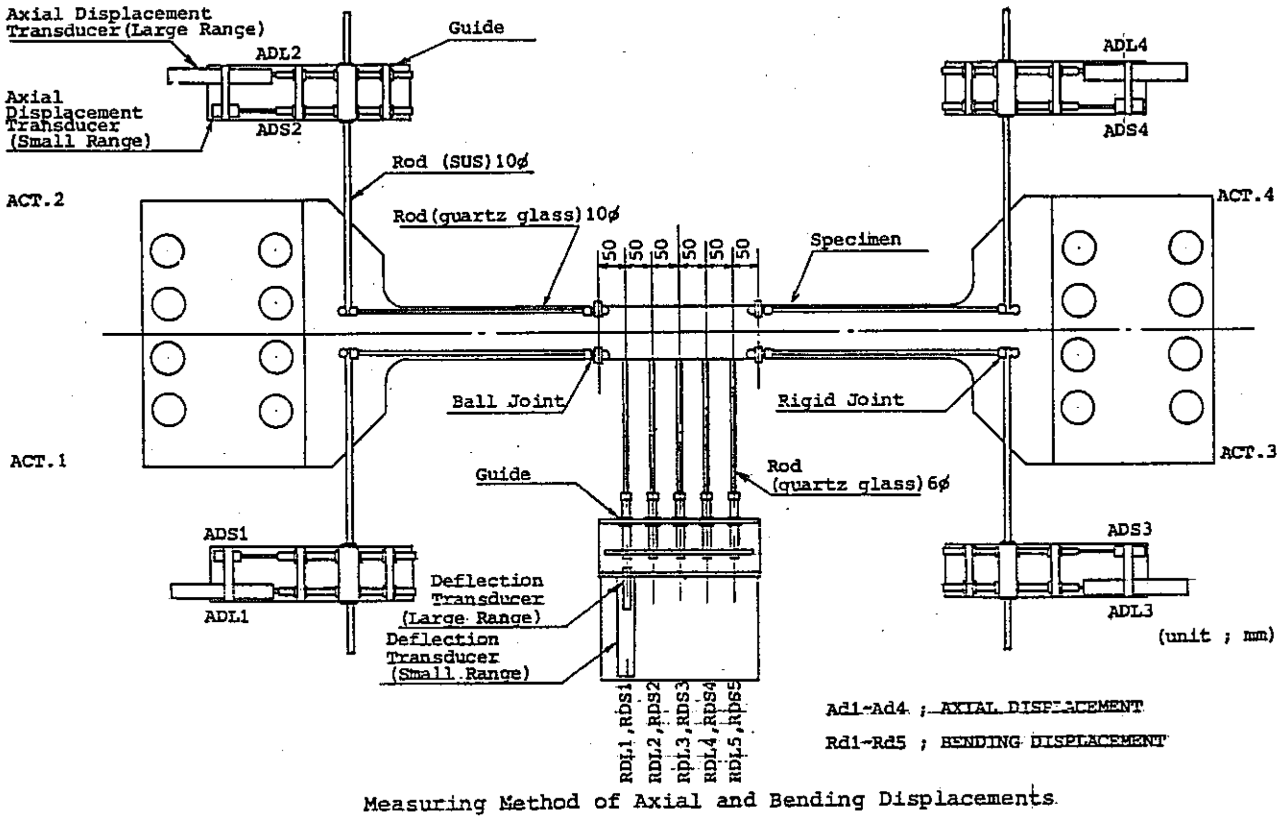


LOADING RATE
- No. 1 ~ 9 loading rate 100 kgf/sec
- No. 10 ~ 16 time for load or displacement change is 10sec
- No. 17 loading rate 64 kgf/sec

Fig. 6. A. 1 Loading condition of four point bending tests



Configuration of Test-piece



Measuring Method of Axial and Bending Displacements

Fig. 6. B. 1 Controlled elastic follow up test

Table 6.C.1 Test conditions

BENDING TEST (SUS304)

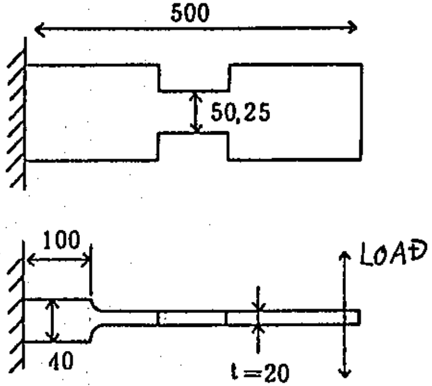
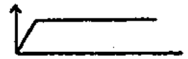
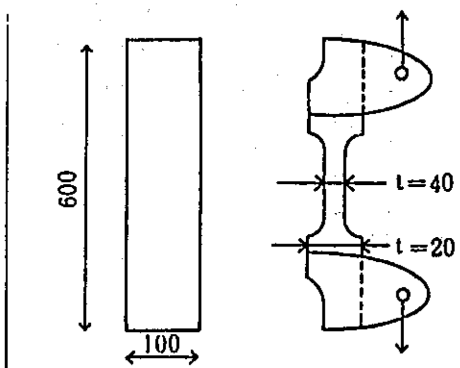
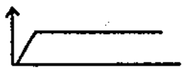
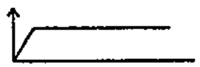
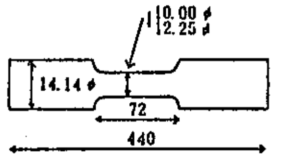
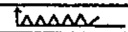
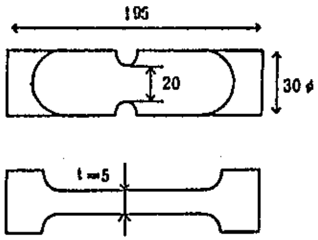
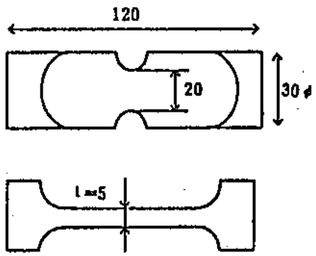
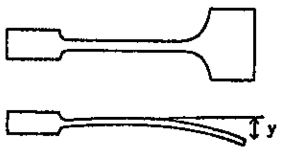
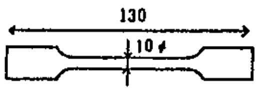
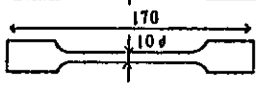
THEME	TEST NAME	SPECIMEN (mm)	TEST CONDITION No.	T ℃	LOAD		TIME CYCLE
• EVALUATION OF ε_n CALCULATION METHOD	RELAXATION		R−1	600	$\varepsilon=\frac{0.5}{3}\times10^{-3}$		426 hr
			2	600	1.5 S_m	〃	365 hr
	CYCLIC TEST WITHOUT T_H		P−1	600	3 S_m		N=50
			2	600	2.5(3 S_m)	〃	N=400
			3	600	2.5(3 S_m)	〃	N=400
• VALIDATION OF Kt	CYCLIC TEST WITH T_H		H−1	600	3 $\bar{S}_m$		t_h=96 hr, N=10
			2	600	2.5(3 $\bar{S}_m$)	〃	t_h=96 hr, N=10
• EVALUATION OF ELASIC FOLLOW-UP STRAIN	BENDING CREEP		C−1	600	1.5 σy		132 hr
			2	600	1.25 σy	〃	600 hr
			3	600	1.0 σy	〃	503 hr
			4	550	1.2 σy	〃	820 hr
	RELAXATION		Ru−1	600	2.29 σy		481 hr

Table 6.C.1 (CONTINUED) TENSION-COMPRESSION (SUS304)

THEME	TEST NAME	TEST MODEL (mm)	No.	T ℃	LOAD		TIME CYCLE	RATIO OF AREA
ε_n , ε_{EF}	Ten. Com. TEST OF BAR WITH VARIED CROSS SECTION		R−1	600	$2.5\times(3\bar{S}_m)$		$t_h=96^{hr}$, N=10	0.75
			2	600	〃	〃	$t_h=96^{hr}$, N=7	0.5
			3	600	$3\bar{S}_m$	〃	$t_h=96^{hr}$, N=5	0.75
			4	600	〃	〃	$t_h=96^{hr}$, N=10	0.5
			F−1	600	$2.5\times(3S_m)$		N=25	0.75
			2	600	〃	〃	N=30	0.5
			3	600	$3S_m$	〃	N=20	0.75
			4	600	〃	〃	〃	0.5
STRAIN DUE TO STRESS CONCENTRATION	NOTCHED PLATE MODEL TEST		1N−1	600	$2.5S_m$		〃	
			2	600	$2S_m$	〃	〃	〃
			3	600	$1.5S_m$	〃	〃	〃
			2N−4	600	$2.5S_m$	〃	〃	K=2.0
			5	600	$2S_m$	〃	〃	〃
			6	600	$1.5S_m$	〃	〃	〃
			7	600	$1.9S_m$		$t_h=0.5^{hr}$	〃
			8	600	$1.74S_m$	〃	〃	〃
			9	600	$1.52S_m$	〃	$t_h=5^{hr}$	〃
			A−1	600	$1.2S_m$		N=20	K=3.0
			2	600	$1.52S_m$	〃	〃	〃
			3	600	$2S_m$	〃	〃	〃
			B−1	600	$1.52S_m$		$t_h=0.5^{hr}$, N=20	K=1.5
			2	600	$2S_m$	〃	〃	〃
			A−4	600	$1.2S_m$	〃	〃	K=3.0
			5	600	$1.52S_m$	〃	〃	〃
			6	600	$1.72S_m$	〃	〃	〃
			C−1	RT				K=1.5
			C−2	RT				K=3.0
RELAXATION UNDER PRIMARY PLUS SECONDARY STRESS	CURVED BEAM TEST		I	600	$1.5S_m$	初期一次応力 0kg/mm²	400^{hr}	
			II	600	〃	1.05 〃	〃	
			III	600	〃	2.10 〃		
			IV	600	$3S_m$	0 〃		
			V	600	〃	1.05 〃		
			VI	600	〃	2.10 〃		
MATERIAL PROPERTY	TENSILE TEST		F−1	550				
			2	550				
			3	600				
			4	600				
	CREEP TEST		G−1	600		14kg/mm²		
			2	600		〃		
			3	600		16kg/mm²		
			4	600		〃		

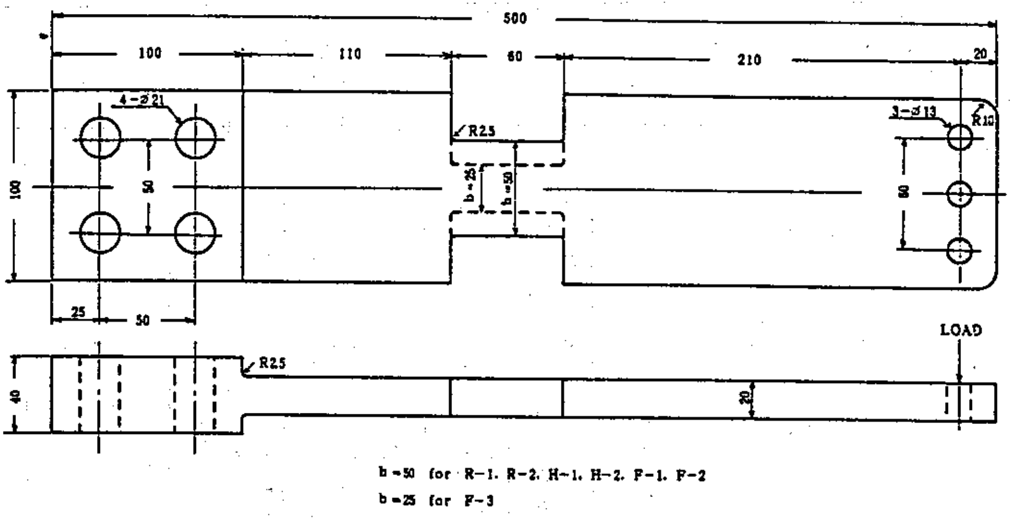


Fig SUS304 Cantilever Type Specimen

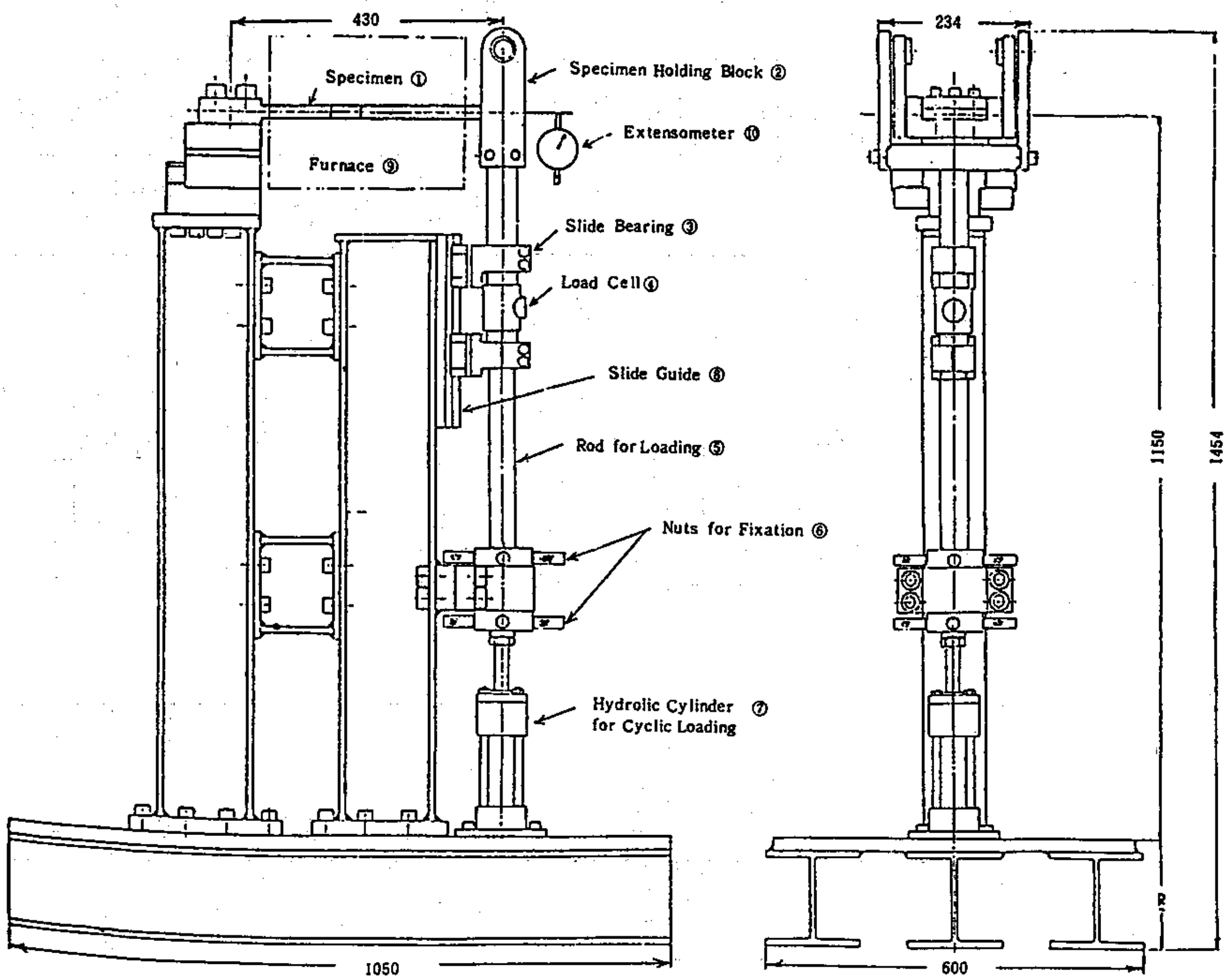


Fig. 6. C. 1 Schematic View of the Testing Apparatus

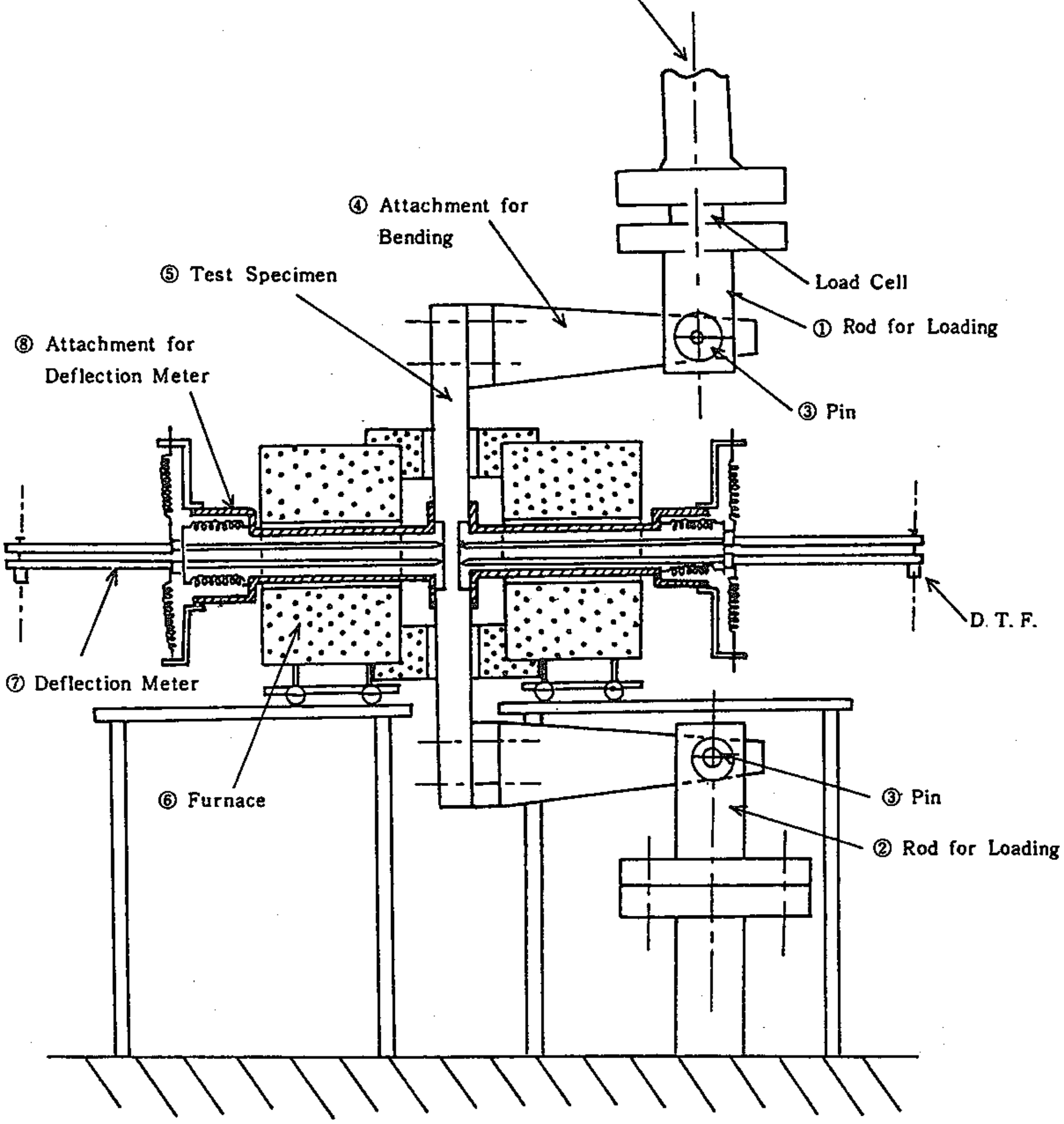
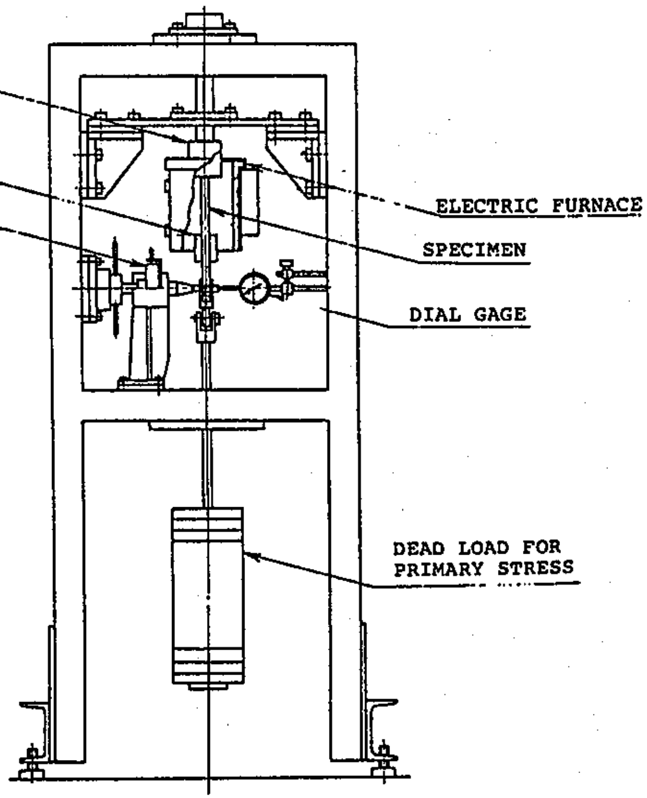
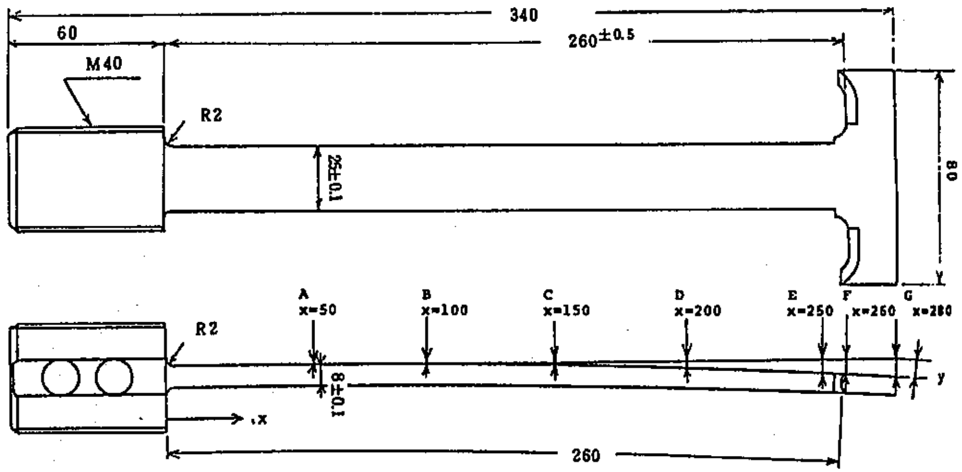


Fig. 6. C. 2　　Schematic View of the Test Apparatus (for Uniform Bending)





FORMULAE OF CURVED SPECIMENS
(1) FOR 1.5 SM $y = 4.709 \times 10^{-3}x + 7.523 \times 10^{-5}x^2$
(2) FOR 3.0 SM $y = 1.539 \times 10^{-2}x + 1.080 \times 10^{-4}x^2$

Configuration and Dimensions of Specimens

Stress Conditions

No	SHAPE	初期二次応力（Q）	初期一次応力（Pm）	TIME
I	(a)	1.5 Sm ≈ 13.8 kg/mm²	0 kg/mm²	400 hr
II			1.05 kg/mm²	〃
III			2.10 kg/mm²	〃
IV	(b)	3.0 Sm = 27.6 kg/mm²	0 kg/mm²	〃
V			1.05 kg/mm²	〃
VI			2.10 kg/mm²	〃

Fig. 6. E　Relaxation test of cured beam under primary plus secondary stresses

ATTACHMENT 7

PERFORATED PLATE

1. ABSTRACT

A perforated plate structure are used in intermediate heat exchanger(IHX) and steam generater(SG). The objectives of this article are to develop the model that can represent the temperature distribution of the tube sheet more accurately than the oradinary multi-plate model, and to develop strain evaluation method based on relatively simple axisymmetric model.

2. ARTICLE OF PERFORATED PLATE TEST

A. TUBESHEET BENDING TEST

B. SG TUBE SHEET MODEL

3. SIMPLE DESCRIPTION

A. TUBESHEET BENDING TEST

A.1 OBJECTIVE

Strain behavior of tubesheet at high temperature is so complex because a three dimensional structure is subjected to three dimensional thermal loadings due to steadily gross temperature distributions and local temperature gradients during thermal transient. So simplified analytical methods are used to stress and strain evaluation in structural design. But the method should be confirmed or modified by experimental and analytical study to attain the structural confidence. Objectives of this article are to observe the behavior of tubesheet under bending load, and to develop inelastic analysis method which is predictable stress-strain behavior.

A.2 TEST DESCRIPTION

The tubesheet models used in the tests are made of SUS 304. The configurations of the models are perforated plate with 38 mm in thickness, 900 mm in length and 90 mm in width as shown in Fig.7.A.1. Dimensions of the holes are 12.6 mm and 9.0 mm in diameter and 18.0 mm in pitch. Twelve models were tested.

The test are classfied into three groups, namely elastic-plastic behavior test at room temperature, elastic-plastic-creep behavior test at 600℃ with constant primary load during 300 hrs and relaxation tests at 600℃ with constant deflection during 50 hrs.

A.3 RESULT

The comparison of the experiment and the computation showed that the inelastic analysis method utilizing the concept of the equivalent solid plate was applicable to the perforated plates when subjected to bending. But sufficient attension should be paid to determine the creep coefficients of the material.

B. SG TUBE SHEET MODEL

B.1 OBJECTIVE

In tubesheets of steam generators, when subjected to thermal transients, interaction forces generated due to different responses between perforated plate portions and solid portions. Moreover, higher stresses are produced additionally around the holes because of the local structural discontinuity effect. In usual case, simplified method are employed for the analyses of tube sheet structures, and the adequacy of the design is evaluated based on such simplified methods. It is strongly desired for further improvement of the evaluation methods to obtain information on cyclic inelastic strain behaviors around holes and to clarify the margin for evaluated strain incorporated in the design evaluation methods. For these objectives, thermal transient tests were conducted on a model of the outlet tubesheet of the evaporator of Japanese prototype FBR.

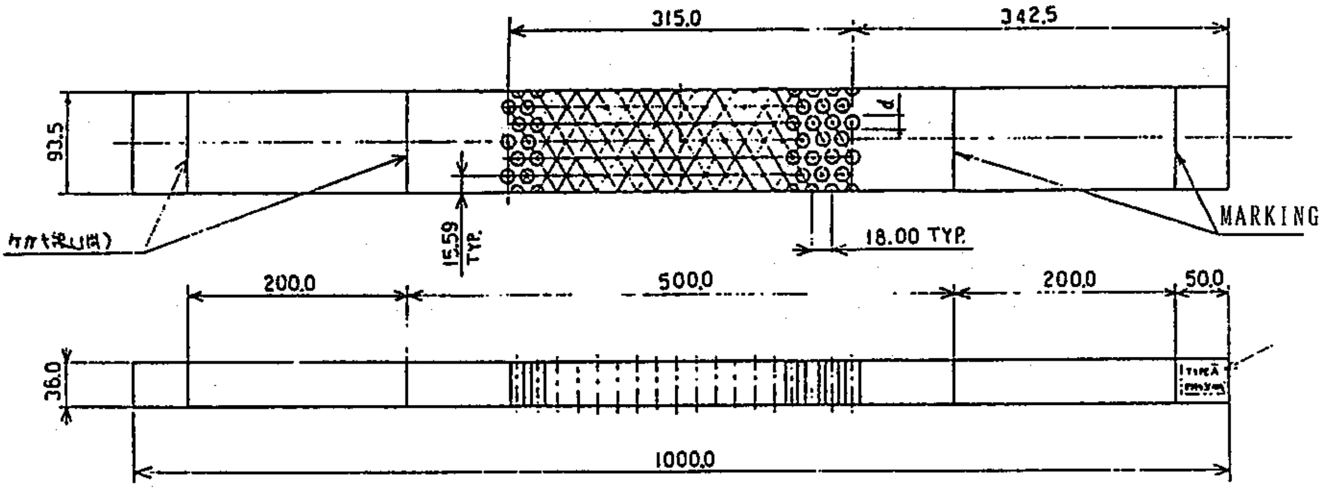
B.2 TEST DESCRIPTION

A test model made of 2.25Cr-1.0Mo steel is one half scale mock up of the outlet tubesheet of 'MONJU' as shown in Fig.7.B.1. Dimensions of a diameter of holes and its pitch are the same as those used in 'MONJU', and a radius of tubesheet is one half of that used in 'MONJU'. Thermal transient tests were performed in Air Cooling Thermal Transient Test Facility(ATTF). The test procedure is such that the model is heated gradually up to 230℃ or 330℃ by electric heater during 12 hrs, then subjected to cold transient by air blow during 4 min. The minimum metal temperature during cold transient are 0 ℃, 40℃ and 110℃. The three case of test condition were adopted and each case included several thermal transirent cycles. Temperature and strain distributions were measured during test. Details are showed in Ref.7.B.1 and 7.B.2.

B.3 RESULT

Axisymmetric simplified methods were developed for strain evaluation. The one is equivalent axisymmetric solid plate model to evaluate junction between rim and shroud. The other is partially perforated equivalent solid plate model to evaluate the outermost holes. These models were validated by comparison with thermal transient test data.

Ref.7.B.1:Kasahara,N. and Iwata,K.,Simplified 2-dimensional thermal analysis method considering 3-dimensional heat transfer,Proceedings of International Conference on Computational Mechanics,Springer-Verlag.1986.5
Ref.7.B.1:Kasahara,N. et al., To be appeared in Vol.E of 10th SMIRT.



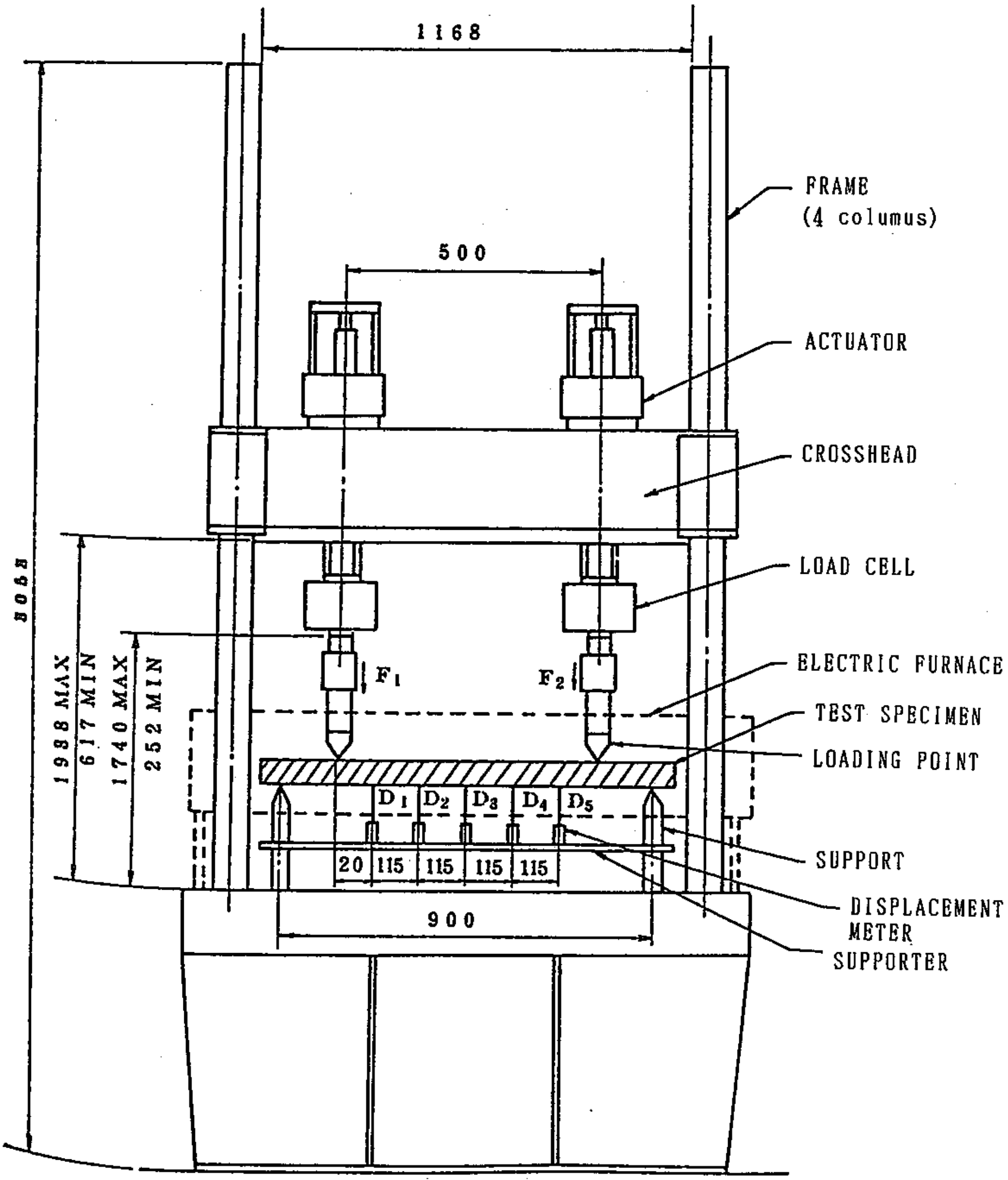
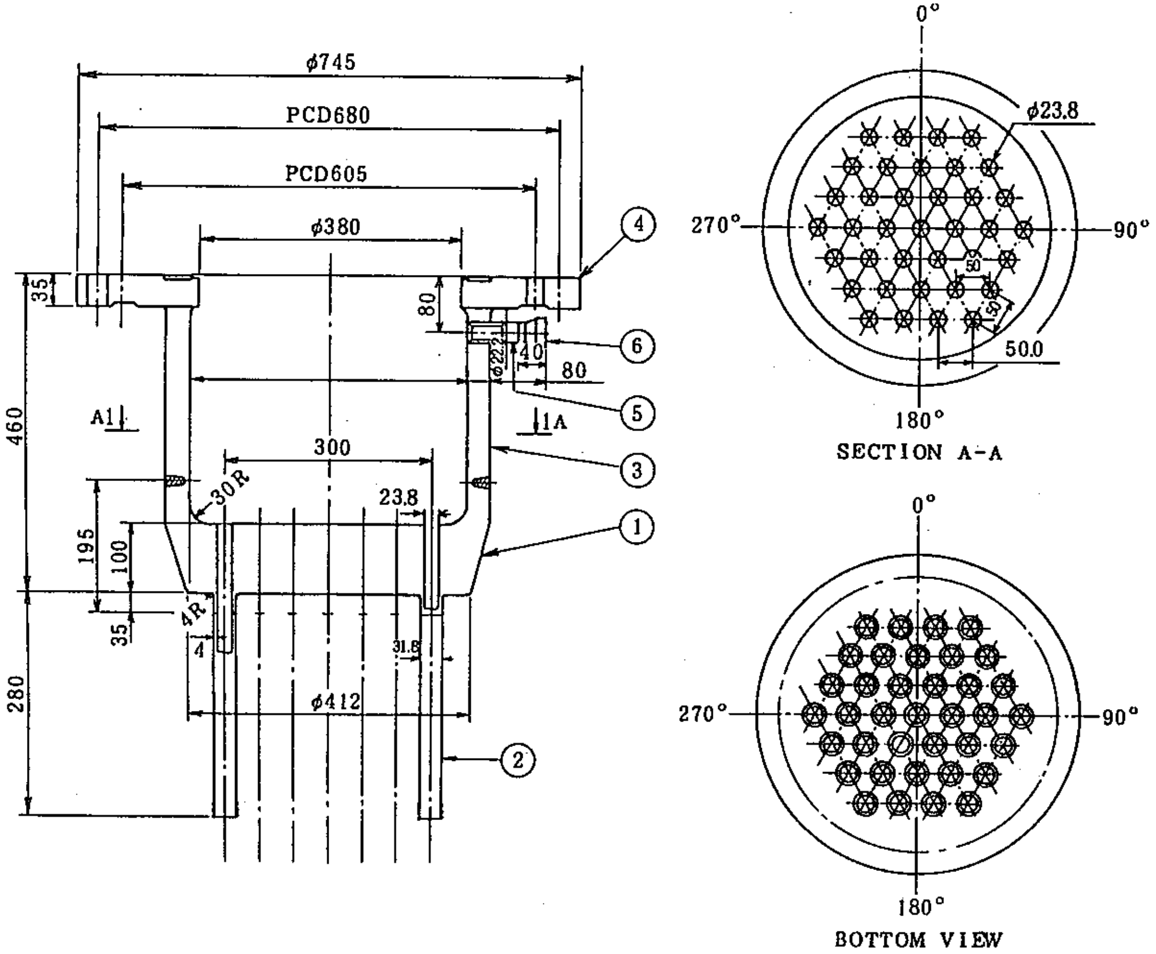


Fig. 7. A. 1 Four Point Bending Tester



DESIGN SPECIFICATION

No.	Name	Number	Materil
1	Tubesheet	1	2¼Cr-1Mo
2	Heat transfer tube	37	2¼Cr-1Mo
3	Shroud	1	2¼Cr-1Mo
4	Flange	1	2¼Cr-1Mo
5	Outlet nozzle of lead Line	12	2¼Cr-1Mo
6	Outlet nozzle of lead Line	12	SUS 304

Fig. 7. B. 1 Configurations of the Steam Generator Test Model

ATTACHMENT 8

THERMAL TRANSIENT FAILURE TEST

1. ABSTRACT

This article is closely related to ATTACHMENT 9 (THERMAL TRANSIENT TEST IN TTS) and describes thermal transient failure test of simple and small models. A study of creep-fatigue failure is classfied to the three category described in Fig. 8. 1. Thermal transient failure tests with simple models clarify the effect of each factors affected on creep-fatigue strength of structures, those are sugested from structural thermal transient test or FBR's structural design. Also comparison of creep-fatigue failure behavior between a simple model and usual material creep-fatigue test brings about well defined conclusions.

Straight pipe model with weldment, dissimilar joint model, configulation discontinuity model and so on were tested in STST and SPTT.

2. ARTICLE OF THERMAL TRANSIENT FAILURE TEST

A. STRAIGHT PIPE MODEL INCLUDING WELDING JOINTS (SPTT)
B. STRAIGHT PIPE MODEL INCLUDING DISSIMILAR JOINTS (SPTT)
C. CONFIGURATION DISCONTINUITY MODELS TESTS (SPTT & STST)
D. CREEP-FATIGUE CRACK INITIATION TESTS (SPTT & STST)

NICKNAME OF TEST FACILITY

TTS ; Thermal Transient test facility for Structures
STST : Small Thermal Shock Test loop
SPTT : Sodium Piping Thermal transient Test loop
SITR : Structural Integrity Test loop for Reactor vessel
TST : Thermal Shock Test loop
ATTF : Air cooled Thermal transient Test Facility

2. SIMPLE DESCRIPTION

A. STRAIGHT PIPE MODEL INCLUDING WELDING JOINTS (SPTT)

A. 1 OBJECTIVE

(1) To investigate thermal fatigue strength of SUS 304 and its weldment

(2) To investigate thermal creep-fatigue strength of Mod. SUS 316 and its weldment

A.2 TEST DESCRIPTION

Test models used in SPTT, which flow diagram is shown in Fig.8.A.1, are straight pipe of 67 mm inner diameter with thickness of 7～13 mm ,which identified as TF-4 ～TF-8 in Table 8.1 and Fig.8.A.2., and made of SUS 304. Testing conditions are also described in Table 8.1. All of these tests are completed.Presently the same test with forged Mod.9Cr model including weldment are planning.

Models of STF-3 and STF-10 tested in STST, which flow diagram is shown in Fig.8.A.3, are straight pipes of 47.5 mm inner diameter with thickness of 12.25 mm as shown in Fig.8.A.4. In STF-10 model penetration bead in inner surface was removed by a lathe to examine the effect of only metalic irregularity without shape discontinuity.

Model of Mod.SUS 316 and its weldment (316LCN-1) , shown in Fig.8.A.5, is testing now. Test condition is such that hot sodium of 550 ℃ flowes into the model during 5.5 hrs and cold sodium of 300℃ during 30 min.

A.3 RESULT

Cracking were observed at weldment, notch root and counter bore for bevel fitting, and propagated mainly in transgranular. Distributions of striation spacing were observed, and by which number of cycles to crack initiation was calculated. From an FEM computation, creep-fatigue damage corresponding to cracking was evaluated.

Cracking were observed in base metal and deposite ,but were not observed at heat affected zone and two metal boundary in STF-10 test.

B. STRAIGHT PIPE MODEL INCLUDING DISSIMILAR JOINTS (SPTT)

B.1 OBJECTIVE

(1) To investigate thermal fatigue strength of dissimilar joints made of sus 321-SUS 304 or 2.25Cr-1Mo steel-SUS 304.

B.2 TEST DESCRIPTION

Test models used in SPTT are straight pipe,which identified as TF-10 and DW1 ～DW10 in Table 8.1 , Fig.8.A and Fig.8.B. Testing conditions are also described in Table 8.1. Temperature of sodium is 550 ℃ in hot transient,and 250 ℃ in cold transient.All of these test are completed.

Test model used in STST are straight pipe,which identified as STF-2 IN Table 8.2 and Fig.8.A.4.Temperature of sodium is 600℃ in hot transient,and 300 ℃

in cold transient.

B. 3 RESULT

Crarking were observed at weldment and counter bore for vevel fitting, and propagated mainly in transgranular. Distributions of striation spacing were observed, and by which number of cycles to crack initiation was calculated. From an FEM computation, creep-fatigue damage corresponding to cracking was evaluated.

C. CONFIGURATION DISCONTINUITY MODELS TESTS (SPTT & STST)

C. 1 OBJECTIVE

(1) To investigate thermal fatigue and creep-fatigue strength at configuration discontinuity of SUS 304 model.

C. 2 TEST DESCRIPTION

NTF-1 model is nozzle like configuration and TF-11 model is a perforate plate as shown in Fig. 8. C. 1. These models were subjected to thermal fatigue loadings in SPTT. The test condition is such that hot sodium of 550℃ and cold sodium of 250 ℃ flow repeatedly into the model. One cycle time is 10 min. STF-1 model , shown in Fig. 8. A. 4, was sujected to thermal creep-fatigue loading in STST, in which hot sodium of 600℃ and cold sodium of 300 ℃ flow repeatedly into the model. One cycle time is 30 min.

C. 3 RESULT

Cracking were observed at inner surface of the nozzle model, corner portions of the perforate plate model and inner surface of STF-10. For NTF-1 and TF-11, distributions of striation spacing were observed, and by which number of cycles to crack initiation was calculated. No striation was observed in STF-10. From an FEM computation, creep-fatigue damage corresponding to cracking was evaluated.

D. CREEP-FATIGUE CRACK INITIATION TESTS (SPTT & STST)

D. 1 OBJECTIVE

(1) To investigate number of crack initiation cycles under thermal fatigue or thermal creep-fatigue condition

(2) To clarify the margin in " Limit to Creep Fatigue Damage"

D.2 TEST DESCRIPTION

The first series consists of three taper models made of SUS 304 named TPR-1 ~TPR-3 as shown in Fig.8.D.1. These models have the same configuration except their degree of finishment. Thermal stresses definitely distributed along axisymmetrical axis. So if each model is subjected to different number of cycles of thermal transient, then extent of cracking is different each other. Simultaneously the effect of surface roughness can be also examined. Sudium temperature is 600 ℃ in hot transient and 250 ℃ in cold transient. One cycle time is 50 min.

The second series consists of three nozzle models made of SUS 304 named NZL-1~NZL-3 as shown in Fig.8.D.2. The maximum stress ranges appear at crotch portions due to gross temperature distribution. Sodium temperature is 550 ℃ in hot transient and 300 ℃ in cold transient. One cycle time is 6 hrs.

The third series is as same as the first series ,but material is Mod.9Cr steel.

D.3 RESULT

The first series test was completed. A relation between number of crack initiation cycles and creep-fatigue damage was confirmed, and the effect of surface finishment was understood. The second series is underway. The third series is planning now.

Table 8.1 Test Specimen Specification and Test Condition

Specimen Number	Material	D (mm)	t (mm)	Tmax (℃)	Tmin (℃)	t_H (hr)	t_C (hr)	σ_z (kg/mm^2)	N
TF-4	SUS304 (WJ)	93	13	550	250	0.083	0.083	3.08	2157
TF-5	SUS304 (WJ)	93	13	550	350	0.083	0.083	3.08	4130
TF-6	SUS304 (WJ)	93	13	550	300	0.083	0.083	3.08	2311
TF-7	SUS304 (WJ)	93	13	550	250	0.083	0.083	1.54	3172
TF-8	SUS304 (WJ)	93	13	550	250	0.083	0.083	1.54	3172
TF-10	SUS304 SUSF321 SUS321HTB (WJ)	48	11.6	550	250	0.083	0.083	0	5000
DW-1	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	4000
DW-3	SUS304, 2¼Cr-1Mo (DJ)	93	13	550 (500)	250	0.083	0.083	3.08	1951 (1000)
DW-4	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	4000
DW-5	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	1459
DW-6	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	3500
DW-8	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	3400
DW-9	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	3400
DW-10	SUS304, 2¼Cr-1Mo (DJ)	93	13	550	250	0.083	0.083	0	3400
NTF-1	SUSF304 (Nozzle)	95~300	14~117	550	280	0.083	0.083	0	4600
TF-11	SUSF304 SUSF321 (Perforated Plate)	90~150	10~24	550	300	0.083	0.083	0	5000

WJ : Welding Joint

DJ : Dissimilar Joint

D : Diameter

t : Thickness

σ_z : Primary axial stress

N : number of cycles of thermal transient

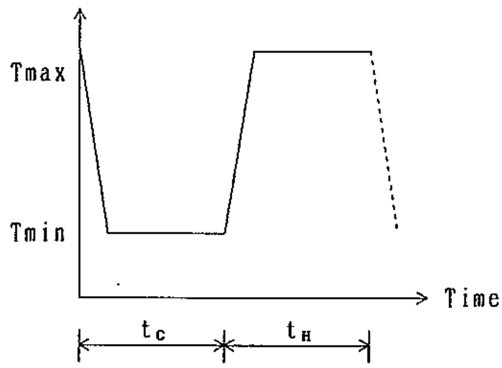


Table 8.2 Test Specimen Specification and Test Condition

Specimen Number	Material	D (mm)	t (mm)	Tmax (℃)	Tmin (℃)	t_H (hr)	t_C (hr)	σ_z (kg/mm²)	N
STF-4	SUS304 (WJ)	120	40	500	250	0.33	0.33	0.0	1510
				(600)		(0.25)	(0.25)	0.0	(3053)
STF-2	SUS304, 2¼Cr-1Mo (DJ)	70	10.5	600	300	1.0	0.05	0.0	2000
STF-3	SUS304 (WJ)	70	～10	600	300	1.0	0.067	0.0	780
STF-10	SUS304 (WJ)	70	14.8	595	333	0.083	0.083	0.0	10100

WJ : Welding Joint

DJ : Dissimilar Joint

D : Diameter

t : Thickness

σ_z : Primary axial stress

N : number of cycles of thermal transient

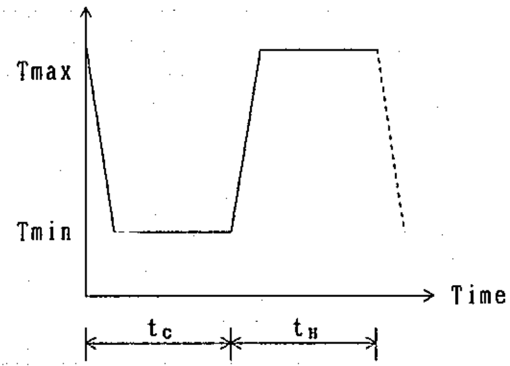
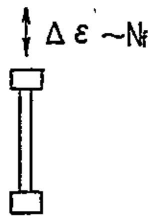
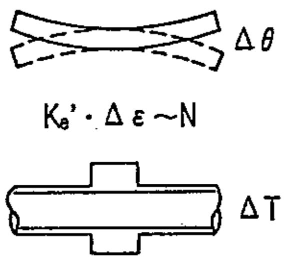
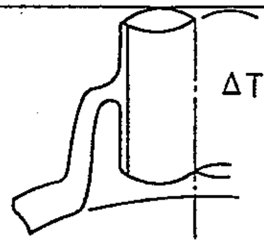
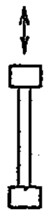
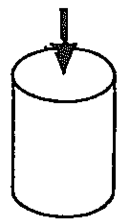
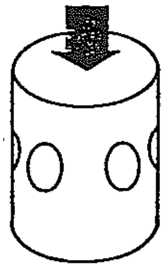
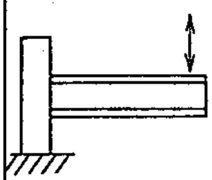
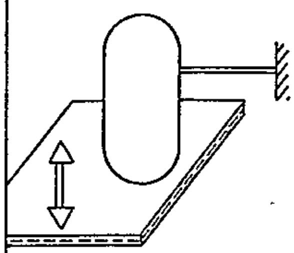


Fig. 8.1 Material Test, Structural Element Model Test and Structural Model Test

		Material testing	Structural element model test and analysis	Structural model test and analysis
Characteristic		material charactereristic test under uniform stress state	simple structural model test under non-uniform stress state	actual structural model test under non-uniform stress state
Example	thermal loading	 low-cycle fatigue test	 $K \cdot K_e' \cdot \Delta\varepsilon \sim N$	 $(\frac{S^*}{S} K^2, KK_e', K_w)\Delta\varepsilon \sim N$
	mechanical loading	 tensile test	 buckling test of cylinder	
	earth-quake	 ultra low-cycle fatigue test (rundam fatigue test)	 beam model (ultra low-cycle fatigue test)	
Design criteria		improvement of evaluation method for dominant bending stress state ↑	improvement of evaluation method for various influencing factors ↑	
		Material strength of critera	Structural design guide	

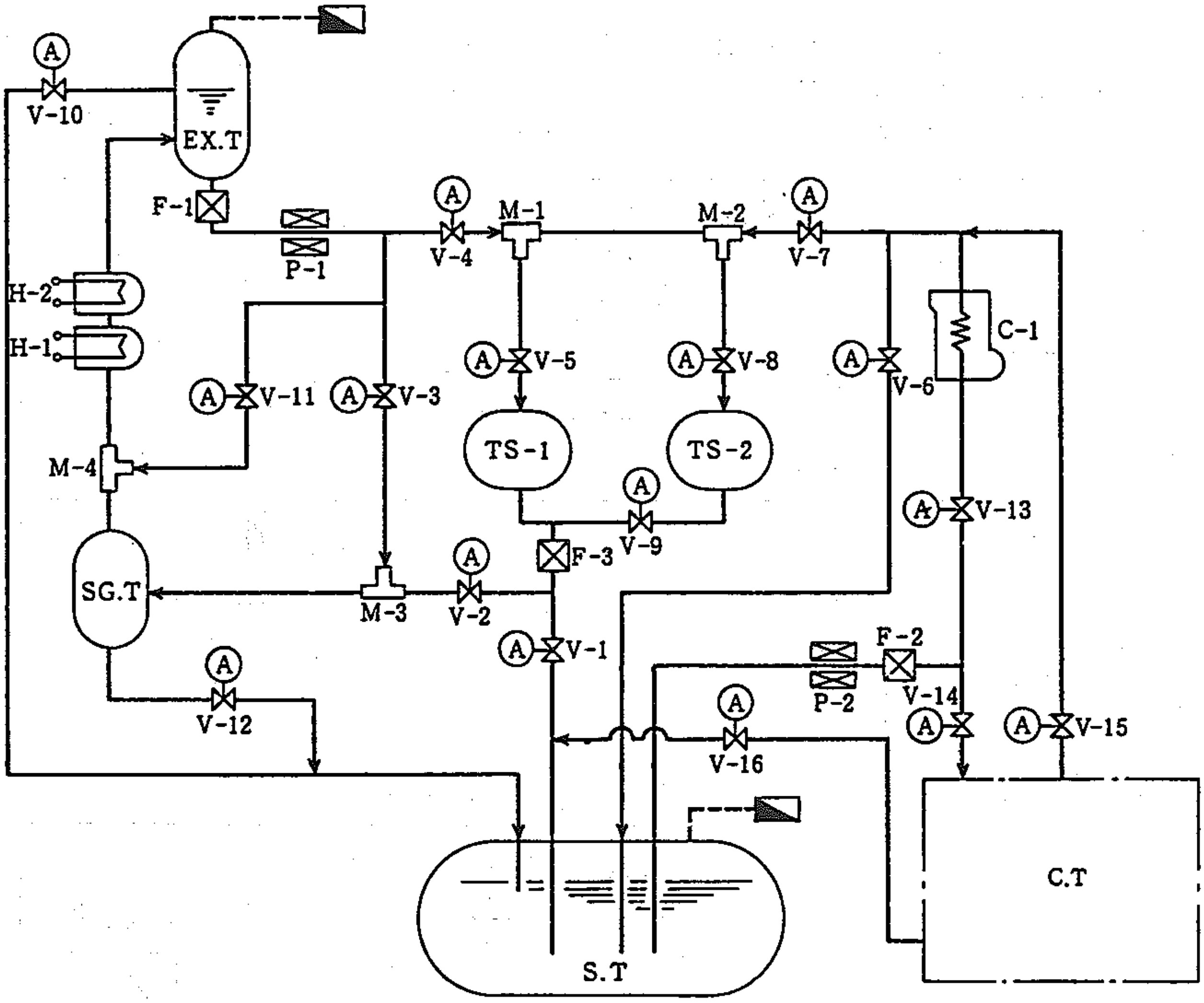
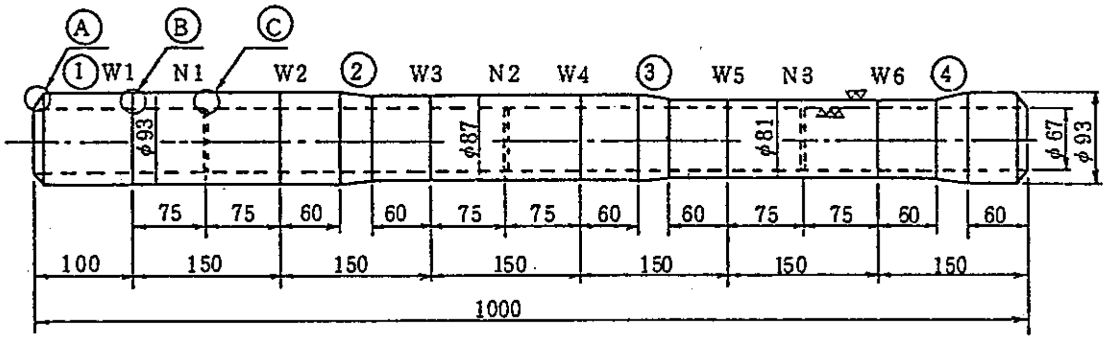
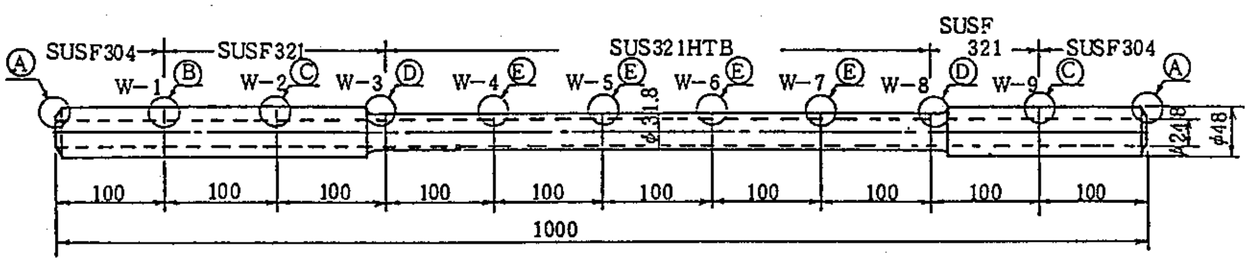


Fig. 8. A. 1　　Flow Diagram of Small Thermal Shock Test Loop(STST)



Test Specimen (TF-4~TF-8)



Test Specimen (TF-10)

Fig. 8. A. 2 Test Specimen

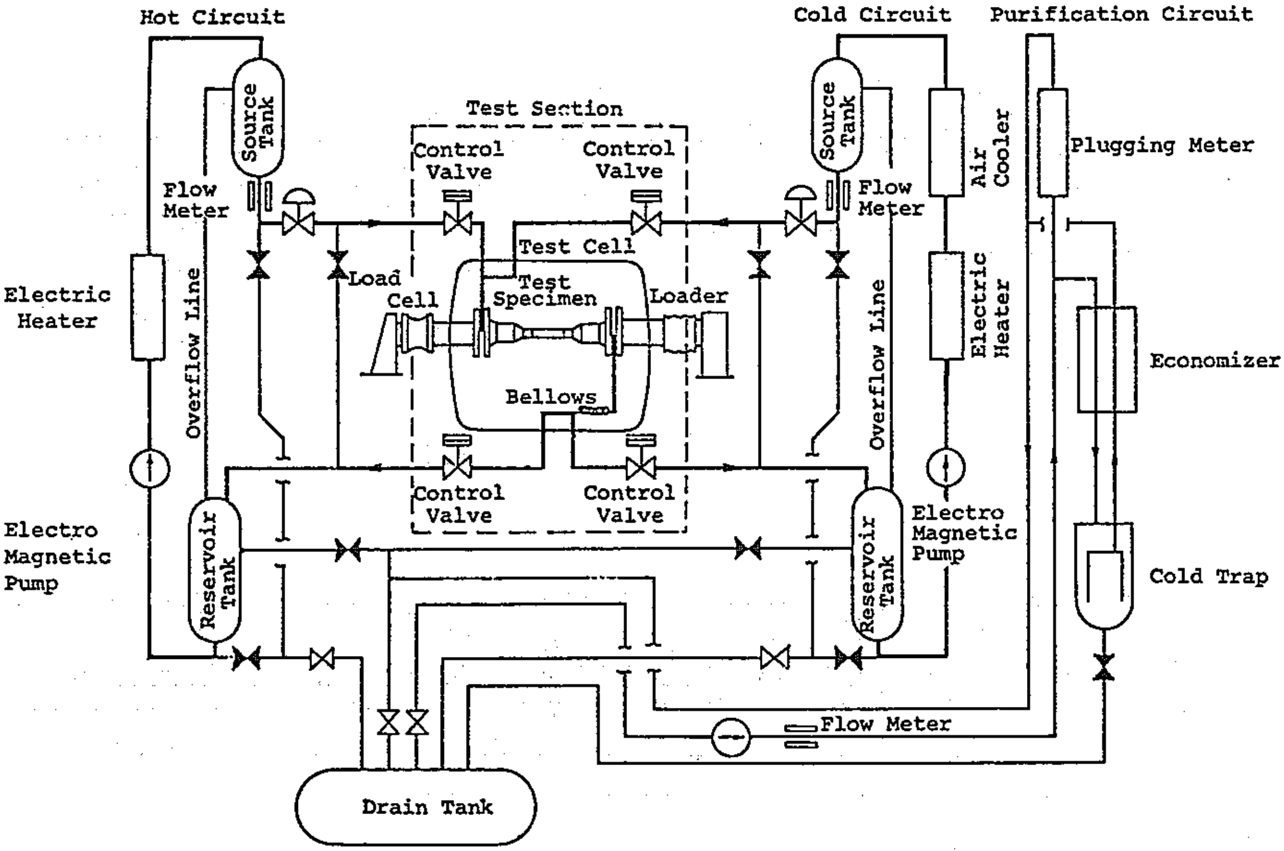
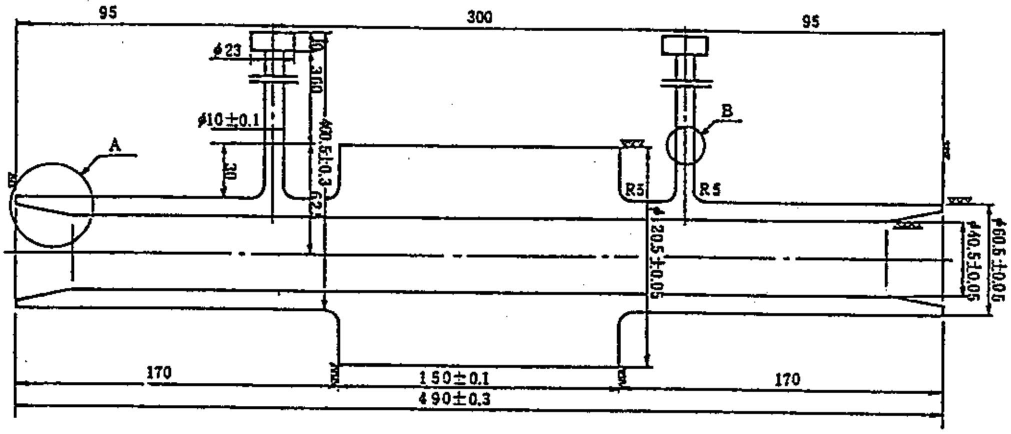
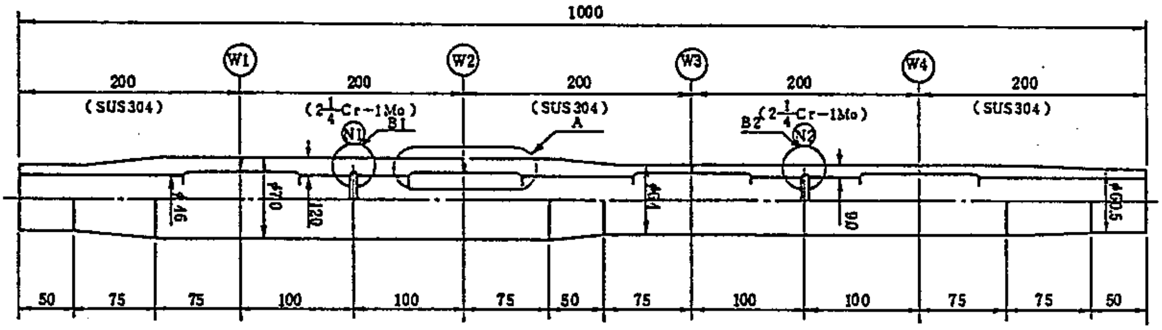


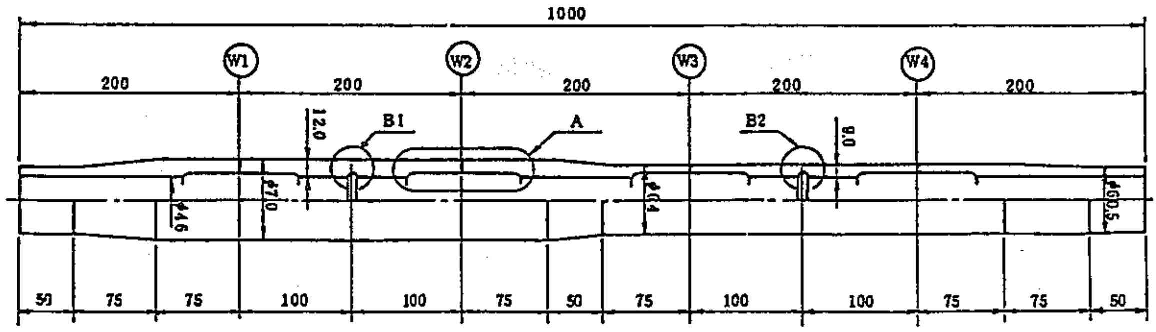
Fig. 8. A. 3　　Schematic of Sodium Piping Thermal Transient Test loop(SPTT)



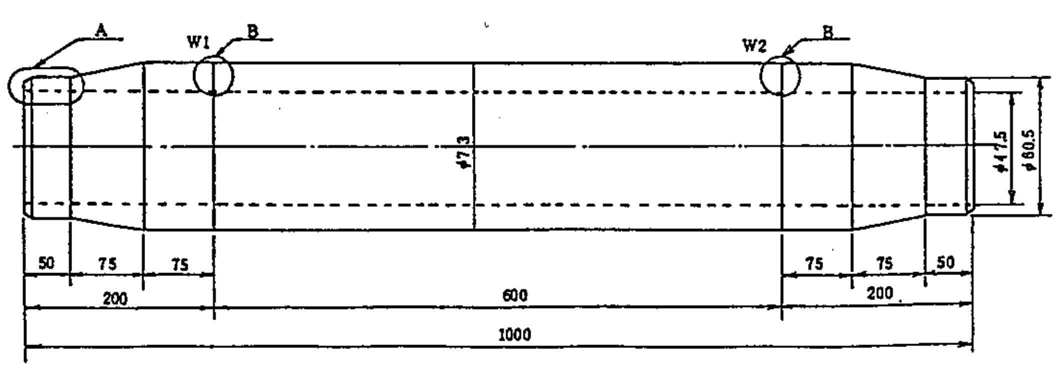
STF−1 Model



STF−2 Model



STF−3 Model



STF−10 Model

Fig. 8. A. 4 Test Specimen

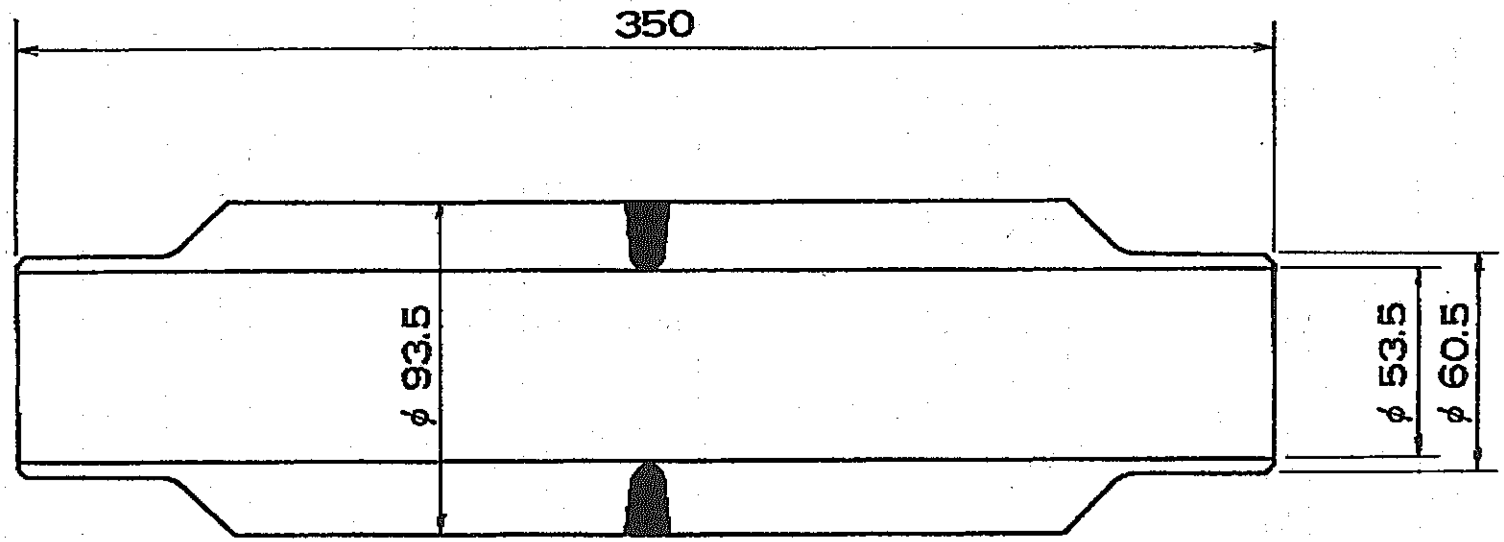
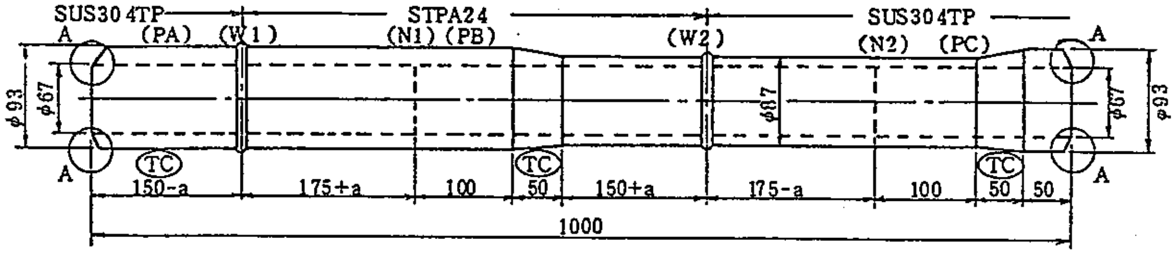
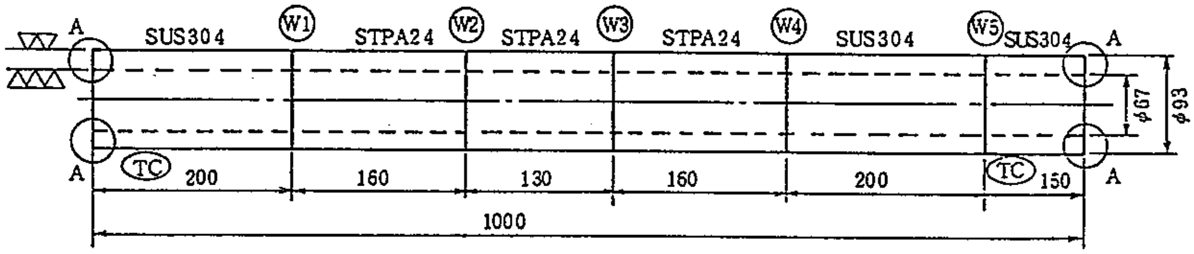


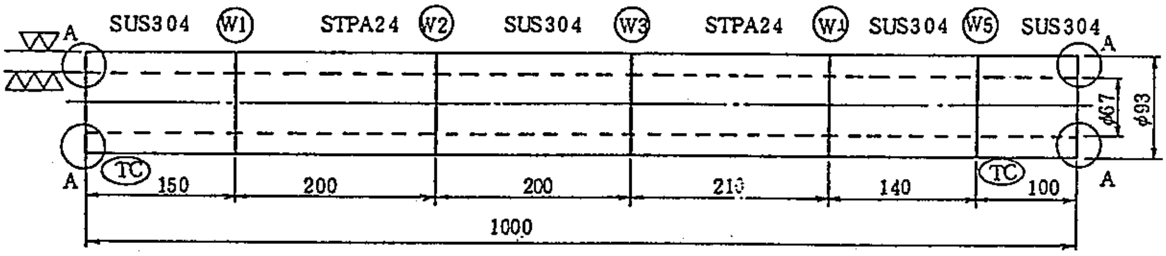
Fig. 8. A. 5 Thermal Creep-Fatigue Test of SUS316 Weldment



(a) DW−1~DW−8 Specimen



(b) DW−9 Specimen

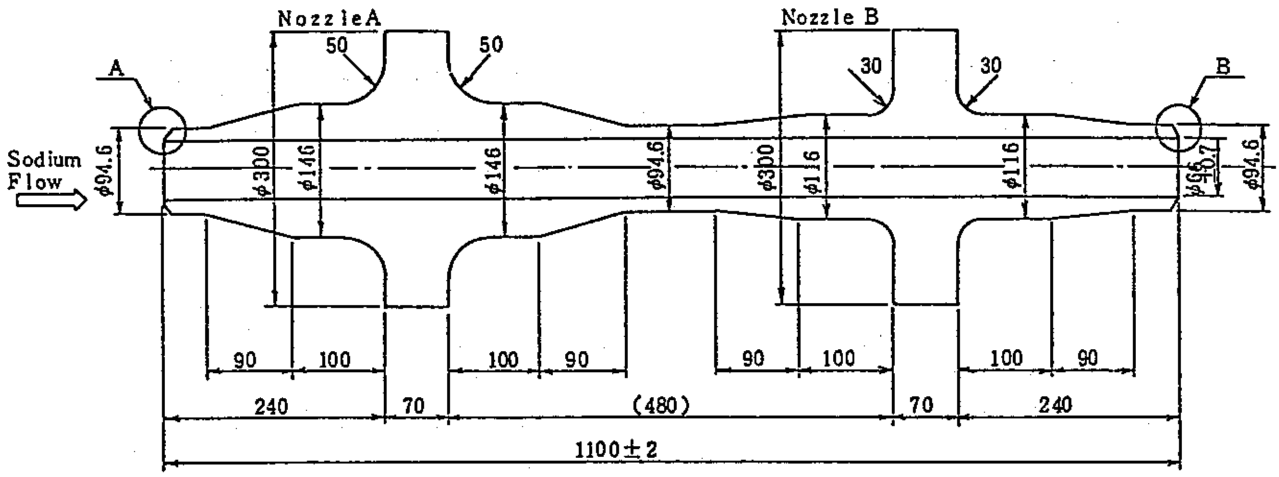


W1~W10 : Dissimilar Metal Weld Joint
N1, N2 : Circumferential Notch

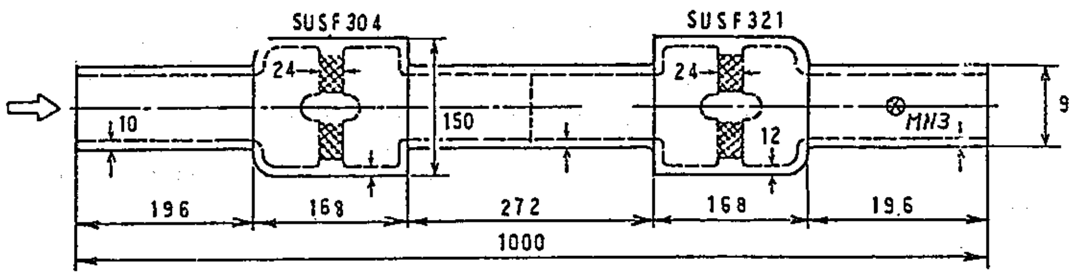
(c) DW−10 Specimen

Test Specimen (DW−1~DW−10)

Fig. 8. B. 1 Test Specimen



Test Specimen (NTF-1)



Test Specimen (TF-11)

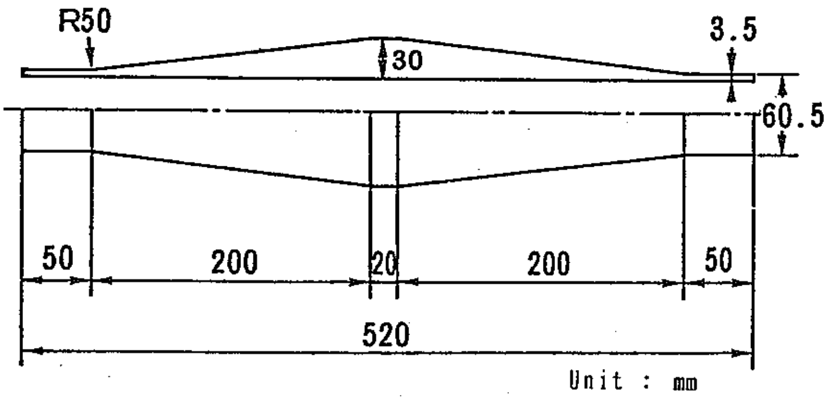
Fig. 8. C. 1 Test Specimen

THERMAL TRANSIENT TEST OF TAPER MODELS

● OBJECTIVE
TO INVESTIGATE THE EFFECTS OF THERMAL STRESS LEVEL AND SURFACE ROUGHNESS ON THERMAL CRACK INITIATION AND GROWTH

● TEST MODELS & TEST CONDITION
CONFIGURATION : TAPERD STRAIGHT PIPE
MADE OF SUS304

MODEL No.	ROUGHNESS LEFT	ROUGHNESS RIGHT	THERMAL TRANSIENT CYCLE	HOT	COLD
1	0.5S	25S	2000	600℃ 40 min	300℃ 10 min
2	6S	25S	1300		
3	50S	25S	700		



● Elastic Stress Analysis

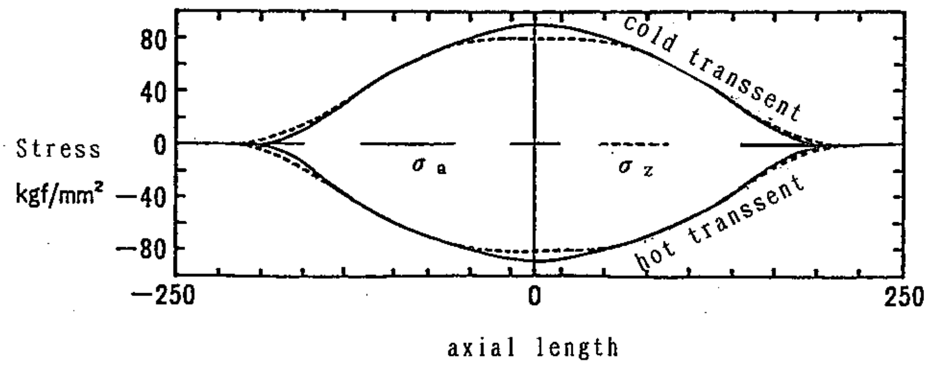


Fig. 8. D. 1 Thermal transient test of taper model

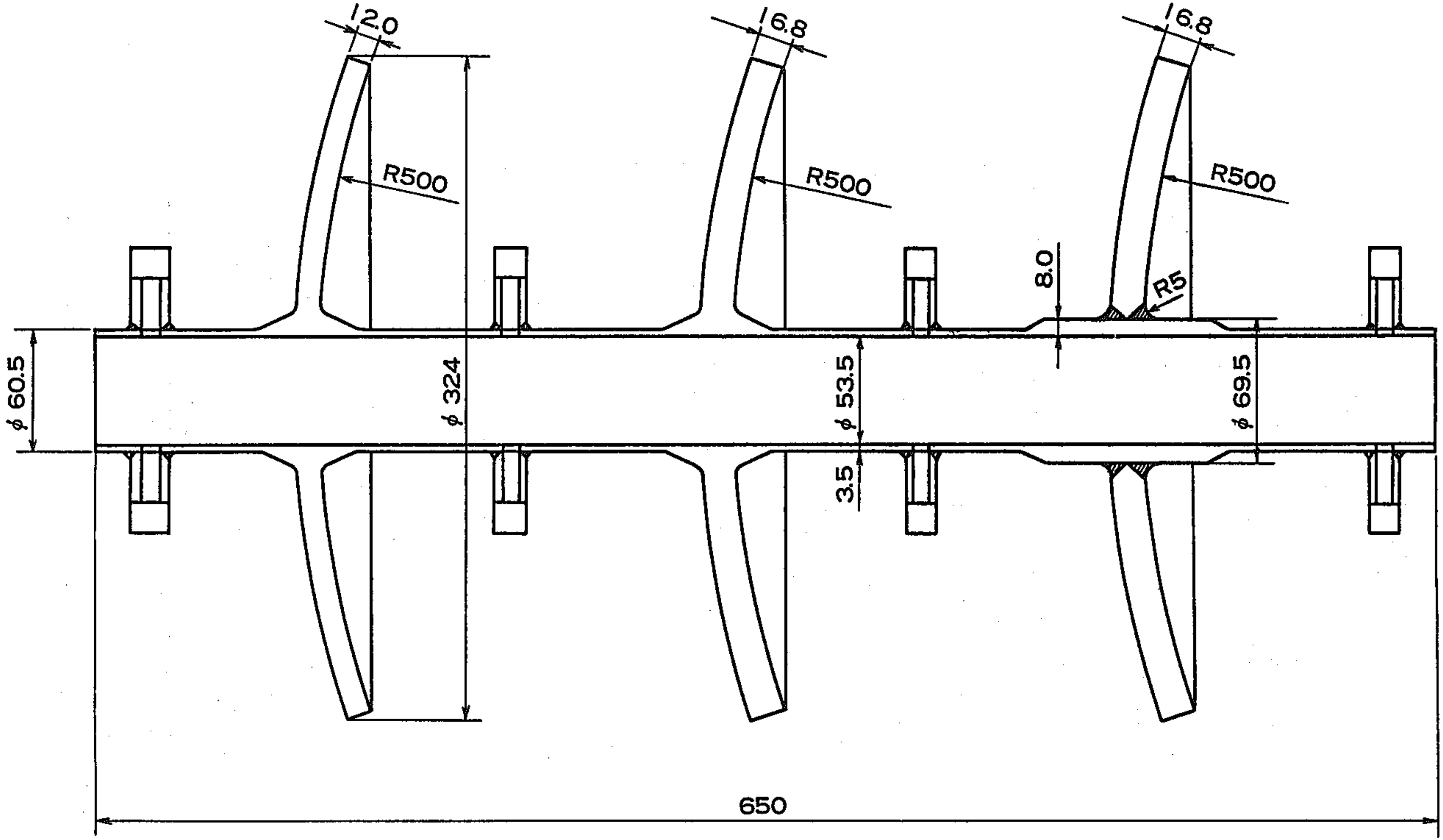


Fig. 8. D. 2　　Thermal Creep-Fatigue Test

ATTACHMENT 9

THERMAL TRANSIENT TEST IN TTS

1. ABSTRACT

FBRs are operated at higher temperature and lower pressure than LWRs. The dominant stresses in FBRs are thermal stresses arising from the temperature change of components during the operation. The structural integrity of FBRs is to be assured for repetitive application of combined thermal and mechanical loadings. High temperature structural design criteria serve to guard FBR structures against the possible failure modes. To establish well-qualified and reliable design criteria, strength test on realistic structural models representing geometric sizes and fabrication procedure of actual components are greatly needed under repetitive severe loadings simulating actual plant condition. TTS can answer such requirements to the full. Objectives of TTS is as follows.

- To validate or develop structural design criteria by identifying safety margin to failure inherent in the design criteria (Fig. 9. 1)
- To develop more reliable and economical structures for mitigating thermal stresses (Fig. 9. 2)
- To qualify or develop reliable and in expensive fabrication methods for the service under FBR operating condition
- To demonstrate the structural integrity or excellent performance of critical components under more severe loadings than actual ones encountered in FBRs (Fig. 9. 3)
- To develop more acurate life prediction method (Fig. 9. 4)

TTS is made up of a hot and a cold sodium loops, their control system, a mechanical force unit, a test section and data aquisition system. By switching valves in hot and cold sodium loops. TTS can repetitively impose very severe thermal transients on a test model. Two-set of electro-hydraulic actuators are usesd to apply mechanical loadings. The test section consists of a rigid test bed and a semi-air tight test cell accomodating a test model. The measures for the possible leakage of sodium are provided.

Key structures which are important from the viewpoint of strength evaluation can be commonly selected irrespectively of the design consept of FBRs. Usually various kinds of structural discontinuities are incorporated into one test model for the efficient accomplishment of the test. All the part of

interest in the test model are designed to have nearly the same lives by means of thermal-hydraulic and stress analysis and strength evaluation preceding the test.

Usual flow diagram of a study in TTS is shown in Fig.9.5, and apparatus of TTS is presented in Ref.(9.1).

Ref.(9.1) ; Nakanishi,S.,Watashi,K.,Kanazawa,S.,Aoki,T.,Imazu,A.,Kano,T.and Ishizaki,K.,Thermal Transient Test Facility for Structure,Stalpaert,J.ed.Trans. 8th SMIRT,Vol.E,pp.37-42

2. ARTICLE OF TESTING MODEL

A. THERMALLY AGED VESSEL MODEL TEST
B. REACTOR VESSEL MODEL TEST
C. BELLOWS EXPANSION JOINTS MODELS TEST
D. THERMAL STRESS MITIGATION STRUCTURE MODEL(1) TEST
E. THERMAL STRESS MITIGATION STRUCTURE MODEL(2) TEST
F. WELDED VESSEL MODEL TEST
G. THREE VESSELS TEST

3. SIMPLE DISCRIPTION

A. THERMALLY AGED VESSEL MODEL TEST

A.1 OBJECTIVE

(1) To confirm the TTS testing capacity
(2) To get creep-fatigue failure data on a long term aged thick-walled vessel
(3) To reflect the experience on the planning of the future test models

A.2 TEST DESCRIPTION

A configuration of a test model is a co-coon like vessel with outer diameter of 1 m and thickness of 50 mm as shown in Fig.10.A.1. Material is SUS 304. The model was constructed from a cylinder which was thermally aged at 600℃ during 10,294 hrs in air. The inner surface of the model was subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3 /min. In cold transient 250 ℃ sodium flows into the model during 15 min, and in hot transient 650℃ sodium during 30 or 15 min. Thermal transient was repeated up to 211 cycles.

A.3 RESULT

After the test crackings were observed at vertical weldment of the cylinder, fillet weldments of rag attachments, small nozzle weldments, and so on.

B. REACTOR VESSEL MODEL TEST

B.1 OBJECTIVE

(1) To get the creep-fatigue data of the model representing FBRs components subject to severer thermal transient loadings than those encountered in FBRs operating condition

(2) To evaluate the performance and structural integrity thermal liner structures

(3) To clarify the safety margin considered in "Limit to Creep-Fatigue Damage" in "Elevated Temperature Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor"

(4) To develop creepv-fatigue life prediction method based on inelastic analysis

B.2 TEST DESCRIPTION

The model is a vertical type vessel, 2.1 m high, 40 mm thick and 800 mm in inner diameter as shown in Fig.9.B.1. The model has 7 testing portions for creep-fatigue strength test ; namely an inlet nozzle with the short pipe, an outlet nozzle with the safe end, a thick wall body, a tapering portion, a Y-piece and stud bolts for thermal liners. In those portions gas tangsten arc weldment, shield metal arc weldment and/or full penetration weldment are included. All parts of the model are made of SUS 304 stainless steel. Especially, the testing portions were made of forged 304 stainless steel well representing large forged structures in FBRs.

The inner surface of the model was subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3 /min. In cold transient 250 ℃ sodium flows into the model during 15 min, and in hot transient 600℃ sodium during 105 min. Thermal transient was repeated up to 1002 cycles.

Acoustic emmision signals were continously recorded and ultrasonic testing at 200℃ was performed.

B.3 RESULT

The creep-fatigue failure test was successfully ended. Creep-fatigue cracks having intergranular crack surface were observed at all of the designed test portions.The thermal liner structures are very effective for mitigation of thermal transient stresses. Acoustic emission has the potential to find the cracking under flowing sodium. The "Limit to Creep-Fatigue Damage" has more than 90 safety margin for the base metal and the finished weldment without reinforcement and penetration bead, and about 40 safety margin for the weldment with penetration bead. These safety margin can be mainly attributed to the overestimated strain range. Creep-fatigue damage evaluation method based on inelastic analysis was proposed. By this method the safety margin can be lowered to 10, then as a result allowerble design region can be expanded. Crack growth evaluation method using inelastic fatigue J-integral and creep J-integral was developed for structures subject to thermal creep-fatigue loadings.

Detail is presented in Ref. (9.2).

Ref. (9.2) ; Watashi, K., Kanazawa, S., Umeda, H., Koide, A., Imazu, A. and Yoshida, H., Creep-fatigue test of a thick-walled vessel under thermal transient loadings, Nuclear Engineering and Design, To be appeared.

C. BELLOWS EXPANSION JOINTS MODELS TEST

C.1 OBJECTIVE

(1) To investigate feasibility of bellows type expansion joints under thermal transient loadings

(2) To investigate an applicability of "Limit to Creep-Fatigue Damage" of ETSDG to specific discontinuities used in bellows type junctions

(3) To investigate thermo-hydraoulic behavior in the junctions during thermal transients for defining thermal boundary condition for thermal stresses analysis

C.2 TEST DESCRIPTION

Two models were constructed for thermal transient. One is an integrated model of critical portions used in vertical type joints of thin walled-bellows and thich walled-bellows. The another is an integrated model of critical portions used in horizontal type junctions of thin-walled bellows. Configurations of the models are shown in Fig. 9.C.1. The junctions of y- and E-types was made of SUS 304, and bellows SUS 316.

The inner surface of the models were subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3/min. In cold transient 250℃ sodium flows into the model during 30 min, and in hot transient 620℃ sodium during 90 min. Thermal transient was repeated up to 427 cycles.

C.3 RESULT

Detail is presented in Ref.(9.3).

Ref.(9.3) ; Saito, T., Umeda, H., Kanazawa, S., Watashi, K. and Imazu, A., Thermal transient test of FBR piping bellows model, ASME-JSME Joint Meeting (1989), Honolulu, To be appeared.

D. THERMAL STRESS MITIGATION STRUCTURE MODEL(1) TEST

D.1 OBJECTIVE

(1) To get the creep-fatigue data of the model representing FBRs components subject to severe thermal transient loadings

(2) To evaluate an effect of welding method on thermal creep-fatigue failure

D.2 TEST DESCRIPTION

The model is a vertical type cylindrical vessel supported by conical skirt, 2400 mm high, 30 mm or 40 mm thick and 1100 mm in outer diameter as shown in Fig.9.D.1. The model has 5 testing portions for creep-fatigue failure ; namely an inlet nozzle of fluid head type, an outlet nozzle of set-in weld type, a conical support skirt, a cylinder with vertical slits and an inner shell with circumferential weld(MIG, SMAW, EBW and TIG are included.) All parts of the model are made of SUS 304 stainless steel.

The inner surface of the model was subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3/min. In cold transient 250 ℃ sodium flows into the model during 40 min, and in hot transient 620℃ sodium during 80 min. Thermal transient was repeated up to 1300 cycles.

D.3 RESULT

After the thermal transient test, inner and outer surfaces of the model were inspected. Creep fatigue cracks were observed at the designed test portions. Heat transfer analyses and thermal stress analyses were carried out, and creep-fatigue damages were evaluated according to "Limit to Creep-Fatigue Damage" in "Elevated Temperature Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor and "TTSDS"(TTS Design Standard for exclusive use). It was confirmed that the "Limit to Creep-Fatigue Damage" has enough safty margin. Crack data and the creep-fatigue damages according to TTSDS were investigated comparatively, then good correlation between the two was confirmed.

This result corresponds well with the former result.

E. THERMAL STRESS MITIGATION STRUCTURE MODEL(2) TEST

E.1 OBJECTIVE

(1) To get the creep-fatigue data of the model representing FBRs components subject to severe thermal transient loadings

(2) To evaluate the performance and structural integrity of internal structures such as tube to perforated plate weld, flow straightener and thermal protection panel

E.2 TEST DESCRIPTION

The model is a vertical type cylindrical vessel supported by conical skirt, 2550 mm high, 25 mm or 40 mm thick and 850 mm in outer diameter as shown in Fig. 9.E.1. The model has 7 testing portions for creep-fatigue strength test ; namely an inlet nozzle, an outlet nozzle of fluid head type, a tapering portion, a Y junction, a cylindrical support skirt and a conical support skirt. The model also has 3 testing portions for performance test ; namely tube to perforated plate welds, a thermal protection panel and a flow straightener. All parts of the model are made of SUS 304 stainless steel, except the liners covering the flow straightener.

The inner surface of the model was subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3/min. In cold transient 250℃ sodium flows into the model during 30 min, and in hot transient 600℃ sodium during 90 min. Thermal transient will be repeated up to 1300 cycles.

E.3 RESULT

The thermal transient test and destructive test were sucessfully ended. Elastic stress analysis and damage evaluation are underwoy. I nelastic stress analysis planed.

F. WELDED VESSEL MODEL

F.1 OBJECTIVE

(1) To get the creep-fatigue data of the model made of SUS 316LCN.

(2) To develop predicting method of creep-fatigue based on the method developed using SUS 304 data.

F.2 TEST DESCRIPTION

The model is a vertical type cylindrical vessel supported by conical skirt, 2114 mm high, 20 mm thick and 800 mm in outer diameter as shown in Fig.9.F.1. The model has three sorts of testing portions for creep-fatigue strength test ; namely an outlet nozzle of fluid head type, several kind of vessel weldments and fillet weldment, and specilly designed structural discontinuity. All parts of the model are made of SUS 316LCN stainless steel.

The inner surface of the model was subjected to repeated cold and hot thermal transients by sodium of the constant flow rate of 1 m^3 /min. In cold transient 250℃ sodium flows into the model during 30 min, and in hot transient 600℃ sodium during 90 min. The model was designed to failure at 1,800 cycles of thermal transient cycles.

F.3 RESULT

We expect sucessful test in this year.

G. THREE-VESSEL MODELS TEST

The models are designed in detail now.

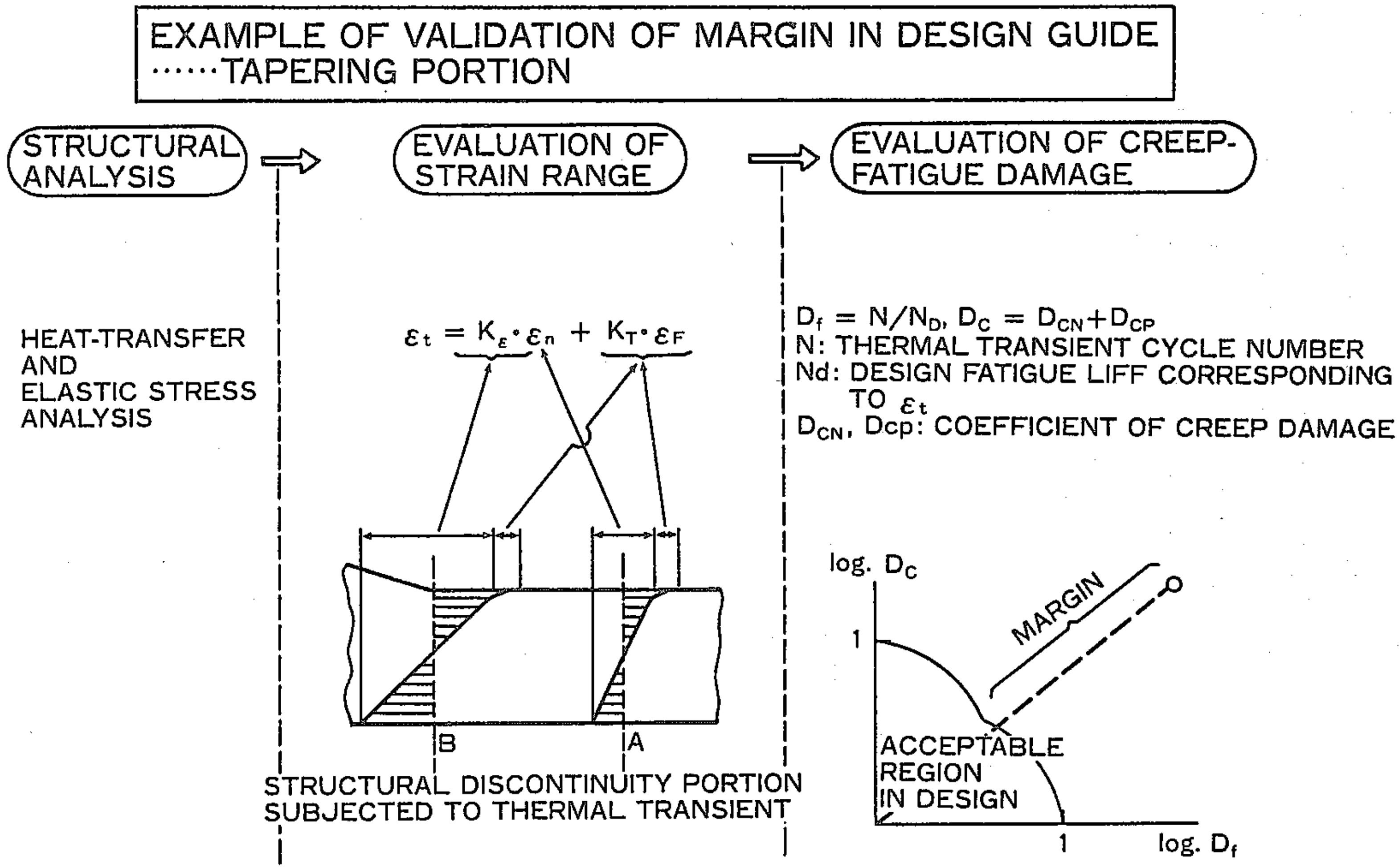

EXAMPLE OF VALIDATION OF MARGIN IN DESIGN GUIDE
……TAPERING PORTION
STRUCTURAL ANALYSIS
EVALUATION OF STRAIN RANGE
EVALUATION OF CREEP-FATIGUE DAMAGE
HEAT-TRANSFER AND ELASTIC STRESS ANALYSIS
$\varepsilon_t = K_\varepsilon \cdot \varepsilon_n + K_T \cdot \varepsilon_F$
B
A
STRUCTURAL DISCONTINUITY PORTION SUBJECTED TO THERMAL TRANSIENT
$D_f = N/N_D$, $D_C = D_{CN} + D_{CP}$
N: THERMAL TRANSIENT CYCLE NUMBER
Nd: DESIGN FATIGUE LIFF CORRESPONDING TO ε_t
D_{CN}, Dcp: COEFFICIENT OF CREEP DAMAGE
log. D_C
1
MARGIN
ACCEPTABLE REGION IN DESIGN
1
log. D_f

Fig. 9.1

DEVELOPMENT OF THERMAL STRESS MITIGATION STRUCTURE

THERMAL LINER STRUCTURE IN R/V

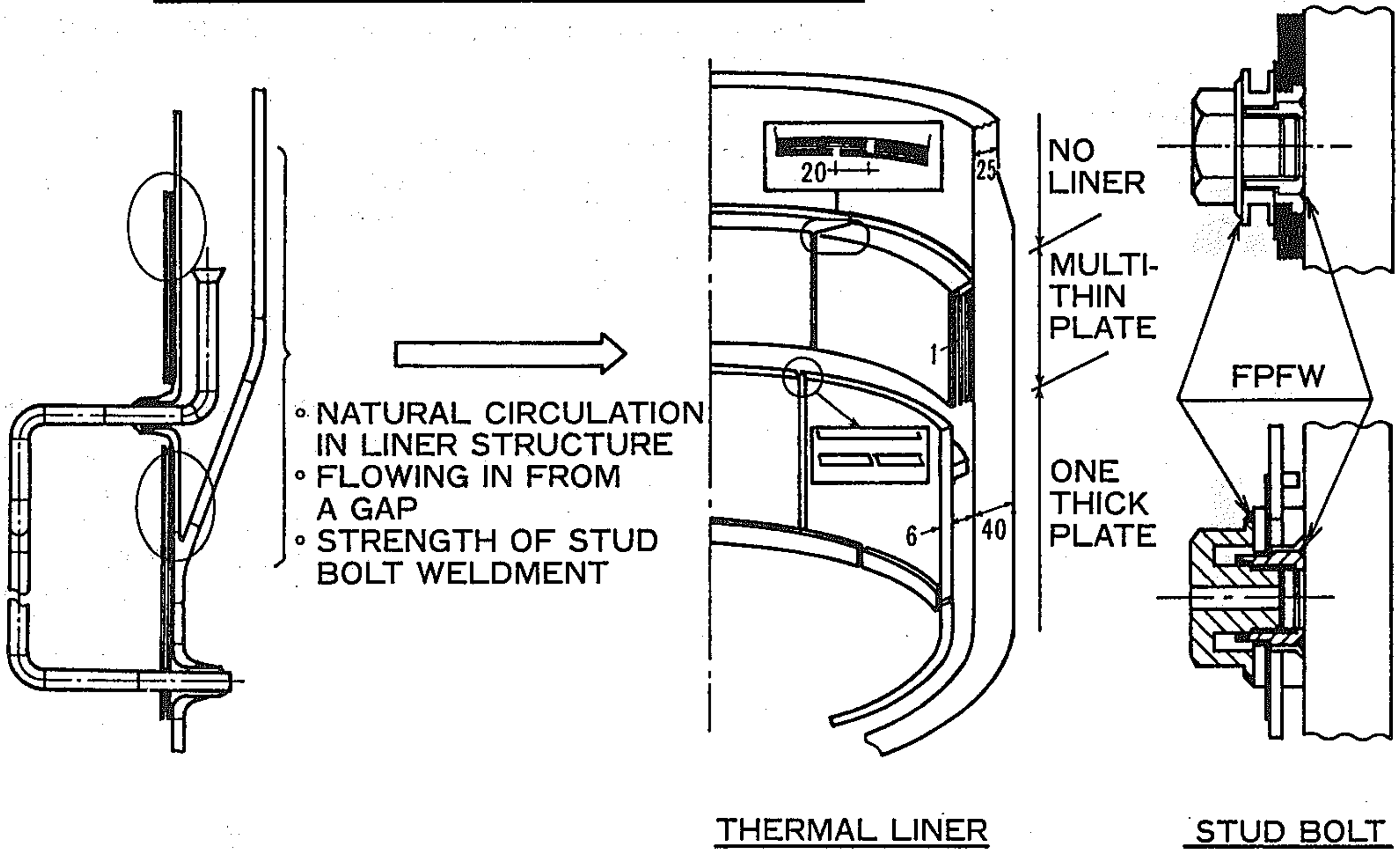
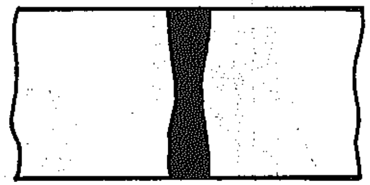


Fig. 9. 2

EXAMPLE OF VALIDATION OF STRUCTURAL INTEGRITY ……WELDING JOINT

PROBLEM

- SHAPE DISCONTINUITY
  - ·PENETRATION BEAD
  - ·REINFORCEMENT
  - ·SHRINKAGE
- METALLURGICAL DISCONTINUITY
- RESIDUAL STRESS



NARROW GAP GTAW WITH FINISHING

- IDEALIZED ANALYSIS ONLY COULD NOT EVALUATE THE STRENGTH.
- STRAIN BEHAVIOR DURING THERMAL TRANSIENTS COULD NOT BE APPRECIATE BY USUAL MATERIAL TEST.

SHIELD METAL ARC WELDMENT WITHOUT FINISHING

R&D

MODEL FABRICATED ACCORDING TO FBR'S FABRICATION AND EXAMINATION RULE WOULD BE TESTED UNDER SIMULATED SEVERER CONDITION TNAN THAT OF FBRS.

Fig. 9. 3

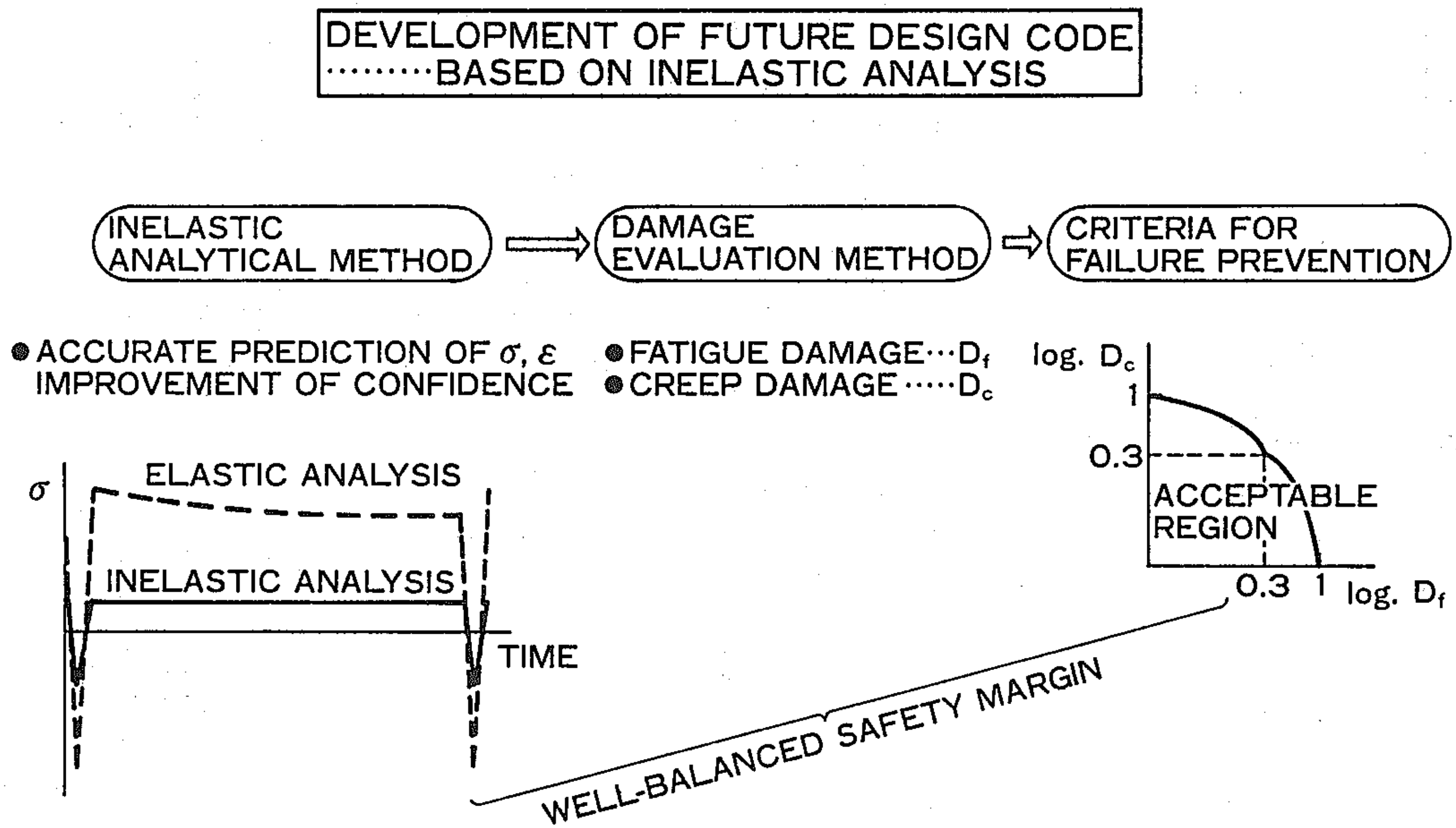

DEVELOPMENT OF FUTURE DESIGN CODE
·········BASED ON INELASTIC ANALYSIS
INELASTIC ANALYTICAL METHOD
DAMAGE EVALUATION METHOD
CRITERIA FOR FAILURE PREVENTION
● ACCURATE PREDICTION OF σ, ε
IMPROVEMENT OF CONFIDENCE
● FATIGUE DAMAGE···D_f
● CREEP DAMAGE·····D_c
σ
ELASTIC ANALYSIS
INELASTIC ANALYSIS
TIME
log. D_c
1
0.3
ACCEPTABLE REGION
0.3
1
log. D_f
WELL-BALANCED SAFETY MARGIN

Fig. 9. 4

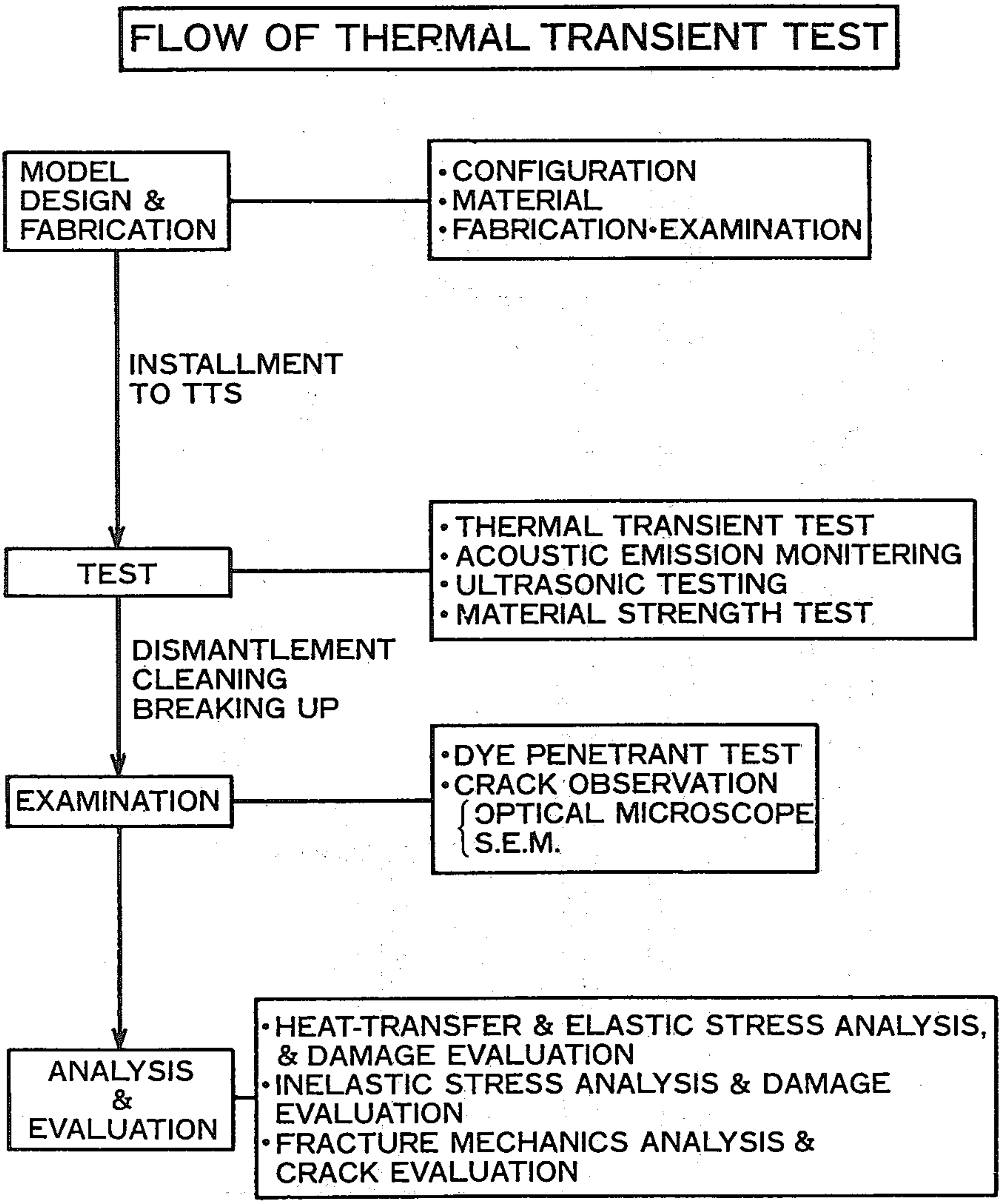

FLOW OF THERMAL TRANSIENT TEST
MODEL DESIGN & FABRICATION
•CONFIGURATION
•MATERIAL
•FABRICATION•EXAMINATION
INSTALLMENT TO TTS
TEST
•THERMAL TRANSIENT TEST
•ACOUSTIC EMISSION MONITERING
•ULTRASONIC TESTING
•MATERIAL STRENGTH TEST
DISMANTLEMENT
CLEANING
BREAKING UP
EXAMINATION
•DYE PENETRANT TEST
•CRACK OBSERVATION
OPTICAL MICROSCOPE
S.E.M.
ANALYSIS & EVALUATION
•HEAT-TRANSFER & ELASTIC STRESS ANALYSIS, & DAMAGE EVALUATION
•INELASTIC STRESS ANALYSIS & DAMAGE EVALUATION
•FRACTURE MECHANICS ANALYSIS & CRACK EVALUATION

Fig. 9.5

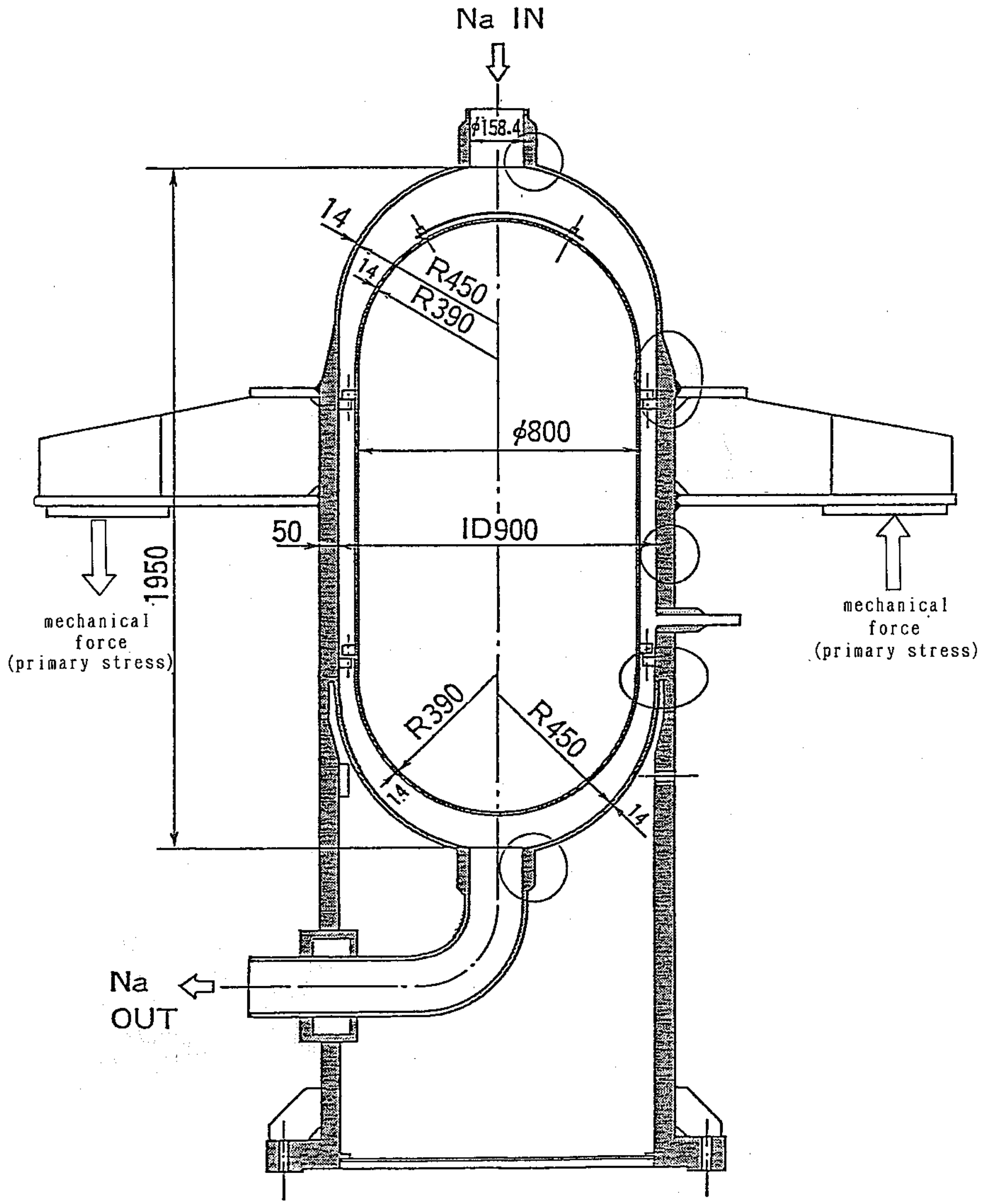


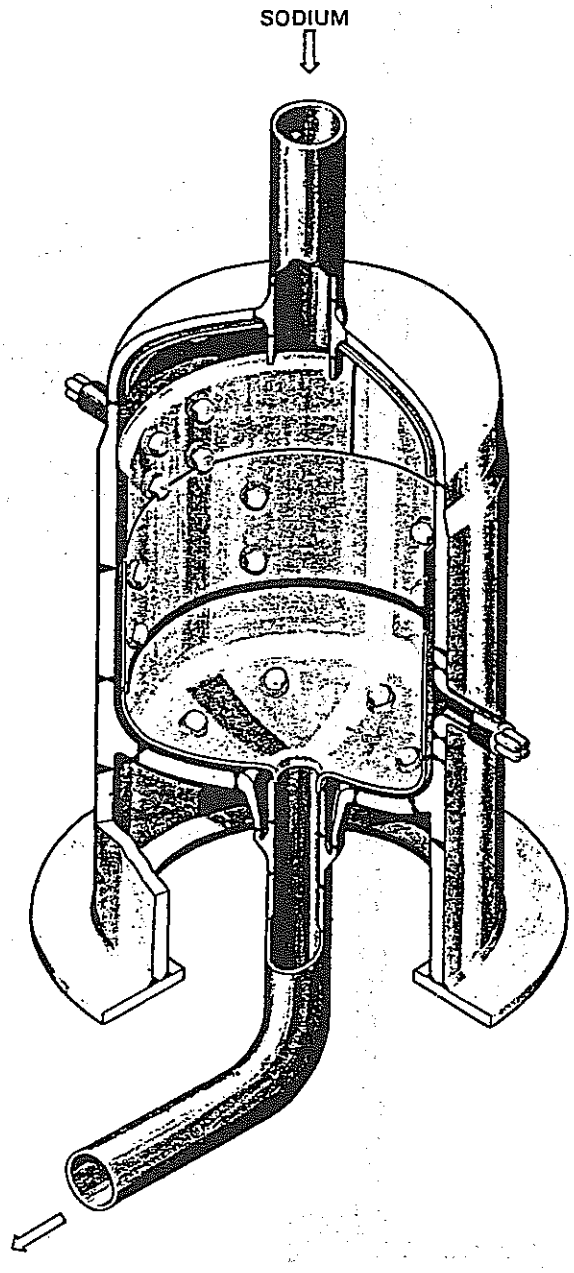
Fig. 9. A. 1　Thermally aged vessel model

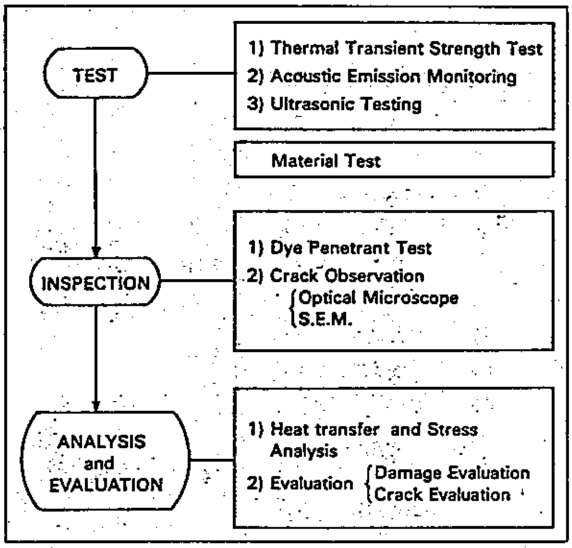
Vessel Model

The model is a cocoon-shaped vessel made of type 304 stainless steel. It has seven portions of interest, namely three nozzles, stud bolts for thermal liner attachment, a Y piece junction, a thick-walled cylindrical body and a tapering portion including gas tungsten arc welding, shield metal arc welding or perfect fillet welding joints.

Test Condition

THERMAL TRANSIENT		600°C ↔ 250°C
CYCLE TIME		2hrs
•DIMENSIONS		
HEIGHT		2100mm
OUTSIDE DIAMETER		880, 850mm
INSIDE DIAMETER		800mm
THICKNESS		40, 25mm
•INSTRUMENTATION		
THERMOCOUPLES	INSIDE	70
	OUTSIDE	50
STRAIN GAGES	OUTSIDE	7
LVDT	OUTSIDE	10






Rock Candy Patterns on Crack Surface of Upper Part of Vessel Model

Fig. 9. B. 1 Reactor vessel model

Bellows Expansion Joint Model

Two models made of stainless steel are connected in series. They are a vertical and a horizontal type piping bellows models. They have eight portions of interest namely four Y piece junctions, two ε type junctions, one T type junction and thick wall bellows.

Test Condition

THERMRL TRANSIENT	600℃→250℃
CYCLE TIME	3 hrs

VERTICAL TYPE

•DIMENSIONS

HEIGHT	3195mm
DIAMETER	610mm
THICKNESS	8, 10, 20, 60mm

•INSTRUMENTATION

THERMOCOUPLES	125
STRAIN GAGES	20
LVDT	8

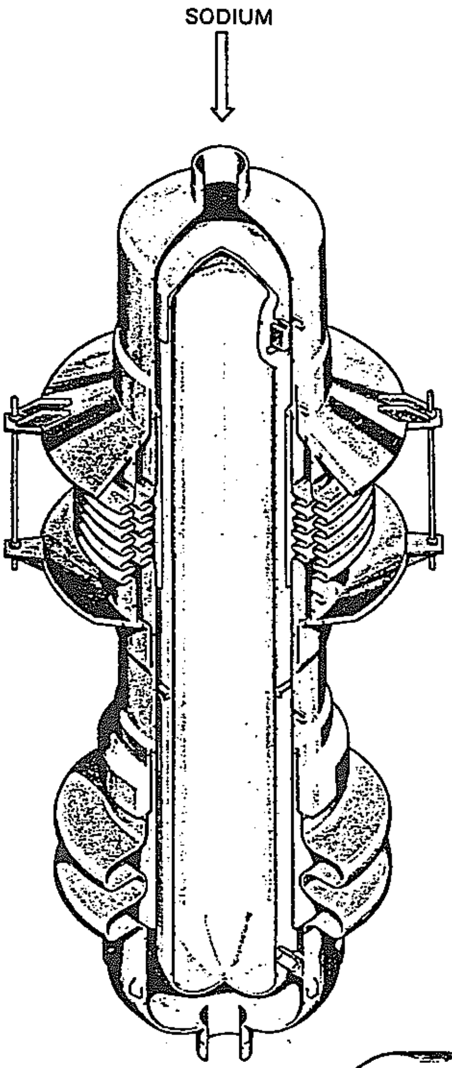
HORIZONTAL TYPE

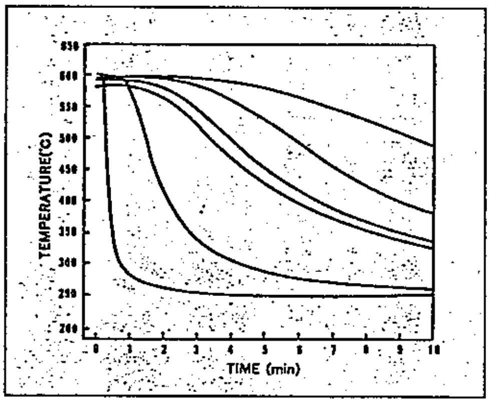
•DIMENSIONS

LENGTH	2575mm
DIAMETER	610mm
THICKNESS	8, 10, 20mm

•INSTRUMENTATION

THERMOCOUPLES	147
STRAIN GAGES	11





Temperature Change of Bellows Expansion Joint Model (Horizontal Type)

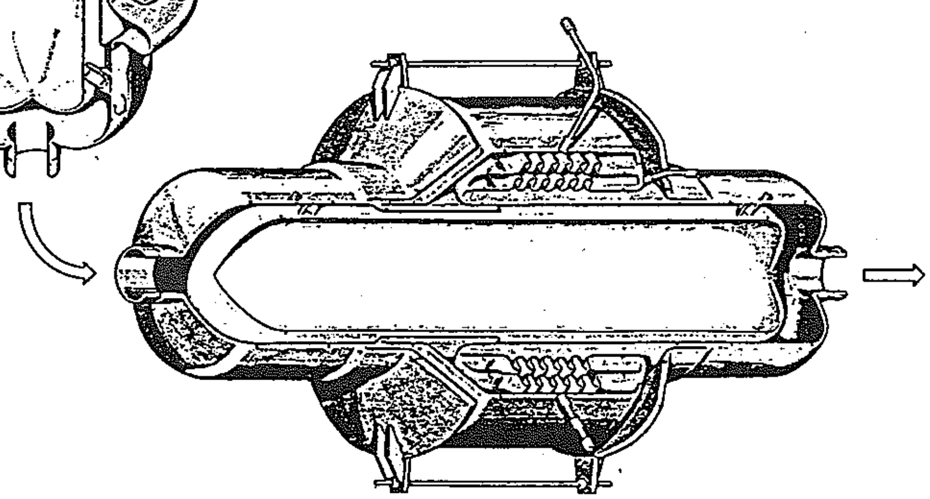
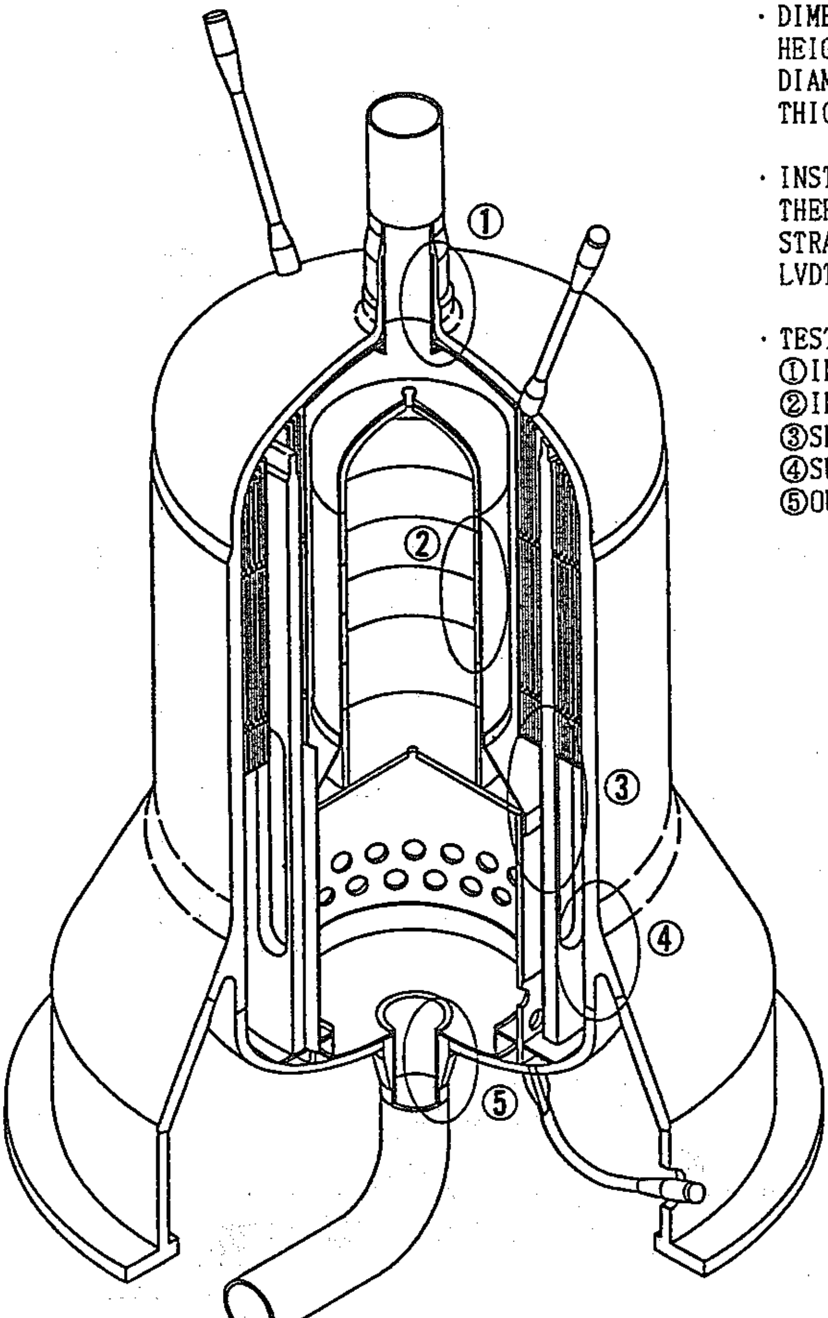


Fig. 9. C. 1 bellows expansion joint model



· DIMENSIONS

HEIGHT	2400mm
DIAMETER	1100mm
THICKNESS	6,20,30,40mm

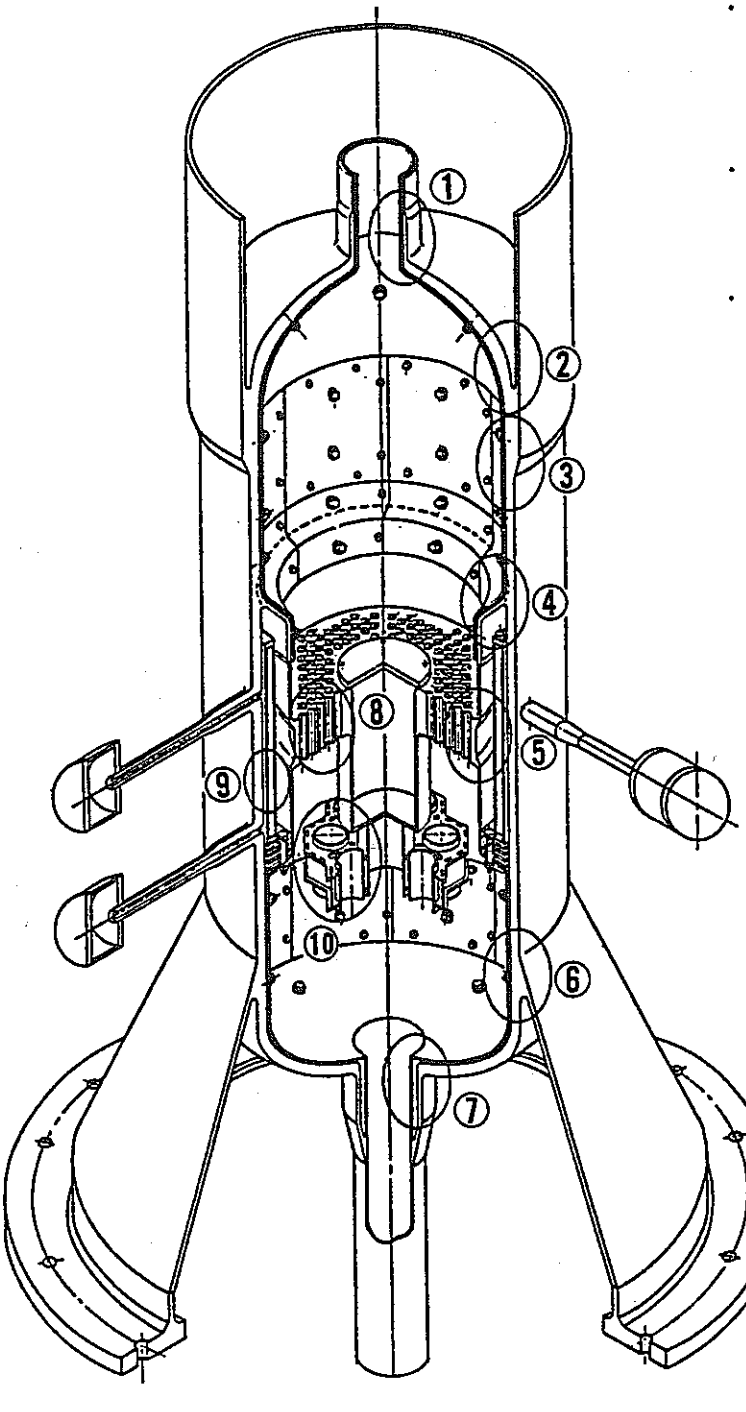
· INSTRUMENTATION

THERMOCOUPLES	182
STRAIN GAGES	8
LVDT	4

· TESTING PORTION

①INLET NOZZLE
②INNER SHELL WELD
③SLITTED CYLINDER
④SUPPORT SKIRT
⑤OUTLET NOZZLE

Fig. 9. D. 1 Thermal Stress Mitigation Structure Model (1)



- DIMENSIONS
  HEIGHT 2455mm
  DIAMETER 850mm
  THICKNESS 5,15,25,40,100mm
- INSTRUMENTATION
  THERMOCOUPLE 192
  LVDT 4
- TESTING PORTION
  ①INLET NOZZLE
  ②CYLINDRICAL SUPPORT SKIRT
  ③THICKNESS DISCONTINUITY
  ④Y-JUNCTION
  ⑤PLATE TO SHELL JUNCTION
  ⑥CONICAL SUPPORT SKIRT
  ⑦OUTLET NOZZLE
  ⑧PERFORATED PLATE
  ⑨THERMAL PROTECTION PANEL
  ⑩FLOW STRAIGHTENER

Fig. 9. E. 1 Thermal Stress Mitigation Structure Model (2)

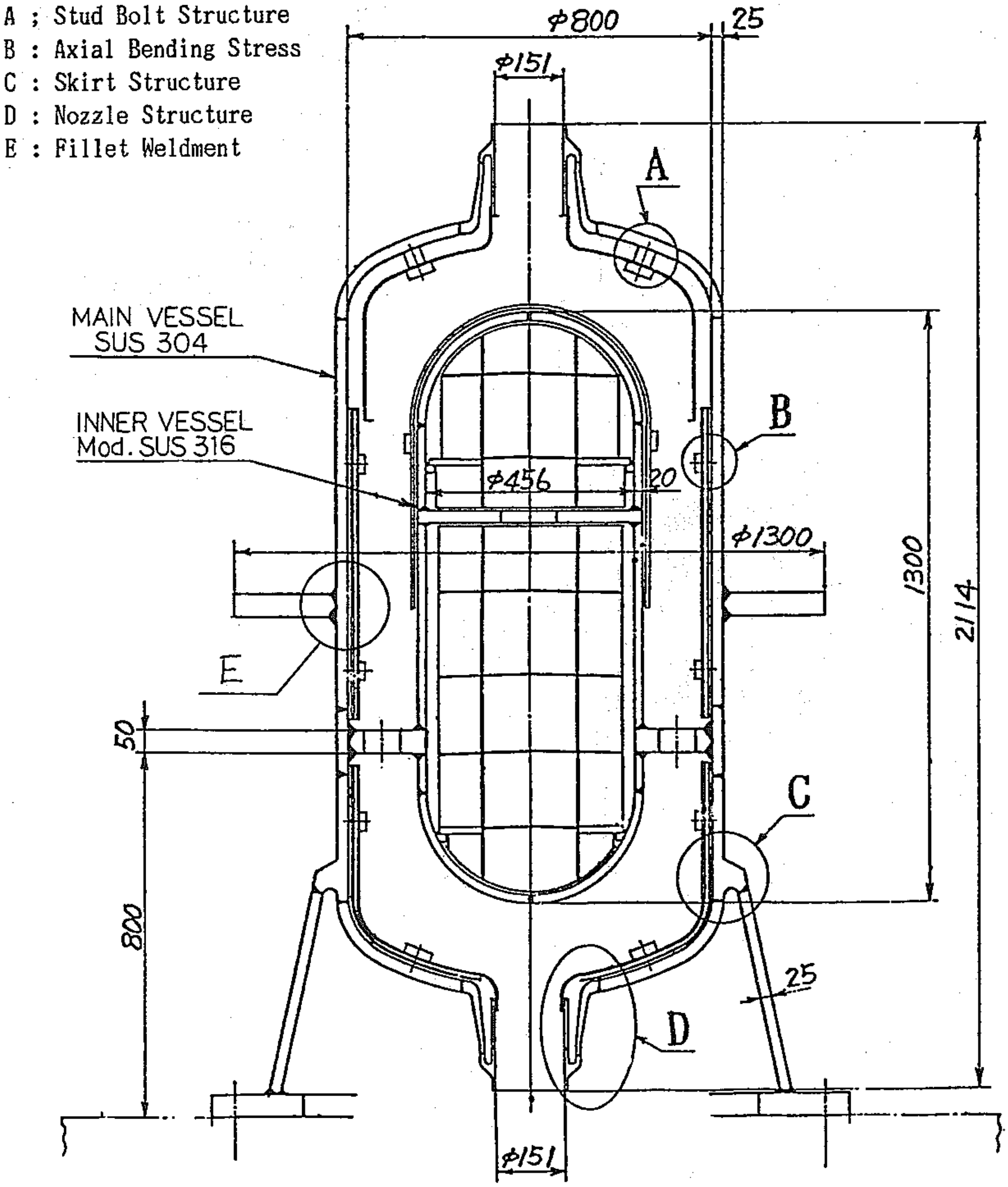


Fig. 9. F. 1 Welded Vessel Model

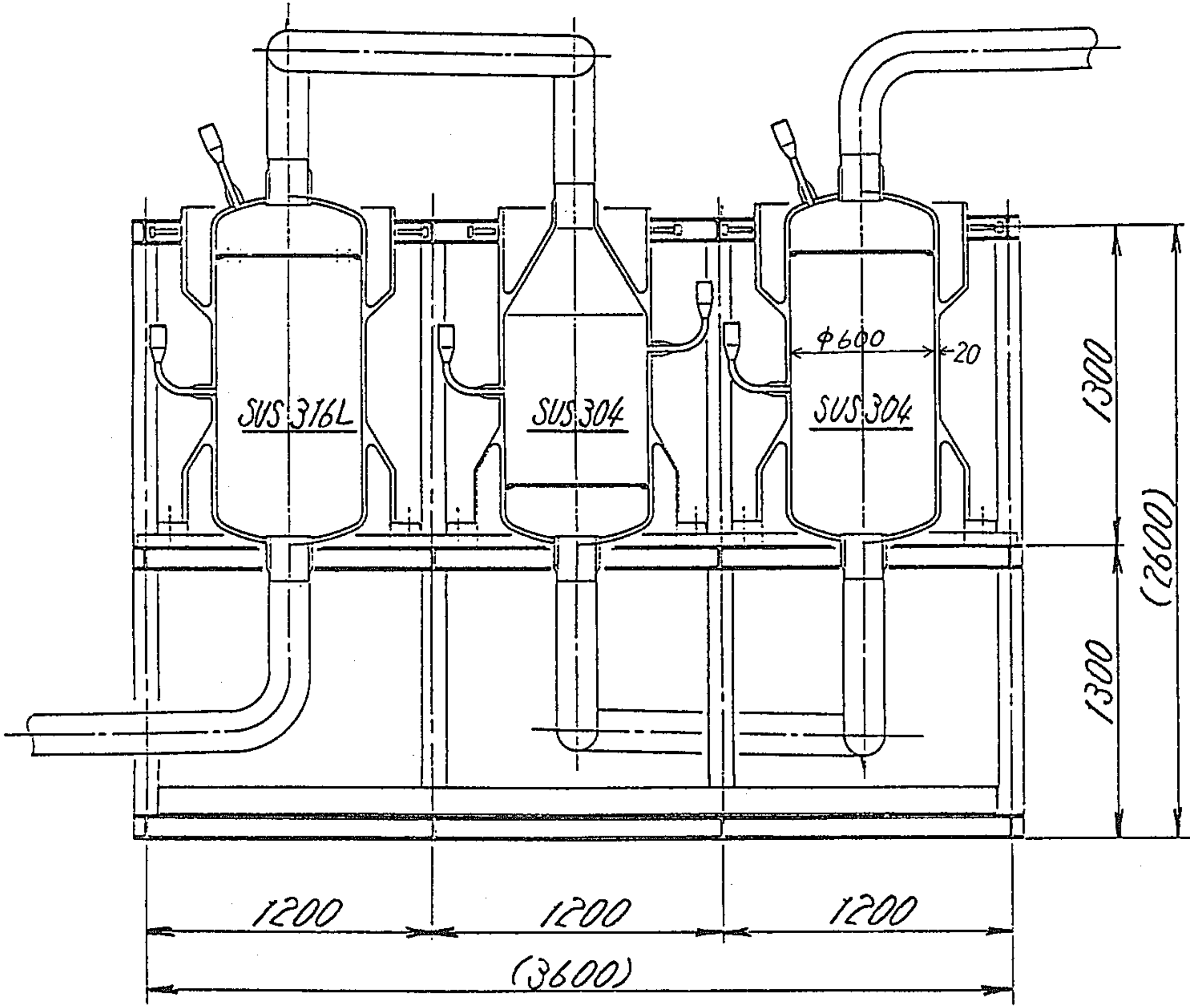


Fig. 9. G. 1　Three vessels model

ATTACHMENT 10

FRACTURE MECHANICS TEST

1. ABSTRACT

Fracture mechanics is a powerful tool for assessments of components and pipings integrity. Stable crack growth test under several sorts of loadings are performing to develop an evaluation method for structural integrity assessment. Unstable fracture test is in plan. Analytical method of inelastic fracture mechanics parameters and crack growth are studied and CANIS computer code were developed. The method was applied to the evaluation to elbow used in hot leg piping of large scale FBR. In near future , the method will be blushed up and probabilistic fracture mechanics code will be prepared.

Flow diagram of fracture mechanics study is shown in Fig. 10. 1.

2. ARTICLE OF FRACTURE MECHANICS TEST

A. FATIGUE CRACK GROWTH TEST (EHA)
   a. PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK
   b. PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK
   c. NOTCHED PLATES WITH A SMALL CRACK

B. CREEP-FATIGUE CRACK GROWTH TEST (EHA)
   a. PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK
   b. PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK
   c. NOTCHED PLATES WITH A SMALL CRACKS
   d. ELBOWS WITH SEMI-ELLIPTICAL SURFACE CRACKS

C. THERMAL FATIGUE CRACK GROWTH TEST
   a. CYLINDERS WITH SEMI-ELLIPTICAL SURFACE CRACK (STST)
   b. CYLINDERS WITH AQXISYMMETRICAL SURFACE CRACK (ATTF)

D. THERMAL CREEP-FATIGUE CRACK GROWTH TEST
   a. CYLINDERS WITH SEMI-ELLIPTICAL SURFACE CRACK (TTS)

E. FRACTURE MECHANICS ANALYSIS CODE
   a. CANIS CODE
   b. EVALUATION METHOD

NICKNAME OF TEST FACILITY

TTS ; Thermal Transient test facility for Structures

STST : Small Thermal Shock Test loop
ATTF : Air cooled Thermal transient Test Facility
EHA : Electro-Hydraulic controlled Actuator

3. SIMPLE DISCRIPTION

A. FATIGUE CRACK GROWTH TEST (EHA)

A.1. OBJECTIVE

(1) To investigate fatigue crack growth behaviors of plate and pipe.

(2) To investigate fatigue crack growth behaviors at configuration discontinui ties.

(3) To confirm prediction method for fatigue crack growth.

A.2 TEST DESCRIPTION

(1) PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK

Cyclic loadings of tension-compression or bending is applied on the plate specimen with 30~60 mm width and 4 ~20 mm thickness as shown in Fig.10.A.1. Testing temperature is 550℃ or 650 ℃. Six tests were completed (Table 10.A.1). Diplacement controlled long term creep-fatigue crack growth test are underway.

(2) PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK

Test model is straight pipes with 6 inches outer diameter and 3 or 6 mm thickness. One test method is four point bending ,the other is cantilever type bending at 600 ℃. The models and test method are shown in Fig.10.A.2 and Fig. 10.A.3.

(3) NOTCHED PLATES WITH A SMALL CRACK

Test model is notched plate with a small crack at the root of the notch as shown in Fig.10.A.4. Stress concentration effect on crack growth behavior is investigated .

A.3 RESULT

Tests are continued. Measureing method of crack shape was confirmed in plate and pipe test. Also it was cleared up to date that the stress concentration effect appeared only in 1 mm depth.

B. CREEP-FATIGUE CRACK GROWTH TEST (EHA)

B.1 OBJECTIVE

(1) To investigate creep-fatigue crack growth behaviors of plate ,pipe and elbow.

(2) To investigate creep-fatigue crack growth behaviors at configuration discontinuities.

(3) To confirm prediction method for creep-fatigue crack growth.

B.2 TEST DESCRIPTION

(1) PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK

Configurations of specimen are as same as A.2.

(2) PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK

Configurations of specimen are as same as A.2.

(3) NOTCHED PLATES WITH A SMALL CRACK

Configurations of specimen are as same as A.2.

(4) ELBOWS WITH SEMI-ELLIPTICAL SURFACE CRACKS

Test model is elbows of 6 inches outer diameter with 3.4 mm thickness. Cyclic in-plane bending with 6 hrs hold time is applied to the model (Fig.10.B.1).

B.3 RESULT

Tests are continued.

C. THERMAL FATIGUE CRACK GROWTH TEST

C.1 OBJECTIVE

(1) To investigate thermal fatigue crack growth behaviors of plate and pipe.

(2) To investigate thermal fatigue crack growth behaviors at configuration discontinuities.

C.2 TEST DESCRIPTION

(1) CYLINDERS WITH SEMI-ELLIPTICAL SURFACE CRACK (STST)

Cylinders of 75 mm outer diameter and 15 mm thickness with an axial and a circumferencial semi-elliptical surface cracks were subjected to repeated thermal transient loadings by sodium of 250 ℃ and 600℃ in STST. One cycle time is 10 min. and number of transient cycle is 6,500.

The models are shown in Fig.10.C.1

(2) CYLINDERS WITH AXISYMMETRICAL SURFACE CRACK (ATTF)

Configuration of test model is cylinders of 150mm outer diameter and 30 mm thickness with axisymmetrical slit as shown in Fig.10.C.2. The model is subjected to cyclic cold shock by compressed air in ATTF.

Testing apparatus is shown in Fig.10.C.3.

C.3 RESULT

The test in STST is completed. Crack growth computation is underway. Prelimanary test for investigation of temperature response was completed. Crack growth test is underway.

D. THERMAL CREEP-FATIGUE CRACK GROWTH TEST

D.1 OBJECTIVE

(1) To investigate thermal creep-fatigue crack growth behaviors of plate and pipe.

(2) To investigate thermal creep-fatigue crack growth behaviors at configuration discontinuities.

D.2 TEST DESCRIPTION

(1) CYLINDERS WITH SEMI-ELLIPTICAL SURFACE CRACK (TTS)

Cylinders of 190mm outer diameter and 20 mm thickness with an axial and a circumferencial semi-elliptical surface slits were being subjected to repeated thermal transient loadings by sodium of 250℃ and 600℃ in TTS. One cycle time is 2 hrs. and the test will be continued up to number of thermal transient cycles of 1800. The model is shown in Fig.10.D.1.

D.3 RESULT

The test is underway. Preliminary elastic crack growth evaluation was completed.

E. FRACTURE MECHANICS ANALYSIS CODE

Fracture mechanics analysis code CANIS was developed. Details will be appear in Ref.10.E.1. Analytical data base of fatigue and creep-fatigue crack growth rate of semi-elliptical surface crack in plate was constructed based on the many analitical results as shown in Fig.10.E.1.Computation was based on three dimensional K , J and J integrals for fatigue ,and J' and J' integrals for creep. The data base is corresponding to secondary load level of $1.5S_m$ and applicable to combined loading of membrane and bending. The data base is expanding to be able to apply to the case of primary plus secondary load.

A development of probablistic fracture mechanics analysis code CANIS-P IS underway.

Ref.10.E.1 Watashi,K.and Yoshida,H.,CANIS computer code for inelastic fracture mechanics,ASME-JSME Joint Conference(1989),HONOLULU, to be appeared.

FRACTURE MECHANICS IN LBB LOGIC FOR LARGE FBR

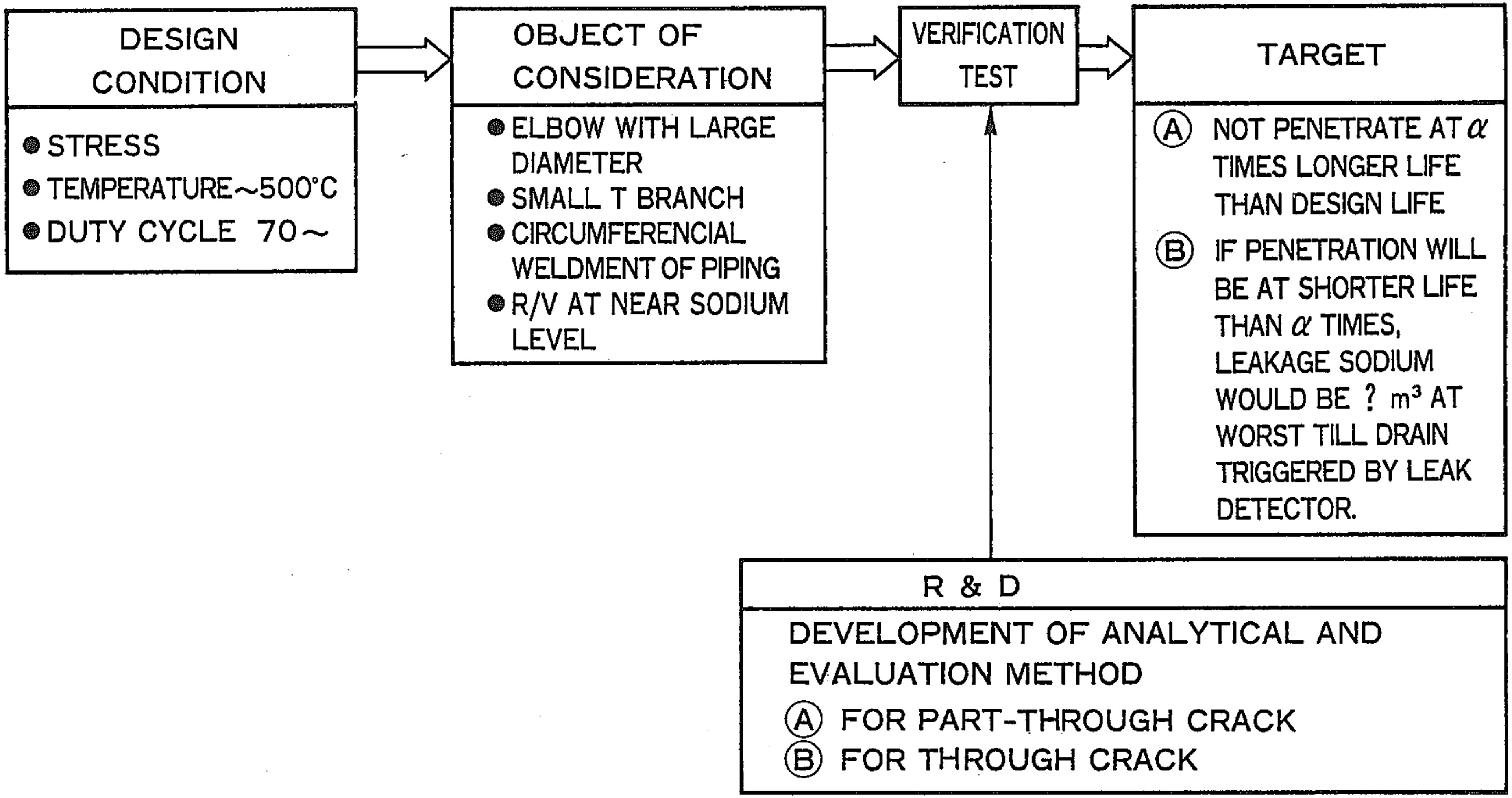
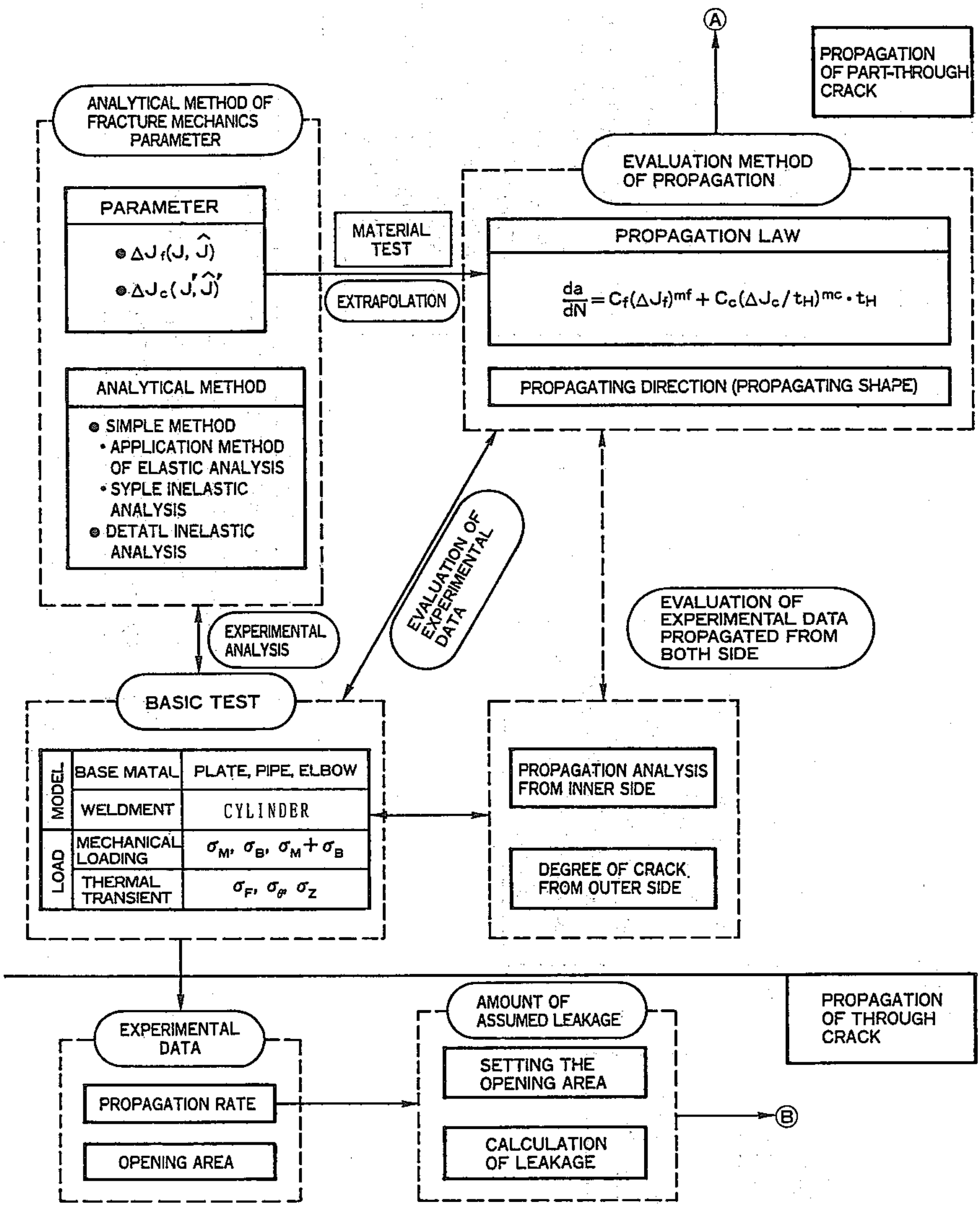


Fig. 10.1 Flow diagram of fracture mechanics study



PRESENT PNC'S ACTIVITY ON FRACTURE MECHANICS UNDER CREEP-FATIGUE CONDITION

Fig. 10. 1 (continued)

No.	Crack growth mode	Specimen size	Loading kgf/㎟	Control	Temp. ℃	Hold time (h)	Initial crack size (㎜)	Method of crack length meas	Method of COD meas.
1	Plate with a surface crack	8t×25w	Axial ±15	Load	550℃	0	$2C_0=5, a_0=2$	Visual Beach mark AC Potential	5㎜GL
2	Plate with a surface crack	8t×25w	Axial ±15	Load	550℃	0	$2C_0=5, a_0=0.5$	DC Potential Beach mark	5㎜GL
3	Plate with a surface crack	16t×80w	Bend ±20	Load	550℃	0	$2C_0=8, a_0=4$	DC Potential Beach mark	5㎜GL
		16t×80w	±25	Load	RT.	0	$2C_0=8, a_0=4$	Visual	
4	Plate with a surface crack	10t×50w	Bend 0～12 (㎜)		RT. 650℃	0	$2C_0=4, a_0=1$	Visual DC Potential	5㎜GL

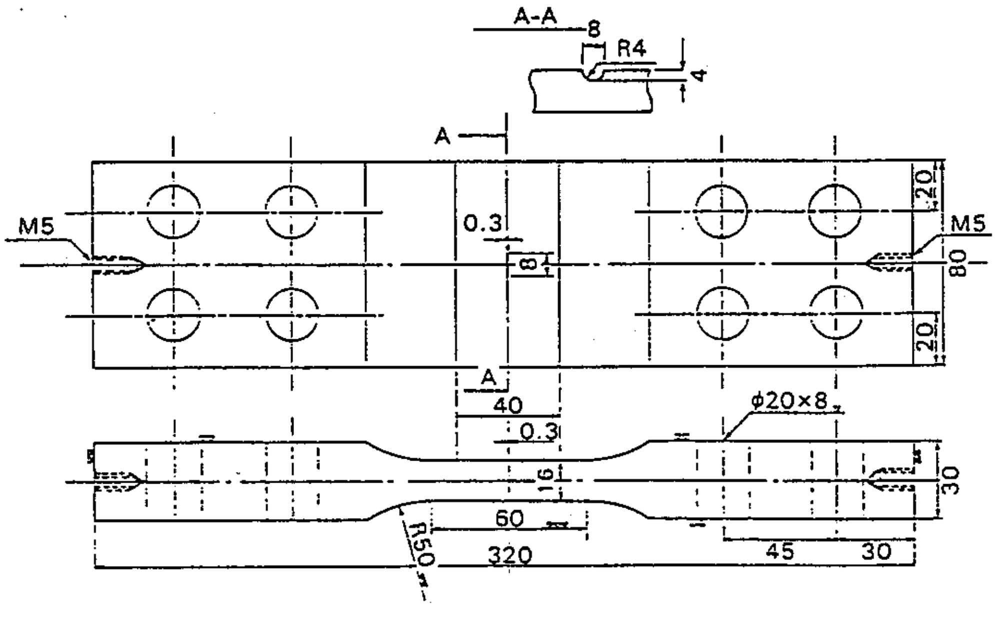


Fig. 10. A. 1　　Specimen configurations

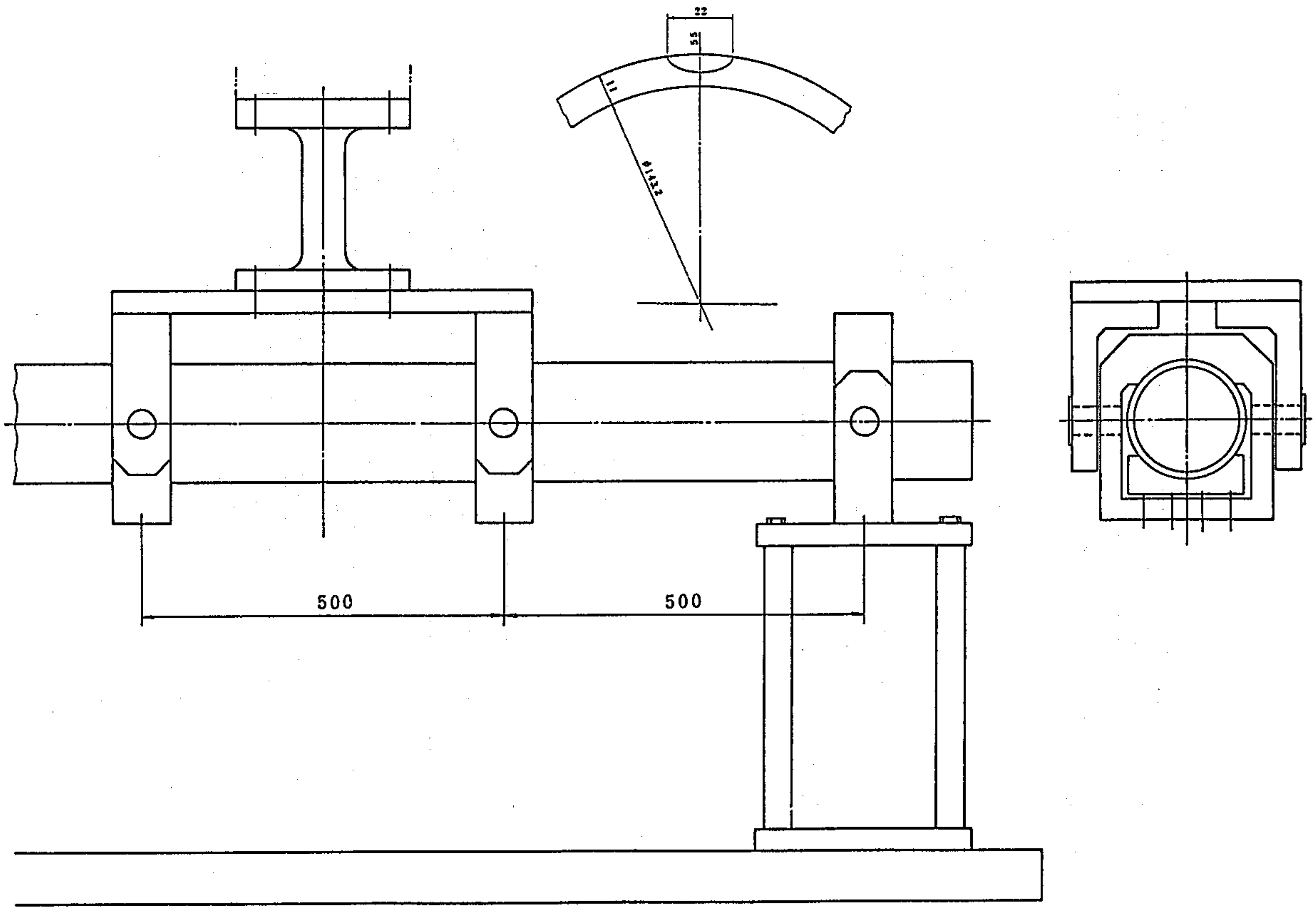


Fig. 10. A. 2　Bending with creep

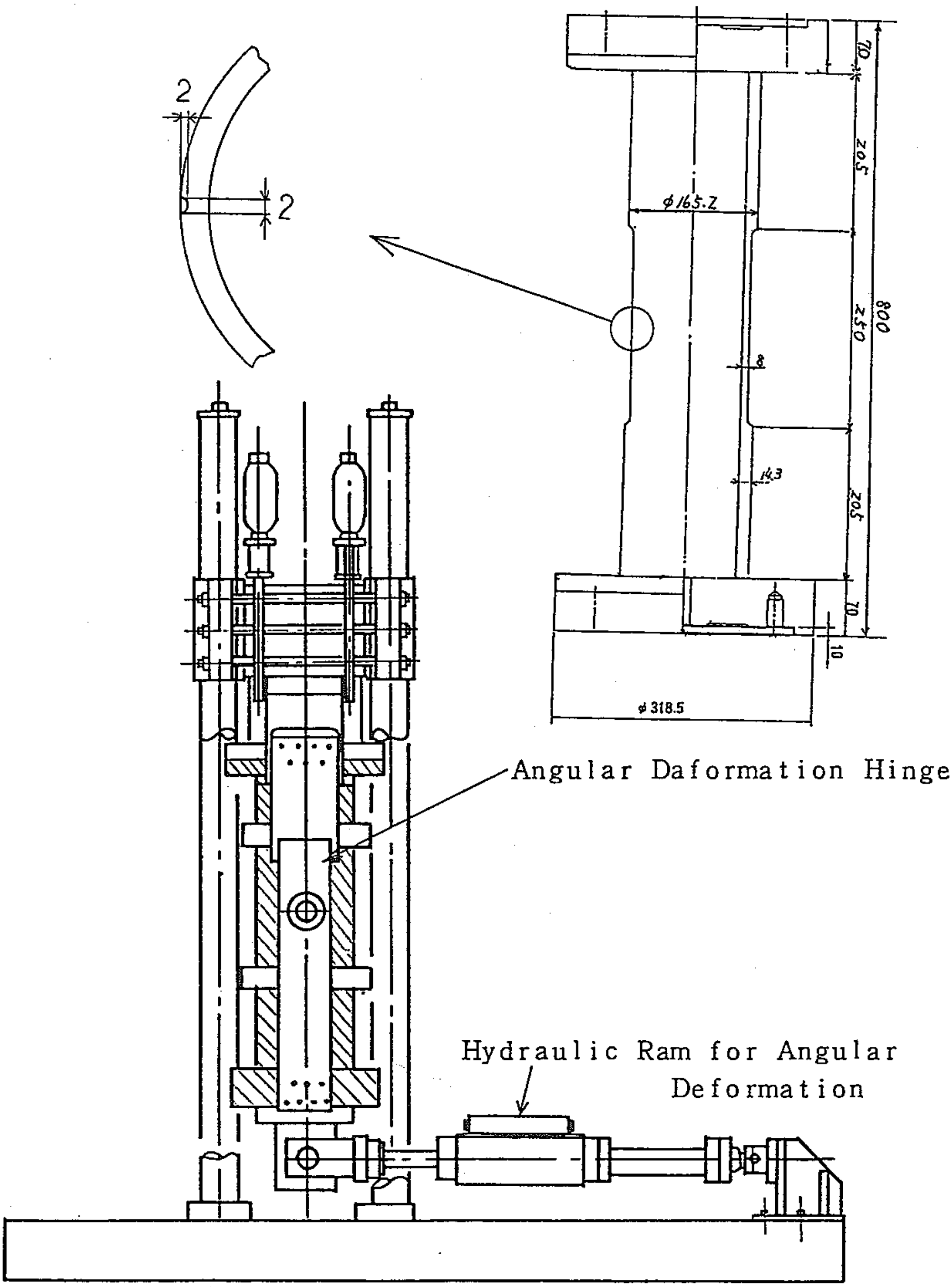
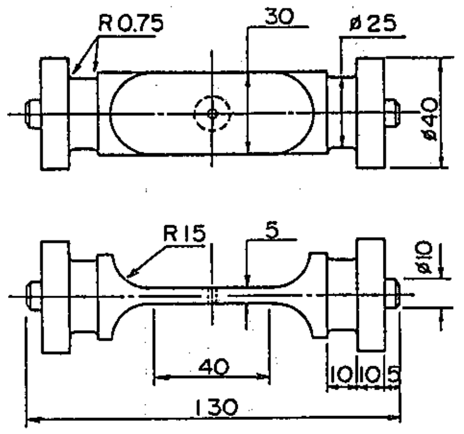
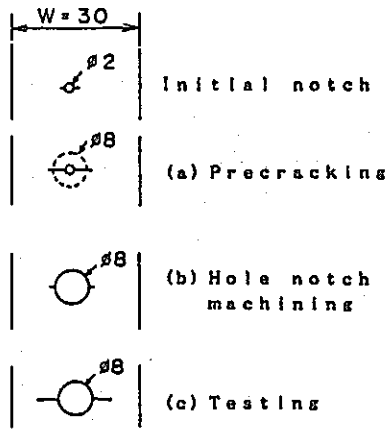
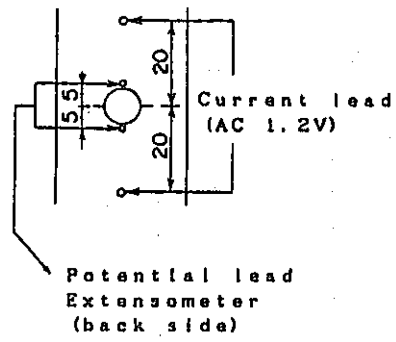


Fig. 10. A. 3 Cantilever type test

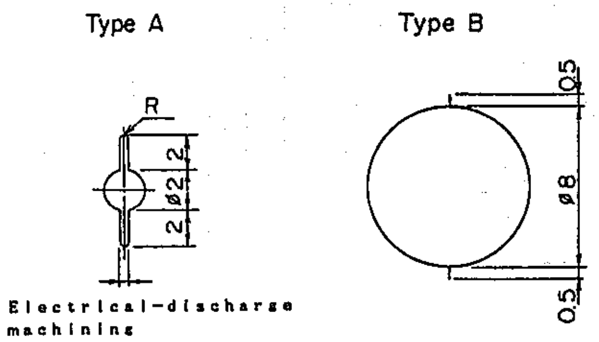




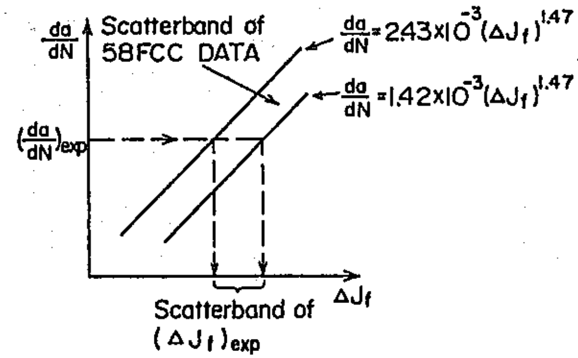
Testing procedure
(Type B)



AC potential and crack opening displacement measurement



Dimensions of a test specimen



Procedure of evaluating the J-integral range

Fig. 10. A. 4 Notched plate model with a small crack

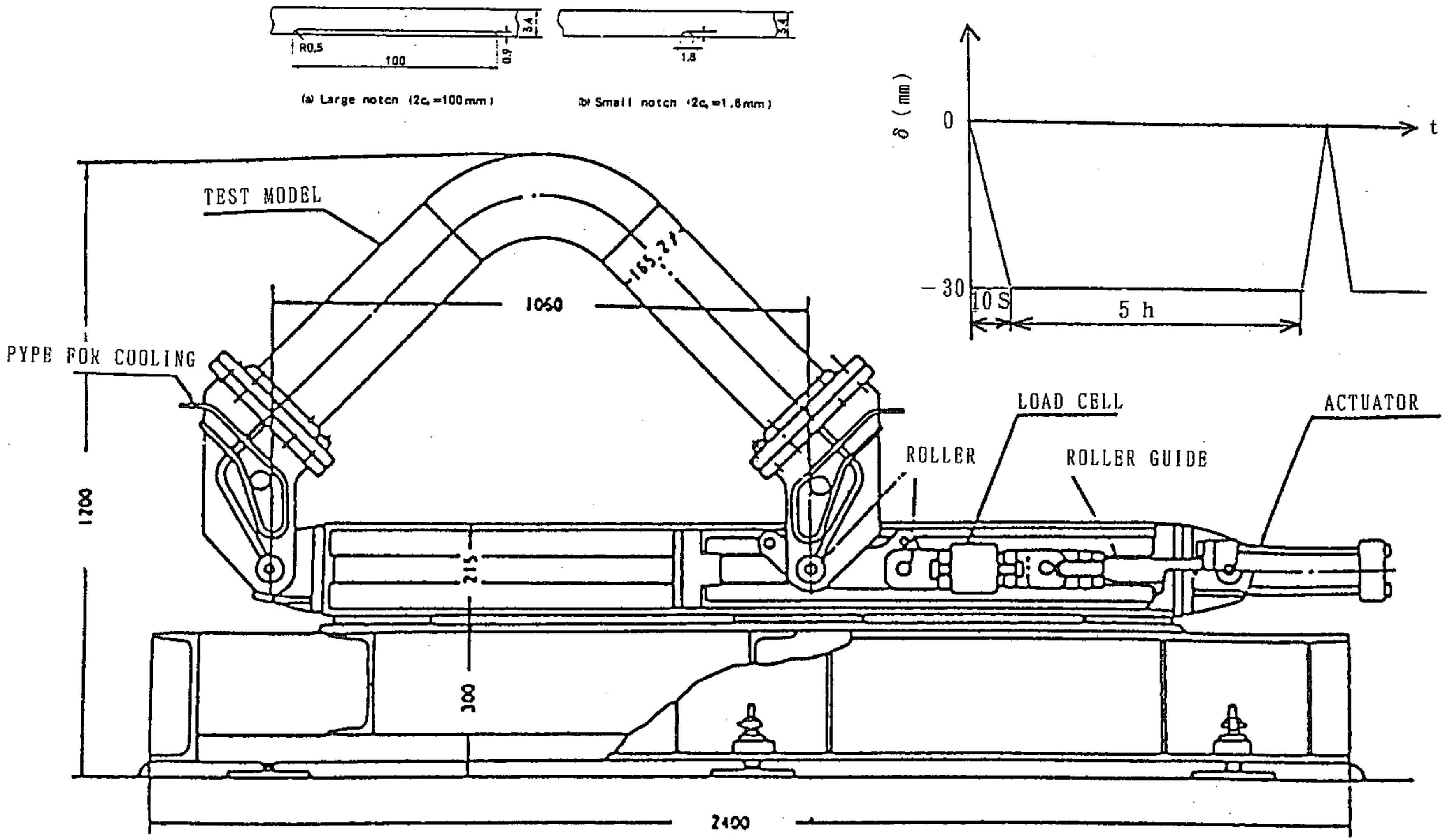
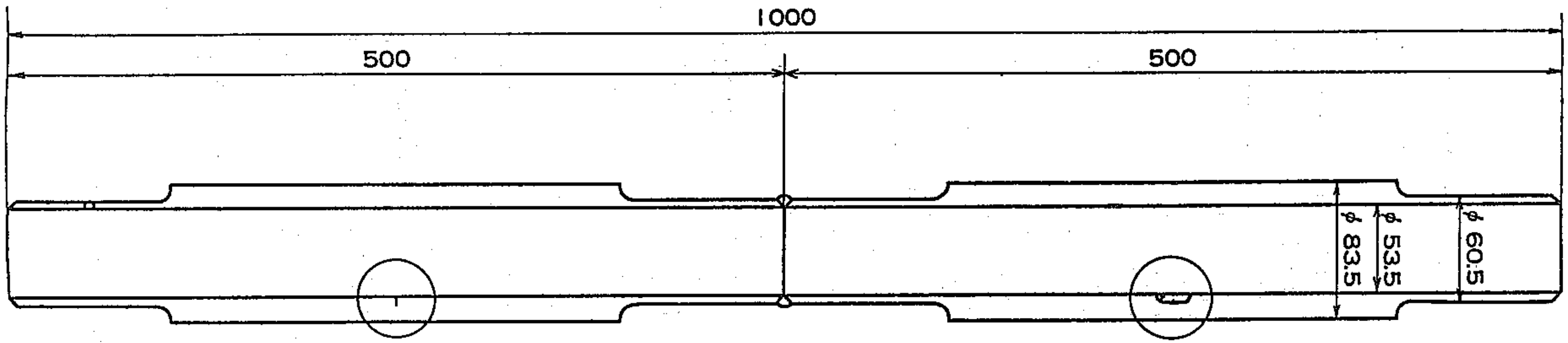


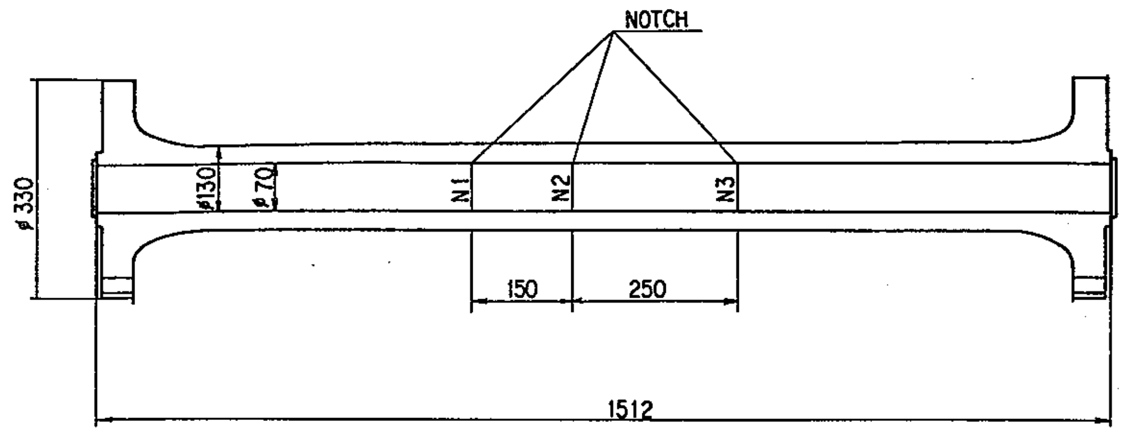
Fig. 10. B. 1 Creep-fatigue crack growth test of elbow

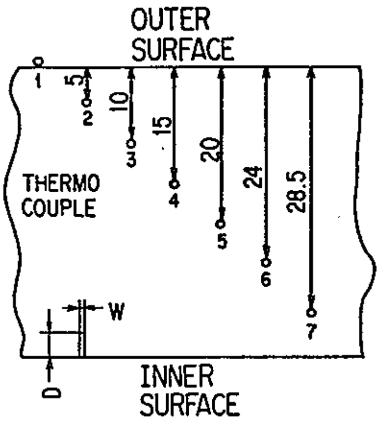


CIRCUMFERENTIAL SLIT
DEPTH 4mm
LENGTH 20mm
WIDTH 0.3mm

AXIAL SLIT
DEPTH 4mm
LENGTH 20mm
WIDTH 0.3mm

Fig. 10. C. 1 Thermal Fatigue Crack Growth Test





	D	W
N 1	1.0	0.2
N 2	1.0	0.3
N 3	3.0	0.3

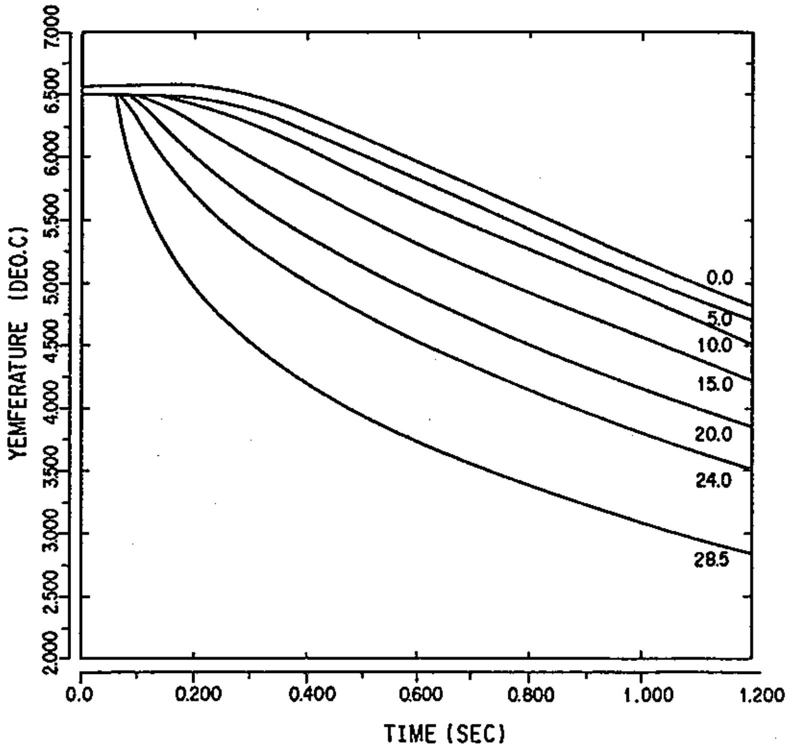


Fig. 10. C. 2 Thermal fatigue crack growth test of cylinder with axisymmetrical surface crack

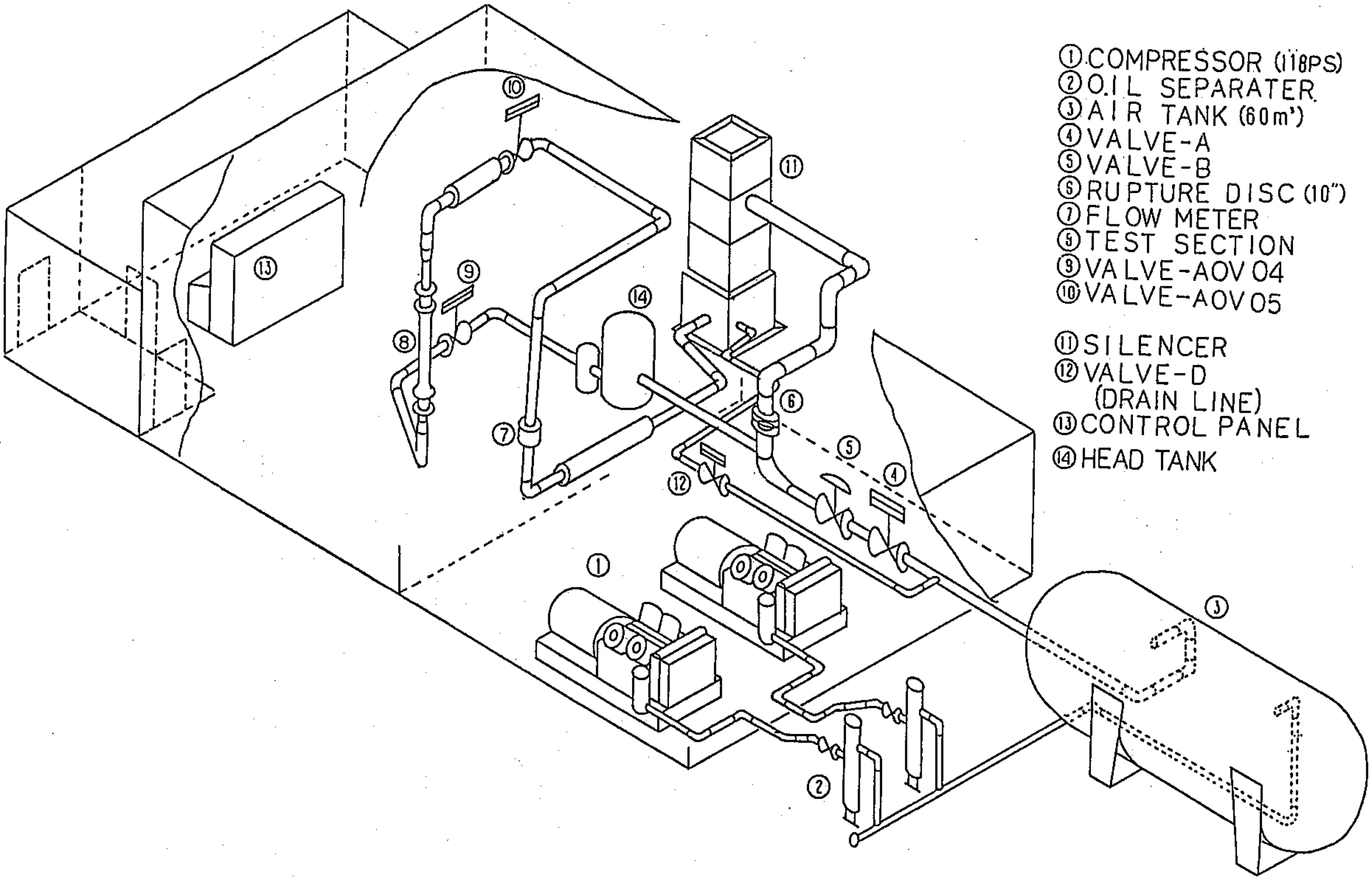


Fig. 10. C. 3 Bird's Eye View of Test Facility

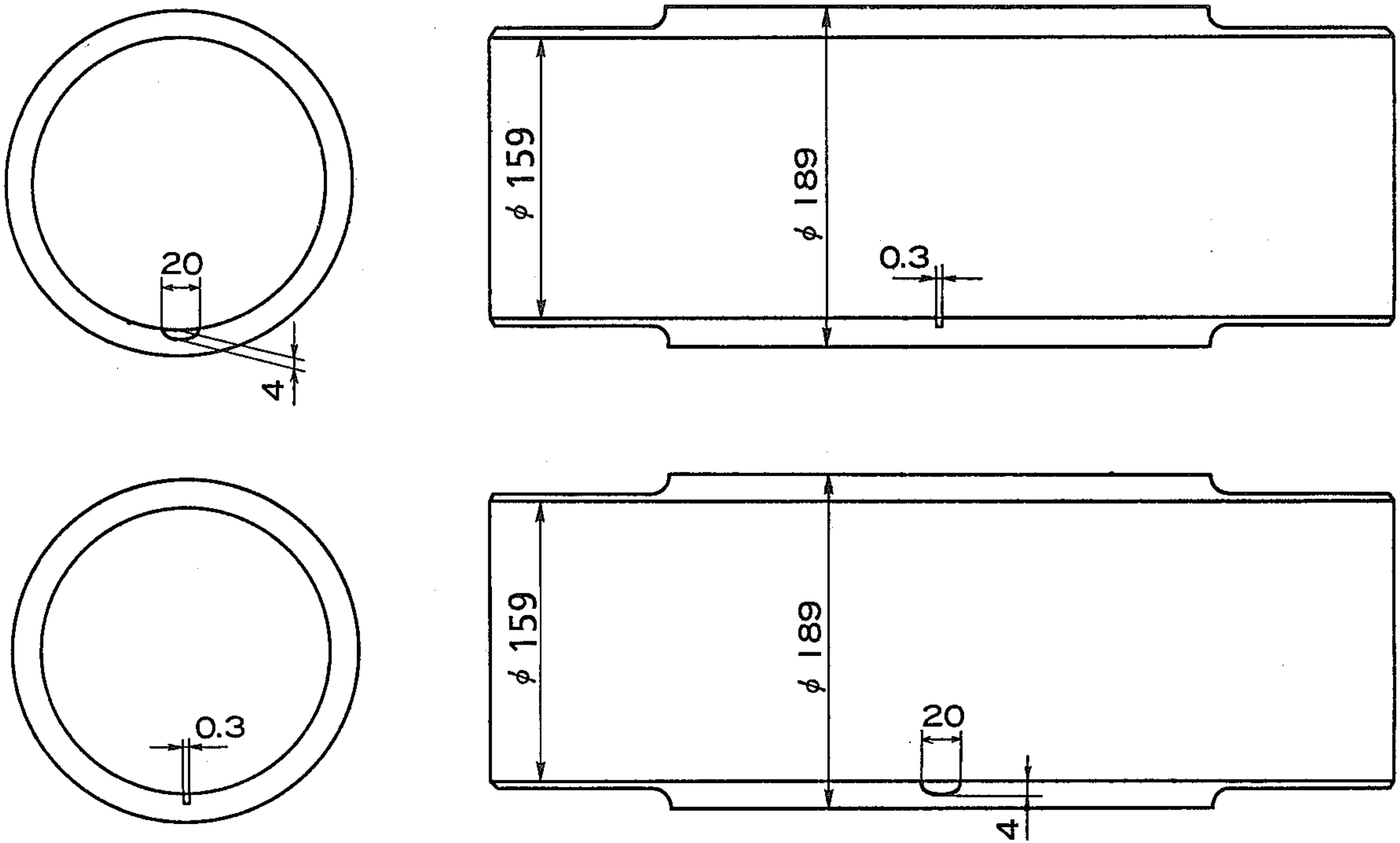
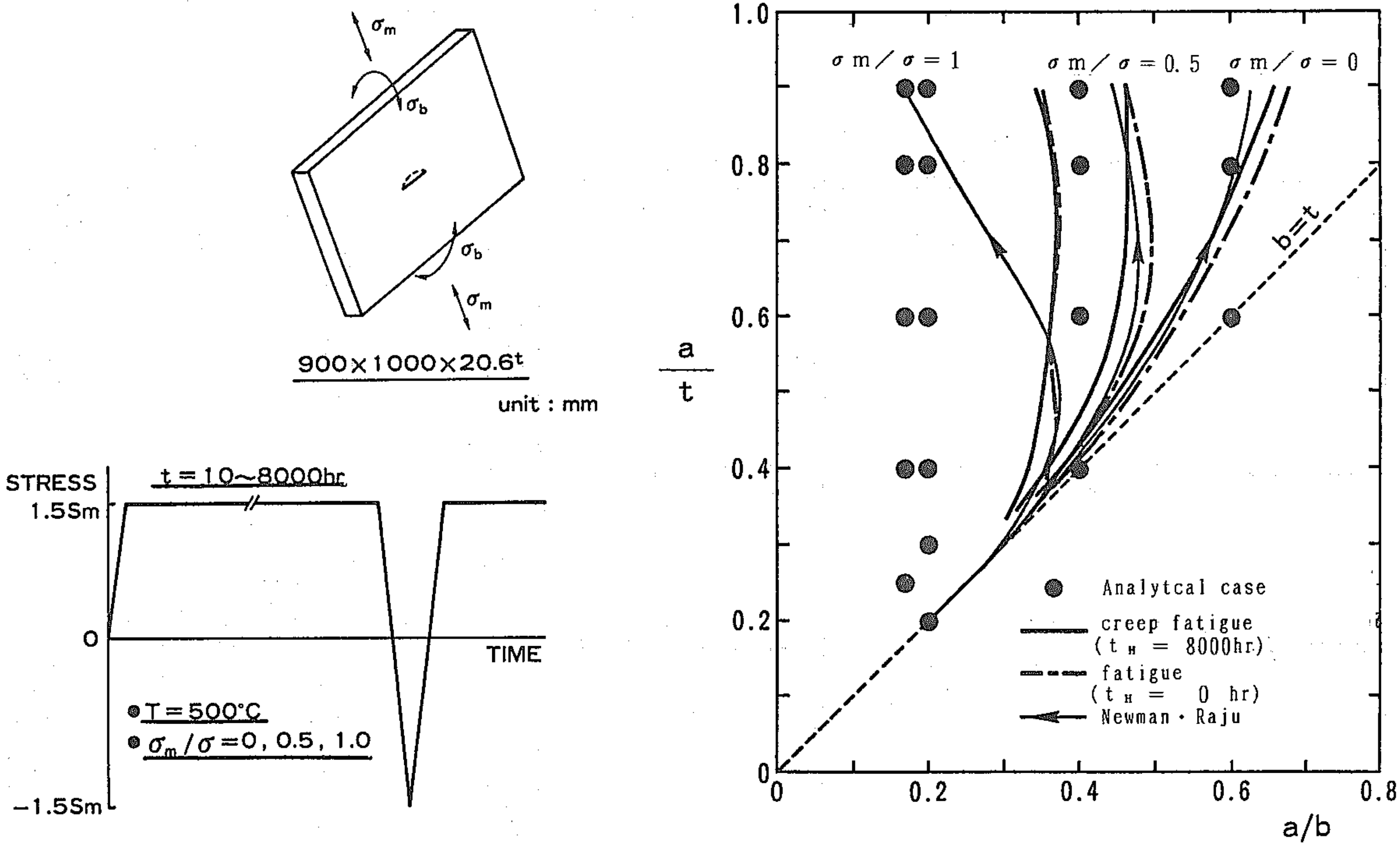


Fig. 10. D. 1　　Thermal Creep-Fatigue Crack Growth Test



Analytical model and loading

analized crack shape

Fig. 10. E. 1 CANIS code and its application

ATTACHMENT 11

THERMO-HYDRAULIC TEST FOR THERMAL BOUNDARY CONDITION

1. ABSTRACT

Thermal stress generated in FBR components and pipings is greatly affected by thermal boundary condition, so many temperature and strain vehavior tests were performed in sodium loops and water loops. These tests include thermal stratification tests in upper plenum of RV , in horizontal pipings and in horizontal type bellows junction, thermal striping tests for upper core structures, thermo-hydraulic tests of shroud of IHX, thermal response test of RV model, thermal shock tests of several types of valves. The results of this article refrect to determine thermal boundary conditions, to demonstrate structural integrity, and to develop thermal flow analysis code.

2. ARTICLES OF THERMO-HYDRAULIC TEST

A. STRATIFICATION TESTS IN UPPER PLENUM OF RV (STST)
B. THERMO-HYDROULIC TESTS AROUND SHROUD OF IHX (TST)
C. THERMAL STRIPING TESTS (TST)
D. THERMAL RESPONSE TESTS OF RV MODEL (SITR)
E. OTHERS

NICKNAME OF TEST FACILITY

STST : Small Thermal Shock Test loop
SPTT : Sodium Piping Thermal transient Test loop
SITR : Structural Integrity Test loop for Reactor vessel
TST : Thermal Shock Test loop

3. TEST DESCRIPTION

A. THERMAL STRATIFICATION TEST FOR REACTOR VESSEL

A.1 OBJECTIVE

In case of reactor scram in FBR, low temperature sodium coming out of the core with its small inertial force produced poor mixing in the upper plenum and results in thermal stratification which forms the density interface in its front. The structure adjacent to the density interface is subjected to large thermal stress as a result of severe temperature gradient. Experimental and analytical studies wewre conducted to investigate the existence of stratification, initiation condition, the degree of temperature gradient and rising speed of the density interface for 'MONJU' ,and to reflect the results on the designs of the reactor vessel structures.

A.2 TEST DESCRIPTION

Many tests using large scale or small scale models were conducted in sodium loop(TST) and water loops. An example of the test models is shown in ,say, Fig. 10.A.1.

A.3 RESULT

Threshhold for the stratification taking place below the top of the inner barrel in the models simulating MONJU reactor upper plenum was correlated with the Richardson number defined at the upper plenum. One-dimensional modelling of the upper plenum was found to be applicable to the evaluation of thermal transient during the stratified condition. Water tests were preferable to small scale sodium tests for the objective of evaluating the thermal transient in the plenum. In particular, influences of heat transfer across the inner barrel and axial thermal conduction on the thermal transients were dominant in the small scale sodium tests than those in the MONJU condition. As the result, it becomes difficult to extrapolate the thermal transient data from the small scale sodium tests to the MONJU condition. Axial temperature distribution above the top of the inner barrel was dominated by thermal conduction only.

B THERMAL STRIPING TEST

B.1 OBJECTIVE

Random temperature fluctuation occurs in the region immediately above the FBR core due to the temperature difference of the core outlet coolant between the fuel assembly(FA) and control rod assembly(CRA). In the case of the MONJU, random temperature fluctuation occurs around the upper core structures(UCS) and the components subject to random thermal cycling(thermal striping) which might cause high cycle fatigue. An objective of this article is to develop an evaluation method of thermal striping.

B.2 TEST DESCRIPTION

Thermal striping tests in water and sodium were performed by use of a seven assemblies model which has the same dimension and configuration as the lower part of UCS of MONJU, as shown in Fig.10.B.1. Parameters in the test were flow rate, flow rate ratio, temperature, temperature difference of the sodium from FA and CRA and the distance(gap) between subassembly outlets and flow straightner inlets.One testing time is about 90 sec, and total test number is 330.

B.3 RESULT

Statistical characteristics of temperature fluctuation depend on Reynold's number and have the tendency to become constant with increasing Reynold's number. Temperature fluctuation behavior are affected by the flow rate ratio and the gap and spatial distribution of the statistical characteristics are change. Although non-steady heat transfer coefficients under thermal striping behavior were estimated, the estimated values scattered in the wide range. On the basis of these results, several kinds of high cycle thermal fatigue evaluation methods were discussed. The comparative study showed that the results based on 'cyclic temperature counting approach' were nearly equal to the results based on 'the time history response approach', and both had adequate safety margin. The results based on 'the random bibration approach', in which the temperature amplitude histgram is expressed by the probability density function, tend to become too safety side.

Also the relation among the standard deviation of the temperature fluctuation and the maximum peak-to-peak amplitude, zero cross frequency, temperature amplitude histgram were investigated. It was shown that the statistical values nesecessary for the thermal striping evaluation could be estimated from the standard deviation only of the temperature fluctuation obtained by thermo-hydraulic analysis.

C. THERMAL BEHAVIOR TEST OF REACTOR VESSEL MODEL

C.1 OBJECTIVE

The thermal stress mitigation measures, such as some types of thermal liners, convection restrain fin, thermal sield plates, laminated plates and so on, are taken for reactor vessel, because reactor vessel is subjected to several types of thermal stresses during normal and transient plant operation. The objective is to demonstrate the structural integrity of reactor vessel and usefulness of the thermal stress mitigation measures.

C.2 TEST DESCRIPTION

The configuration and dimension of the reactor vessel model is the same as the actual one ,but the diameter is 1/4 scale of MONJU as shown inFig.11.C.1. The sield plug is designed to be consistent with thermal boundary condition of MONJU. The upper and lower thermal liners, protection liner and two sodium level control method as thermal stress mitigation measures are the same as the actual one. The sodium loop was designed to give the test model the same thermal transient condition as the actual start up and shut down operation and scram, and havs the specification that the main pipe is 3 inches in diameter, the steady flow rate is 350ℓ/min ,the maximum flow rate is 1000 ℓ/min, the maximum up ramp is 25 ℃/hr, the maximum down ramp is 0.1 ℃/sec. The sodium level of plenum and bucket is able to be controlled each.

C.3 RESULT

The complex thermal conditions were determined from this test. The results include thermal flow behavior in cover gas space, convection produced by radiation between free surface of sodium and structure, characteristic change of heat transfer property caused by adhering sodium, coefficient of overall heat transmission in integrated liner structures, heat protection structures, radiation sield block and thermal liner, natural convection in annuras space, the degree of sodium mixing in backet.

D. THERMAL TRANSIENT TEST OF IHX MODEL

D.1 OBJECTIVE

The rest is omitted.

ATTACHMENT 12

ASSOCIATED TEST

1. ABSTRACT

2. TEST ARTICLE

A. STRENGTH TEST FOR CELL LINER STRUCTURES

B. CRACK INITIATION TEST

C. STRAIN CONCENTRATION TEST OF NOTCHED PLATE

3. SIMPLE DESCRIPTION

A. STRENGTH TEST FOR CELL LINER STRUCTURES

A.1 OBJECTIVE

Floating type cell lining structures is adopted for lining of rooms used for secondary heat transport systems in MONJU. This type should be absorbed thermal expansion of cell liners by shearing deformation of stud bolts, when posturated sodium leak occurs according to 'Level D' in ETSDG. Cell liner plate itself should be also withstand cyclic out-of plane bending deformation due to posturated air conditioner trip according to 'Level B' in ETSDG. Shearing failure tests of stud bolt and fatigue tests under out-of plane bending load were performed to investigate the failure strength and to develop design guide of cell liner structures.

A.2 TEST DESCRIPTION

The apparatus of stud bolt test is shown in Fig.11.A.1. Test models are stud bolt with 13 mm in diameter welded to base plate made of carbon steel SM41B. Eleven models with two sort of stud length were tested under shearing force at room temperature and 530℃. Tensile test of this material were also conducted at seven temperatures with 10^{-3} and 10^{-4} $_{1/sec}$ in strain rate.

Four sorts of specimen, as shown in Fig.11.A.2, were tested under cyclic out-of plane bending at room temperature. Total number of tested specimen is eighteen.

A.3 RESULT

Large displacement inelastic analysis by FEM showed good agreement with stud behavior resulted from the tests. Evaluated ultimated displacement from

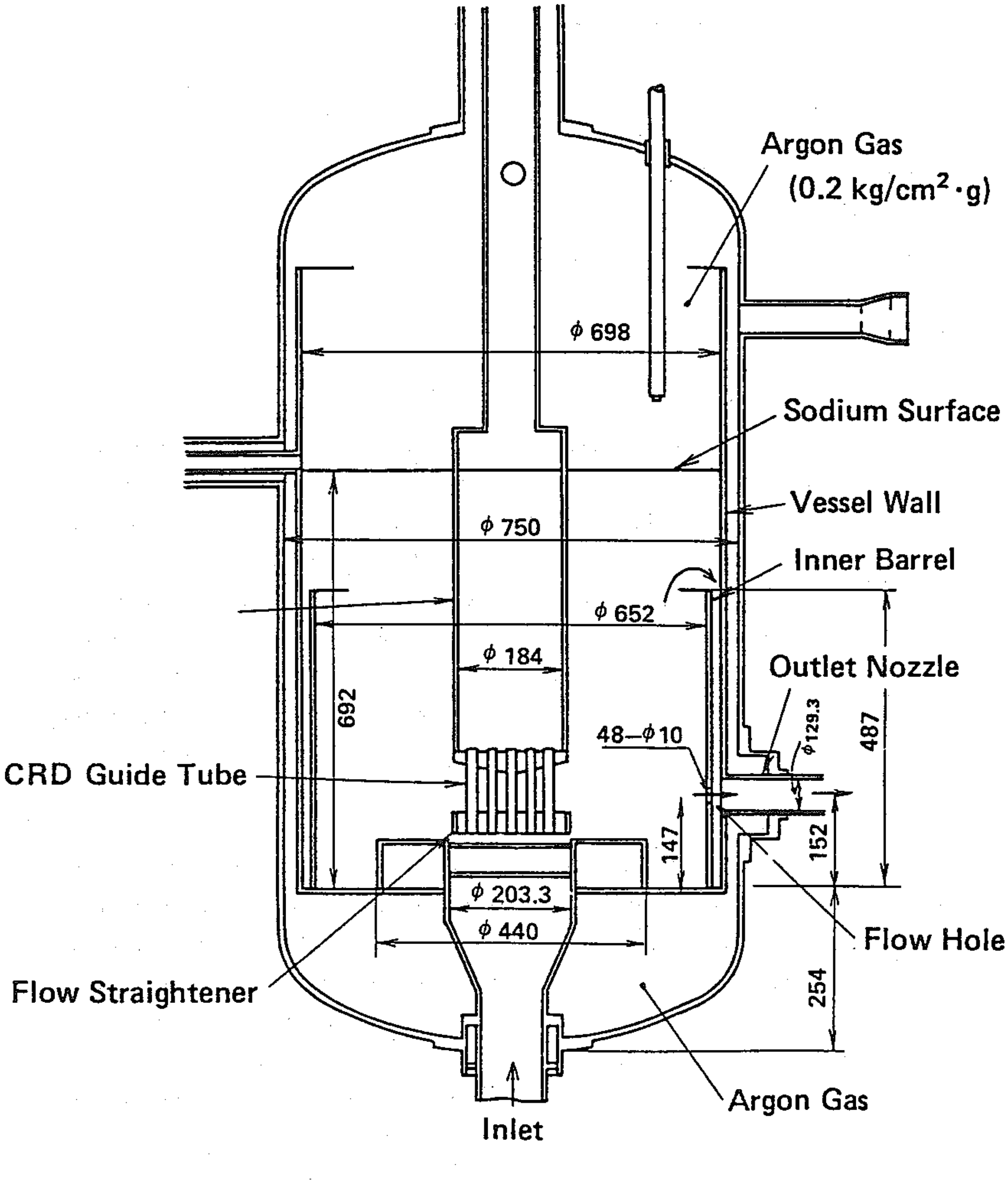
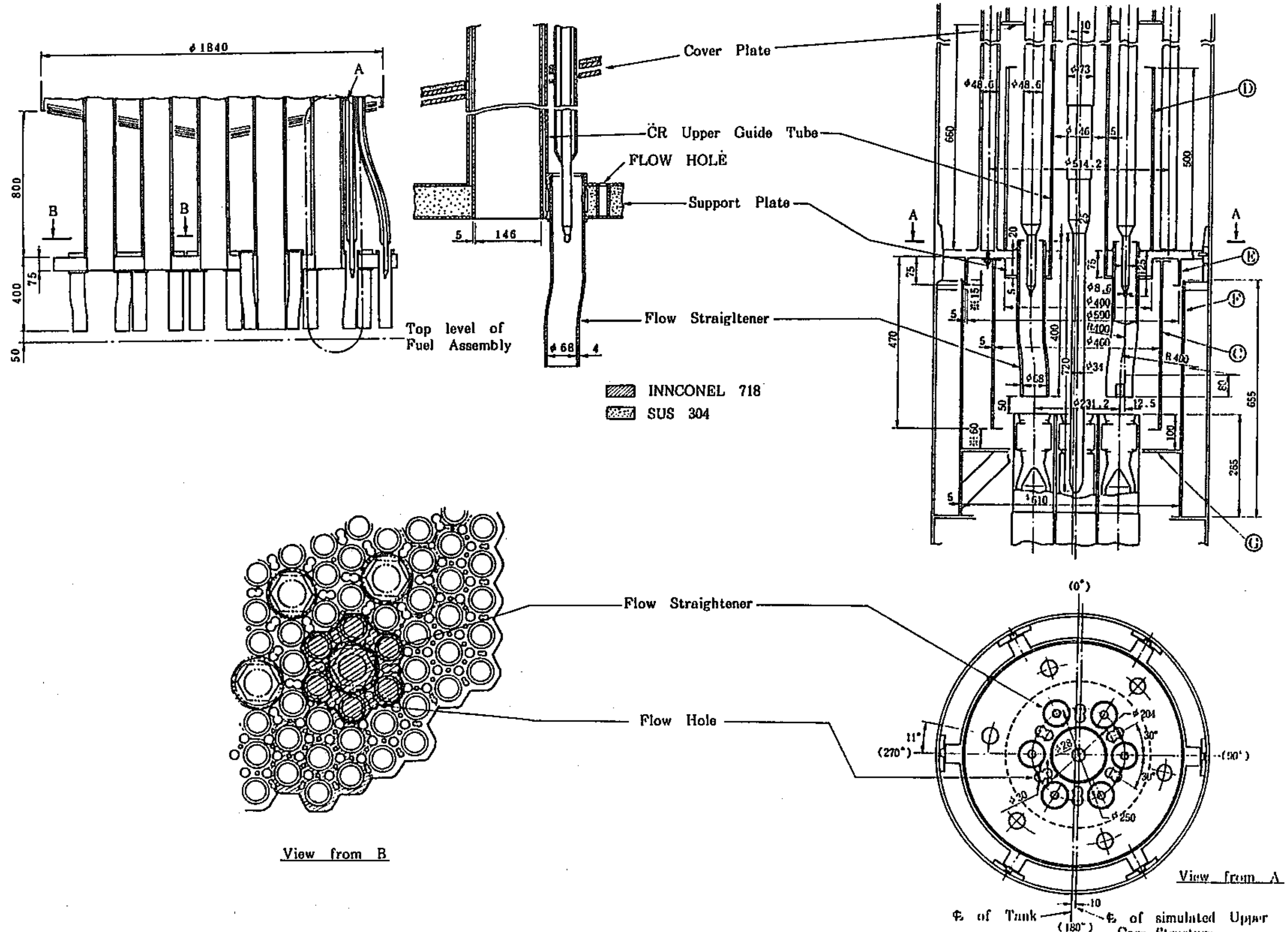


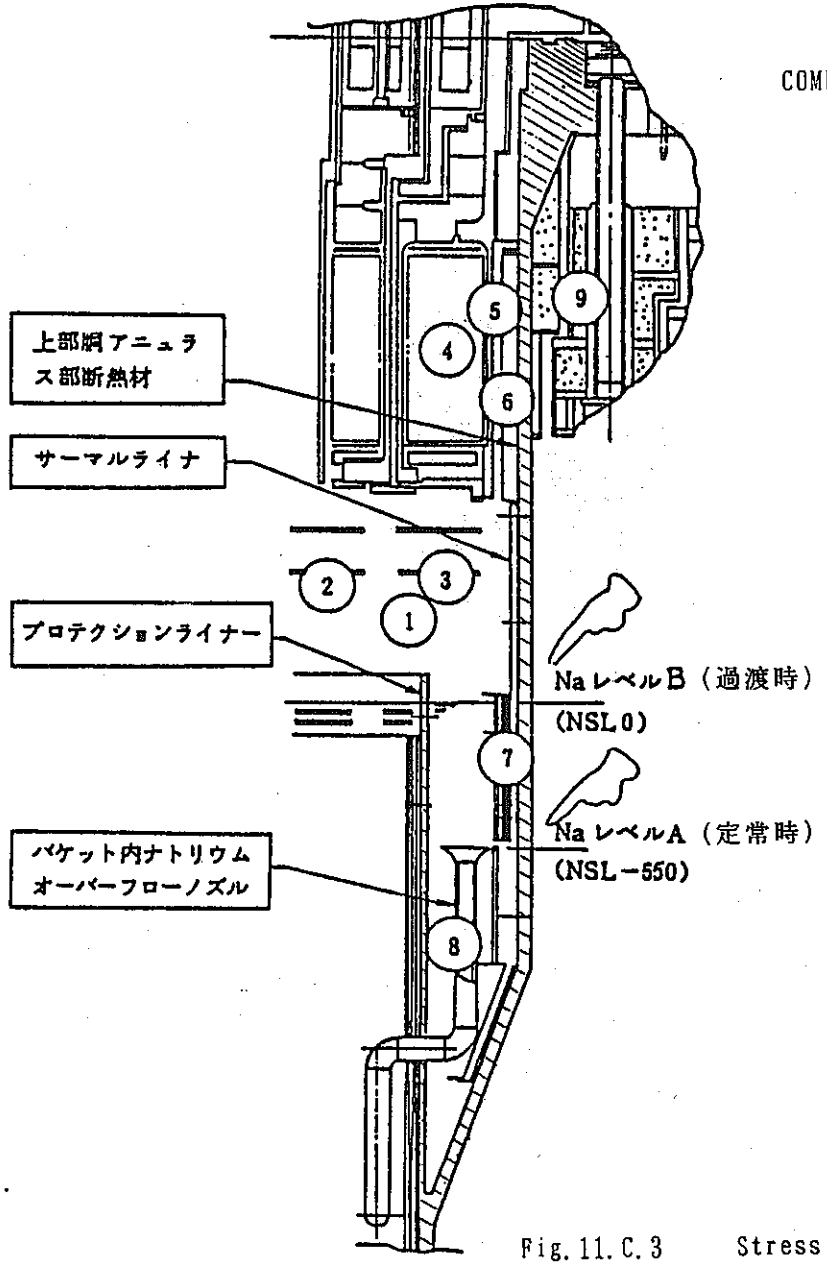
Fig. 10. A. 1 Schematic diagram of test section of 1/10 scale model test I in sodium



(a) Upper Core Structure of Monju

(b) Upper Core Structure of Test Model

Fig. 10. B. 1 Upper Core Structure of Monju and Test Model



COMPLEX THERMAL BOUNDARY CONDITION

① Thermal blow behauio in cover gas space

② Convection due to radiation between sodium level and structurd surface

③ Radiation rate change due to sodium mist

④ Thermal performance of layered plate

⑤ Natural concection in anulas space

⑥ Coefficient of overall heat transmission of thermal insulation

⑦ Coefficient of overall heat transmission of thermal liner

⑧ Mising of sodium in bucket

⑨ Coefficient of overall heat transmussion in thermal protection block

Fig. 11. C. 3 Stress Analysis near sodium level of R/V

rupture elongations of tensile tests and analyses were good agreement with those of strength test at room temperature, but smaller than those at 530℃. The limit for displacement controlled shearing force under level D condition was confirmed as 0.667 δ_u, in which δ_u was ultimate displacement.

Fatigue curves for each liner plate weldment were developed and adequate welding method were determined.

B. CRACK INITIATION TEST

B.1 OBJECTIVE

To investigate a relation between usual low-cycle fatigue life of bar specimen under tension-compression loading and crack initiation life of notched plate under bending load.

B.2 TEST DESCRIPTION

Configuration of test specimen is notched plate with 12 mm in thgickness, 30 mm in width and 5 mm in radius of carvature of notch as shown in Fig.11.B.1. Testing parameters are strain range, holding time and surface roughness. Test condition is such that the specimen is subjected cyclically to displacement controlled bending moment at 600℃ until several mm of generated crack depth. Furthermore usual low-cycle and creep test were conducted to compare with the results of the crack initiation test.

B.3 RESULT

Observation during tests showed that very small oxides or cracks appeared at the notch root in early stage of low cycle fatigue life and growed to macro cracks. Specially defined cycles of crack initiation were larger than usual low-cycle fatigue life. And surface roughness perpendicular to specimen's width direction was not affected so much on the cycles to crack initiation.

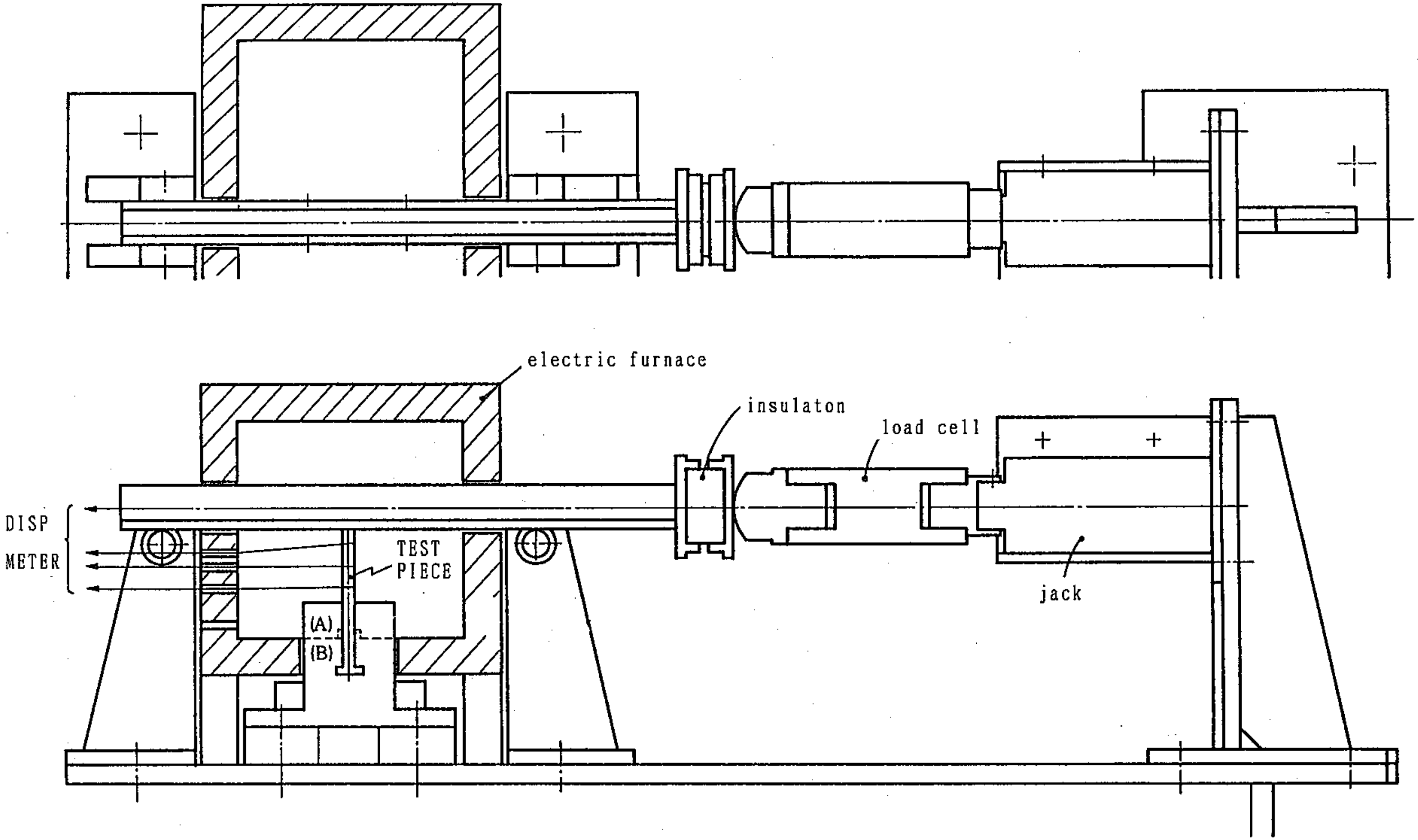


Fig. 12. A. 1 Test equipment

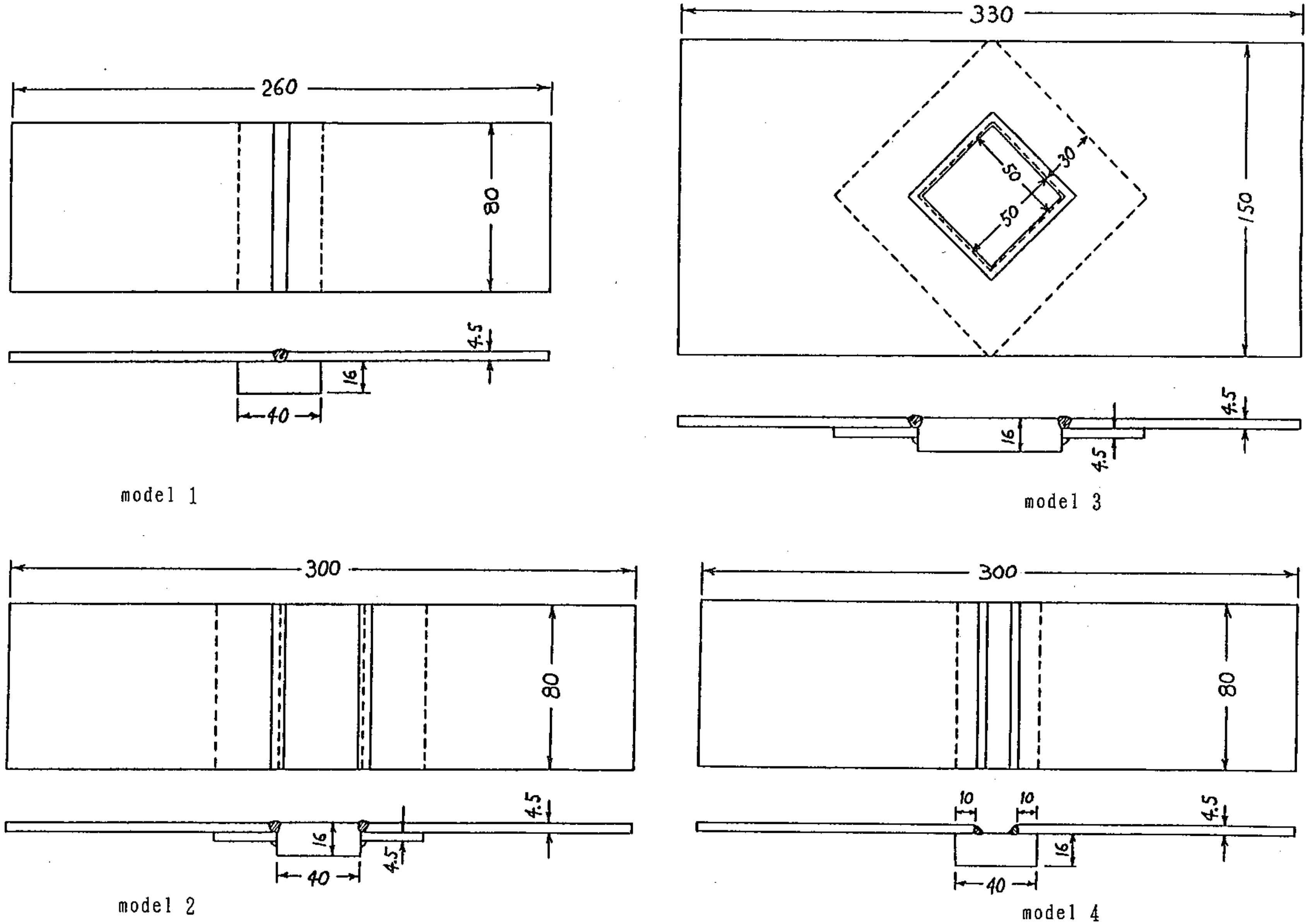


Fig. 12. A. 2 Bending fatigue test of cell liner structures

CRACK INITIATION TEST UNDER BENDING

● OBJECTIVE : TO INVESTIGATE NUMBER OF CRACK INITIATION CYLLE UNDER BENDING LOAD

● MATERIAL : SUSF 304

● TEST CONDITION : TEMPERATURE : 600℃

STRAIN RANGE : 1.2%, 1.6%

STRAIN RANGE : 10^{-3}1/S, 10^{-4}1/S

HOLD TIME : 0 mim, 30min

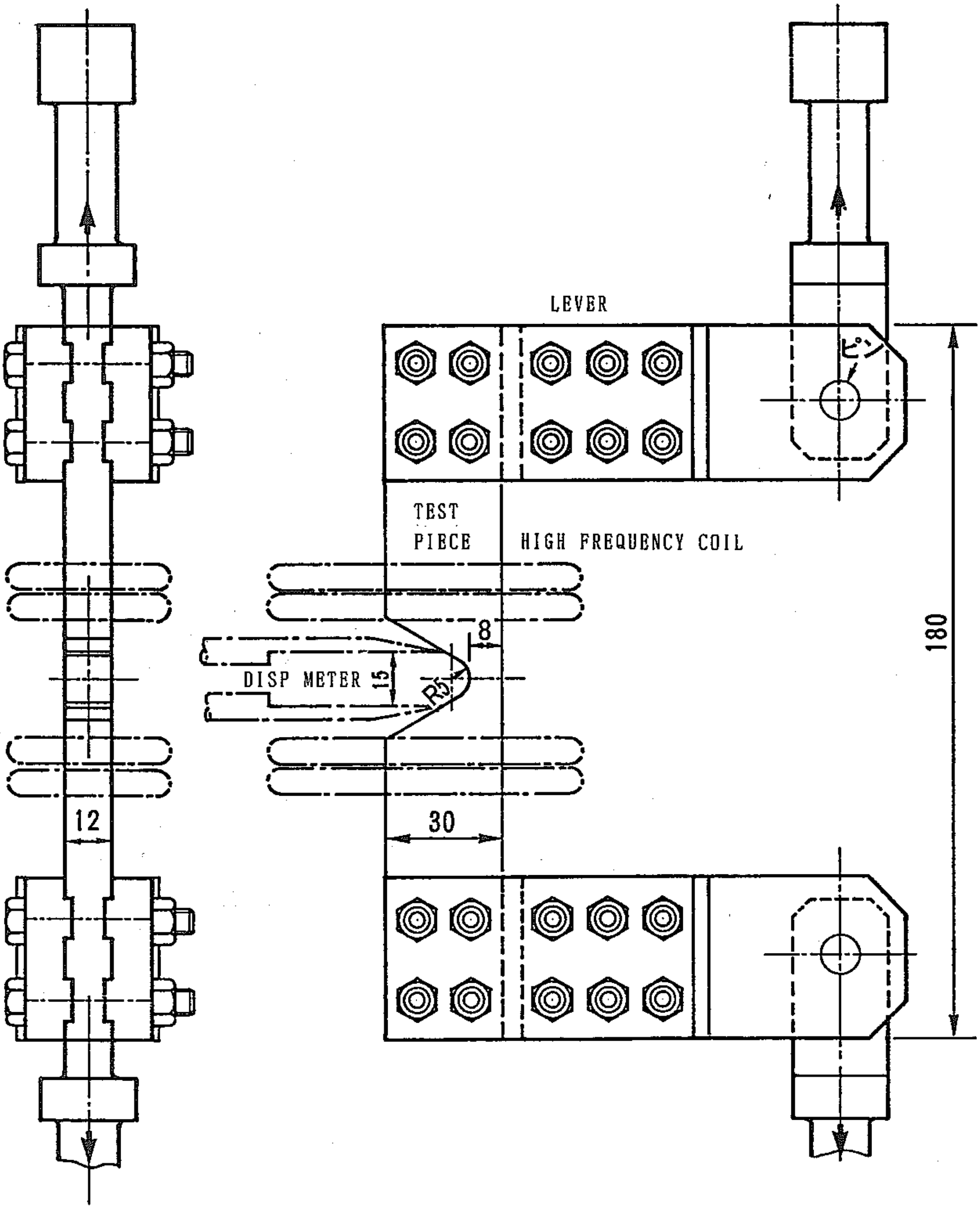


Fig. 12. B. 1 Crack initiation test

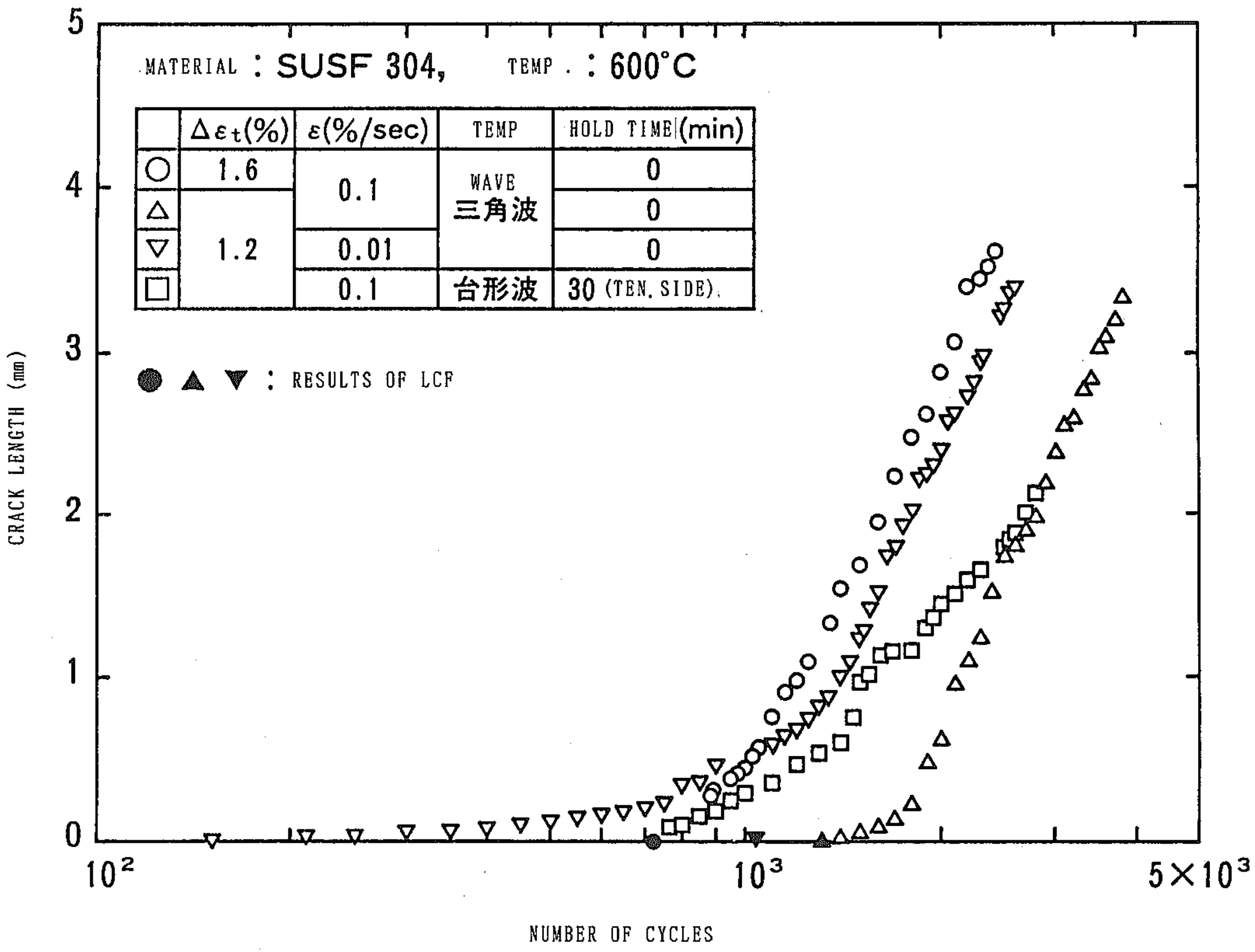


Fig. 12. B. 2 Crack initiation and growth behavior of notched plate under bending load

PNC TN9410 89-001

Pamphlet for 6th review meeting.

CURRENT ACTIVITIES OF STRUCTURAL DESIGN R&D

"SIRIUS" PROGRAM

POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

SCOPE OF THE SIRIUS PROGRAM

1. HIGH TEMPERATURE STRUCTURAL DESIGN AND ANALYSIS METHODS
2. STRUCTURAL BEHAVIOR AND FAILURE TESTS AND ASSESSMENTS
3. STRUCTURAL INTEGRITY ASSESSMENT OF FLAWED AND CRACKED STRUCTURES
4. PIPING BELLOWS DESIGN METHODS AND SAFETY ASSESSMENT
5. SEISMEC DESIGN TECHNOLOGY

1. HIGH TEMPERATURE STRUCTURAL DESIGN AND ANALYSIS METHODS (1/3)

RECENT ACTIVITIES

■GENERAL PURPOSE NONLINEAR STRUCTURAL ANALYSIS SYSTEM "FINAS"

- INPLEMENTATION OF ADVANCED CONSTITUTIVE MODELS
- DEVELOPMENT OF EFFICIENT ONE-POINT INTEGRATION SHELL ELEMENTS
- DEVELOPMENT OF AUTOMATIC INCREMENTAL SOLUTION ALGORITHM
- EXTENTION OF DYNAMIC DAMPING OPTIONS
- DEVELOPMENT OF AXISYMMETRIC SHELL HARMONIC SERIES EXPANSION ELEMENTS

■INELASTIC CONSTITUTIVE MODELS

- DEVELOPMENT OF SIMPLE BUT ACCURATE CYCLIC PLASTICITY MODELS
- STUDY OF UNIFIED CONSTITUTIVE MODELS

— DEVELOPMENT OF INELASTIC BEHABIOR SIMULATION PROGRAM USING ADVANCED CONSTITUTIVE MODELS (ADMODEL)

■ SIMPLIFIED ANALYSIS METHODS FOR TUBESHEET-SHELL STRUCTURES

— COMBINATION OF AXISYMMETRIC AND PLATE MODELS

— LOCAL STRESS/STRAIN CONCENTRATION IN LIGAMENT AND RIM-LIGAMAMENT REGIONS

■ IMPROVEMENT OF HIGH TEMPERATURE STRUCTURAL DESIGN GUIDE

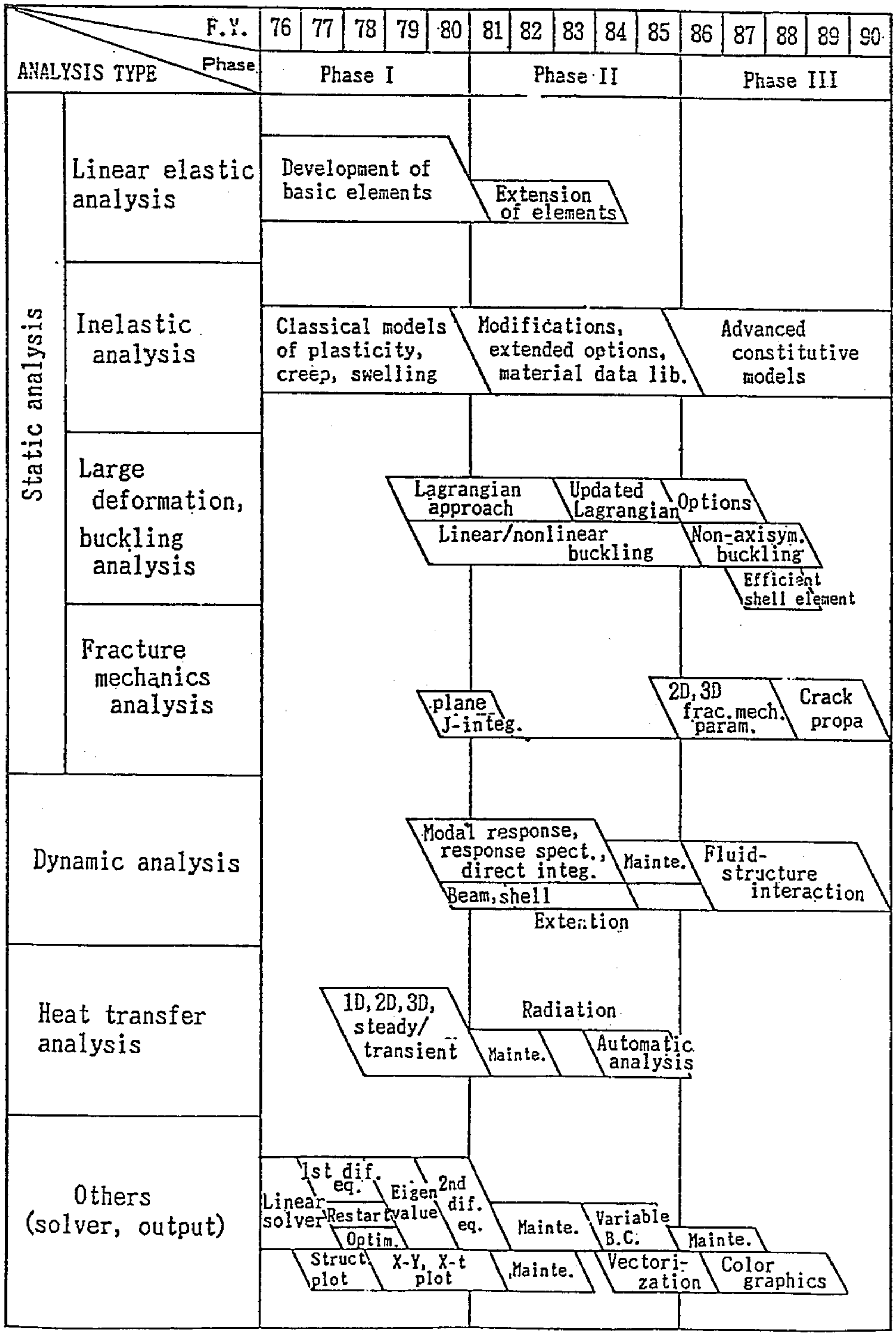
— CREEP-FATIGUE DESIGN METHODS BASED ON ELASTIC ANALYSIS

— DESIGN METHODS FOR WELDMENT

— STRAIN LIMIT CRITERIA (RATCHETTING)

— PROPOSAL OF IMPROVED HIGH TEMPERATURE DESIGN GIDE

FINAS DEVELOPMENT HISTORY AND CURRENT PROGRAM



2. STRUCTURAL FAILURE AND BEHAVIOR TESTS AND ASSESSMENTS (1/2)

FACILITIES

- THERMAL TRANSIENT TEST FACILITY FOR STRUCTURES (TTS)
- SMALL THERMAL SHOCK TEST LOOP (STST)
- SODIUM PIPING THERMAL TRANSIENT TEST LOOP (SPTT)
- MULTI LOADING TEST RIG (MLT)
- ELECTRO-SERVO CONTROLLED ACTUATORS

RECENT ACTIVITIES

- THERMAL CREEP-FATIGUE TEST USING SIMPLE MODELS
  - TAPERED MODELS TEST COMPLETED
  - NOZZLE MODELS TEST STARTED
  - CYLINDER MODELS IN FABRICATION

- THERMAL CREEP-FATIGUE TEST USING STRUCTURAL MODELS
  - THERMAL STRESS MITIGATION MODEL (1) TEST COMPLETED
  - THERMAL STRESS MITIGATION MODEL (2) TEST STARTED
  - WELDED VESSEL MODEL IN FABRICATION

2. STRUCTURAL FAILURE AND BEHAVIOR TESTS AND ASSESSMENTS (2/2)

- CREEP-FATIGUE CRACK INITIATION TESTS
  - — NOTCHED PLATES SUBJECT TO BENDING LOAD

- BUCKLING TEST OF THIN CYLINDER STRUCTURES
  - — INPERFECTION SENSITIVITY
  - — ASSESSMENT OF SAFETY FACTOR

- VERIFICATION TEST OF INELASTIC BEHAVIORS OF STRUCTURES
  - — CYCLIC PLASTICITY BEHAVIOR OF SIMPLE PLATE WITH A HOLE
  - — RATCHETTING BEHAVIOR OF THREE BAR MODEL

3. STRUCTURAL INTEGRITY ASSESSMENT OF FLAWED AND CRACKED STRUCTURES (1/2)

FACILITIES

- ELECTRO-SERVO CONTROLLED ACTUATORS
- AIR COOLING THERMAL TRANSIENT TEST FACILITY (ATTF)
- SMALL THERMAL SHOCK TEST LOOP (STST)
- THERMAL TRANSIENT TEST FACILITY (TTS)

RECENT ACTIVITIES

- FATIGUE CRACK GROWTH TEST
  - PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK
  - PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK
  - NOTCHED PLATES WITH A SMALL CRACK

- CREEP-FATIGUE CRACK GROWTH TEST
  - PLATES WITH A SEMI-ELLIPTICAL SURFACE CRACK
  - ELBOWS WITH SEMI-ELLIPTICAL SURFACE CRACKS
  - PIPES WITH A SEMI-ELLIPTICAL SURFACE CRACK
  - NOTCHED PLATES WITH A SMALL CRACK

3. STRUCTURAL INTEGRITY ASSESSMENT OF FLAWED AND CRACKED STRUCTURES (2/2)

- THERMAL FATIGUE CRACK GROWTH TEST
  - — CYLINDERS WITH SEMI-ELLIPTICAL SURFACE CRACKS
  - — CYLINDERS WITH CIRCUMFERENCIAL SURFACE CRACKS

- THERMAL CREEP-FATIGUE CRACK GROWTH TEST
  - — CYLINDER WITH SEMI-ELLIPTICAL SURFACE CRACKS

- FRACTURE MECHNICS ANALYSIS CODE (CANIS)
  - — ELASTIC AND INELASTIC FRACTURE MECHANICS PARAMETERS
  - — ENGINEERING GROWTH COMPUTATION
  - — DETERMINISTIC AND PROBABILISTIC CRACK ASSESSMENTS

4. PIPING BELLOWS DESIGN METHODS AND SAFETY ASSESSMENT (1/2)

- MATERIAL STRENGH TEST
  - CREEP-FATIGUE, CREEP AND TENSILE TESTS OF SHEET METAL
- CREEP-FATIGUE TEST OF BELLOWS
  - AXIAL AND BENDING CYCLIC LOADING WITY HOLD TIME USING 42B BELLOWS
- BUCKLING OF BELLOWS
  - INTERNAL PRESSURE BUCKLING OF 42B, 20B AND 12B BELLOWS WITH AND WITHO INITIAL DISPLACEMENTS
  - EXTERNAL PRESSURE BUCKLING OF 20B BELLOWS
- THERMAL TRANSIENT TEST OF BELLOWS EXPANSION JOINTS
  - CREEP-FATIGUE DAMAGE ESTIMATION OF Y AND E JUNCTIONS OF HARDWARE

4. PIPING BELLOWS DESIGN METHODS AND SAFETY ASSESSMENT (2/2)

- SEISMIC TEST
  - VIBRATION TEST OF BELLOWS AND BUILT-UP EXPANSION JOINT
  - VIBRATION TEST OF SIMPLE PIPING MODEL WITH EXPANSION JOINTS
- STRENGTH TEST FOR LBB
  - CRACK PROPAGATION TEST OF BELLOWS
  - SEVERE TEST ON THE POSIBILITY OF UNSTABLE FRACTURE OF BELLOWS
- STRENGTH TEST UNDER SHOCK PRESSURE WAVE
  - INTEGRITY OF PIPING SYSTEM WITH BELLOWS EXPANSION JOINTS AT DESIGN ACCIDENTS

Research and development of piping bellows expansion joints

Applicability to Sodium Piping

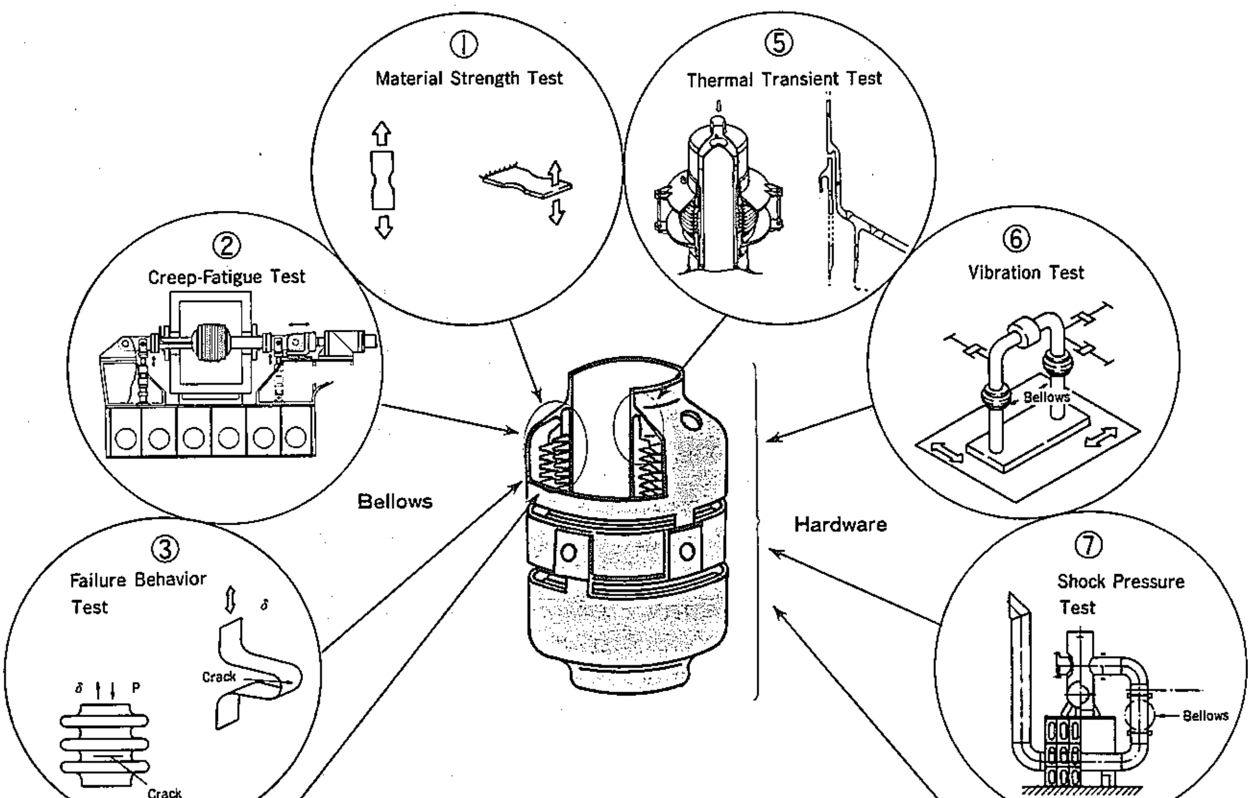
In order to confirm structural integrity and reliability of piping bellows expansion joint for FBR plants, in-sodium test was carried out by 42inch full scale models of expansion joints.

Standards

The standards for the design, manufacture and inspection of bellows expansion joints have been developted to assure high reliability sufficient for the component to be used in nuclear plants.

Strength Evaluation

The testing for creep-fatigue, thermal shock, buckling, resistance to impulsive pressure, leak before break (LBB) and the development of relevant evaluation methods have been conducted to assure the structural integrity of bellows under severe service condition such as high temperatures, repeated thermal shocks, relatively high primary stresses.



Items \ Year	1983	1984	1985	1986	1987	1988
①		Material Strength Test	—	—	—	
②	Creep-Fatigue Test	—	—	—	—	
③				Failure Behavior Test	—	
④		Buckling Strength Test	—	—	—	
⑤		Thermal Transient Test	—	—		
⑥			Vibration Test	—	—	—
⑦				Shock Pressure Test	—	
⑧		Large Model Demonstration Test	—	—	—	—

Feasibility Study of FBR Piping Bellows Expansion Joints

5. SEISMIC DESIGN TECHNOLOGY

FACILITY

■ 2-D SEISMIC TABLE (3m×2.5m)
- CONSTRUCTION COMPLETE IN LATE 1989.

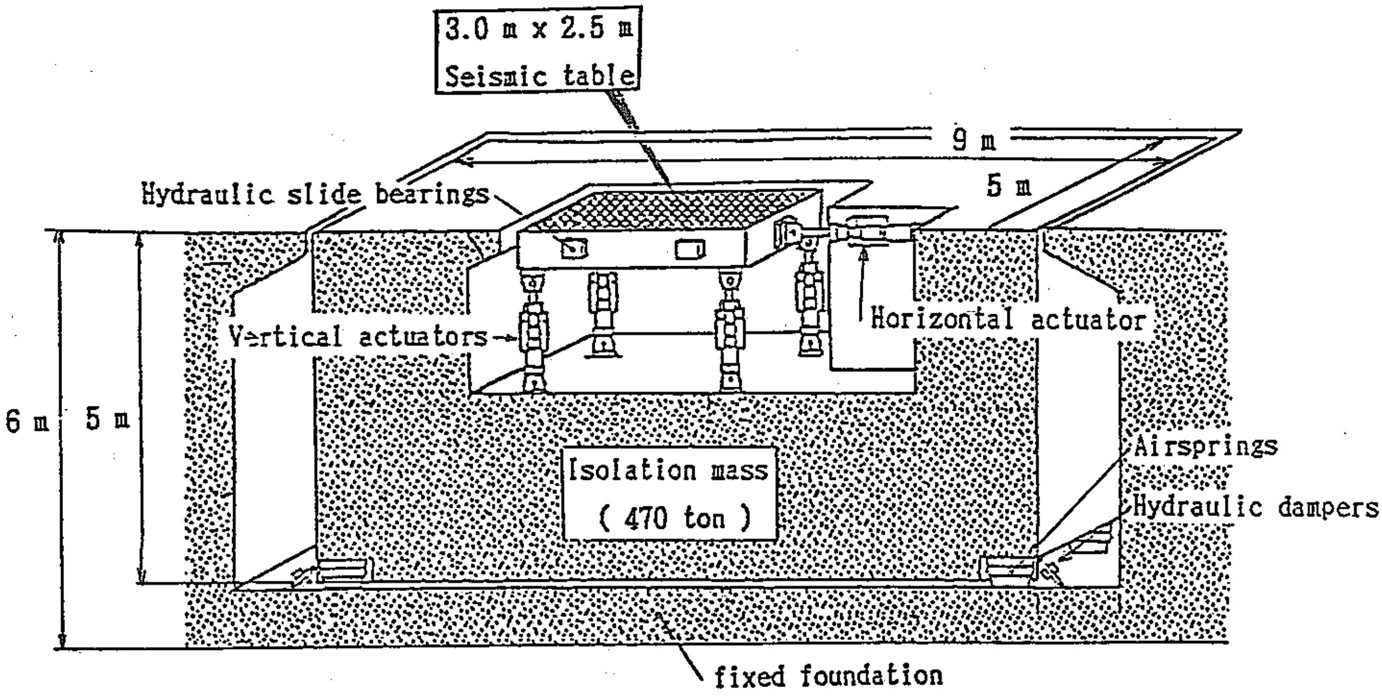
RECENT ACTIVITIES

■ SEISMIC ISOLATION
- APPLICATION TO LARGE SCALE LMFBR BUILDING
- RUBBER BEARING AND ENERGY ABSORBING DEVICES
- DETAILED ANALYSES AND VIBRATION TESTS WITH SMALL SCALE MODELS

■ FLUID-STRUCTURE INTERACTIONS AND SLOSHING
- ANALYSIS BY FINAS CODE
- VERIFICATION BY EXISTING TEST DATA

■ CORE SESMIC ANALYSIS METHODS
- ANALYSIS BY FINAS CODE
- VERIFICATION BY EXSISTING DATA
- APPLICATION TO LARGE CORE
  COMPARATIVE STUDY OF FREE STANDING AND RESTRAINED CORE

■ ADVANCED SEISMIC SUPPORT SYSTEMS
- ENERGY ABSORBING DEVICE BY INELASTIC DEFORMATION



DOHNEN SEISMIC SYSTEM

PERFORMANCE of SEISMIC TABLE

Max. loading weight	(ton)	6
Table size	(m)	3 x 2.5
Direction of excitation		Biaxial simultaneous
Max. displacement	(mm)	H=±100 V=±75
Max. velocity	(cm/sec)	H=±100 V=±100
Max. acceleration	(G)	H=±3 V=±2
Overturning moment	(ton*m)	10
Exciting frequency range	(Hz)	DC～100
Driving system		Electro-hydraulic servo system
Control system		Analog-degital control

RESEARCH AND DEVELOPMENT TIME SCHEDULE