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JNC Contribution to the Benchmark Problem on Thermal Transient Strength Evaluation of a Welded Vessel

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JNC contribution to the Benchmark Problem on thermal transient strength evaluation of a welded vessel

(Research Report)

Naoto Kasahara*

Abstract

Fatigue and creep-fatigue strength of welded joints are lower than base metals, when applied to elevated temperature components subjected to cyclic thermal transient loading. CEA and JNC have developed design evaluation procedures for considering strength reduction of weldments in elevated temperature components. It was planned to compare both procedures based on the same benchmark problems under EJCC contract. One of benchmarks provided by CEA is fatigue and creep-fatigue evaluation of welded plates due to reverse bending at 550℃. Another problem by JNC is creep-fatigue evaluation of a welded vessel due to cyclic thermal transient loading. Point of view of the later problem is comparison of total strength evaluation of base metal and welded joints against actual loading conditions. This report describes details of the TTS experiments and defines the JNC benchmark problem.

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溶接容器の熱過渡強度評価に関するJNCベンチマーク問題

（研究報告書）

笠原 直人*)

要　旨

高温構造設計ではクリープ疲労損傷が主要破損モードとして想定される。特に溶接部は、繰り返し熱過渡荷重が加わる実機条件下において母材より強度が低下するため留意が必要である。このため、CEAとJNCは高温機器における溶接部の強度低減を設計で考慮するための評価法を整備してきている。両者の評価法を相互比較するため、日欧高速炉協定に基づく国際協力によりベンチマーク問題を設定した。一つはCEAから出題されたもので、550℃の温度で繰り返し曲げ荷重を受ける溶接平板の疲労およびクリープ疲労強度評価に関するものである。もう一つはJNCから出題したもので、繰り返し熱過渡荷重を受ける溶接容器のクリープ疲労強度評価に関するものである。

後者は大洗のTTS試験装置で実施された試験に関するものであり、着眼点は実機荷重に対する母材と溶接部の総合強度評価に関する裕度と適用性の確認にある。本報告書ではTTSによる試験概要の説明を行うと共にベンチマーク問題を定義する。

尚、本内容は1999年9月から2000年8月までの期間にCEAカダラッシュ研究所にて実施した業務の一部である。

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Contents

List of figures

1 INTRODUCTION

Fatigue and creep-fatigue strength of welded joints in components are generally lower than base metal under elevated temperature operative conditions. In order to take strength reduction of welded joints into account for elevated temperature structural design, design codes are required to provide rational evaluation methods for welded joints.

CEA and JNC have developed design evaluation procedures for considering strength reduction of weldments. Under EJCC framework, intercomparison of both procedures is planned through application to the same benchmark problems. For benchmark, CEA and JNC have submitted two complementary problems. One of benchmarks, which was provided by Dr. Laurent LE BER of CEA, is fatigue and creep-fatigue evaluation of welded plates due to reverse bending at 550℃[1]. Another problem, proposed by JNC is creep-fatigue evaluation of a welded vessel due to cyclic thermal transient loading. The objective of the later problem is comparison of creep-fatigue evaluation methods of base metals and welded joints on actual components due to cyclic thermal transients. This report describes details of the welded vessel experiment and defines the benchmark problem.

2. THERMAL TRANSIENT TEST OF A WELDED VESSEL MODEL

A thermal transient strength test was conducted on a welded structure model by using a sodium test facility [2]. The test model is a vessel type structure, which has an outer container and an inner vessel as Fig.1. 1055 cycles of thermal transients were applied by alternate flow of hot (600℃) and cold sodium (250℃) which passed though the annulus space between the outside container and the inner vessel. During each cycle, creep damage was accumulated by 2 hours of holding time in 600℃.

As for materials, the outside container and half of the structure of the inner vessel are made of SUS304 (Japanese Type304SS), and the remainder half is made of 316FR (Japanese 316L with midium nitrogen for FBRs), which is low carbon nitrogen stainless steel for Liquid Metal Fast Reactors as in Fig.2. Circumferential and longitudial welded joints are incorporated in both SUS304 and 316FR portions.

A photograph of the vessel model and an outline of the sodium test facility are as in Fig.3 and Fig.4.

Fig.5 describes the dimensions of the test model, where the outside container of the vessel model is 2210mm high and 980mm in diameter with 25 mm thickness wall, and the inner vessel is 456mm inner diameter with 20 mm thickness wall. The inner vessel has a restraint plate with 25mm wall thickness to make stress gradient on the inner vessel.

Fig.6 and Fig.7 show initiated cracks on the surface of the inner vessel observed by the liquid flaw detection test (PT) after 1055 cycles of thermal transients. In the 316FR division of inner vessel, few small cracks were found only at welded joints, while many cracks were observed at both base metals and welded joints in the 304SS parts. Here, the cracks at welded joints were observed to be deeper than that of the nearby base metal.

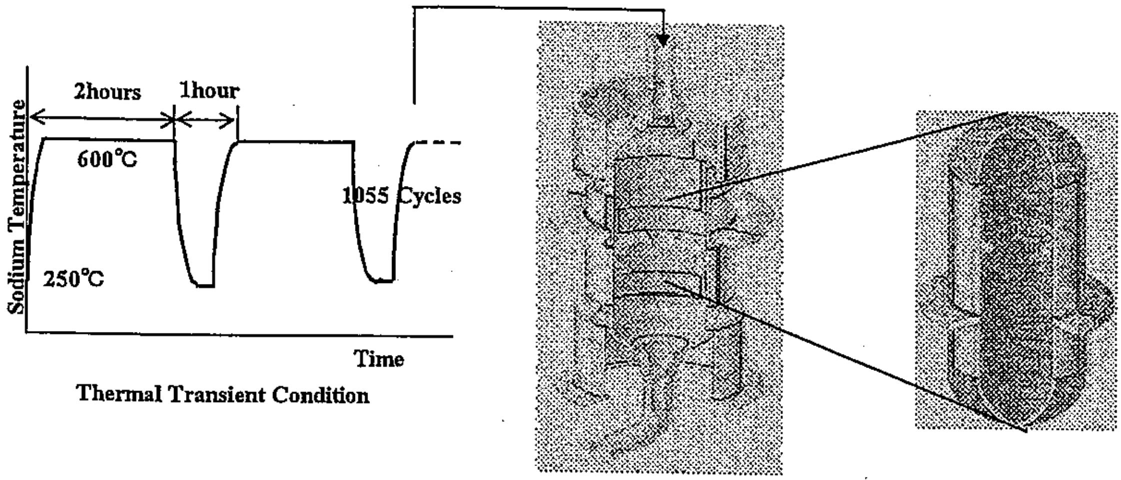

Fig.1 Thermal transient strength test of welded vessel model

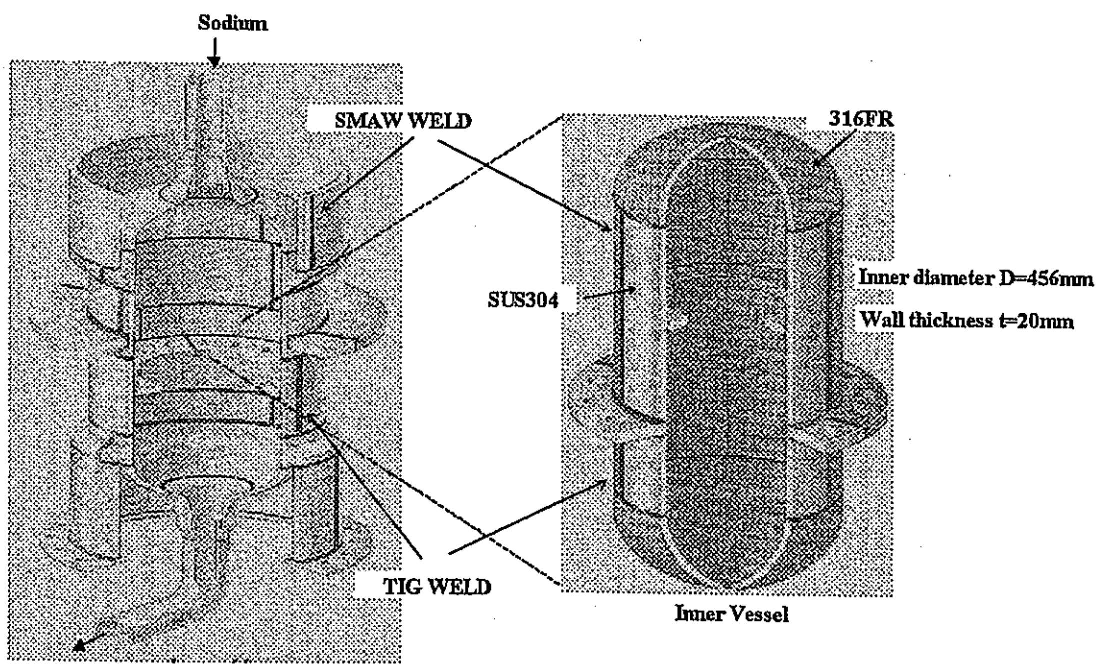

Fig.2 Welded joints in the welded vessel model

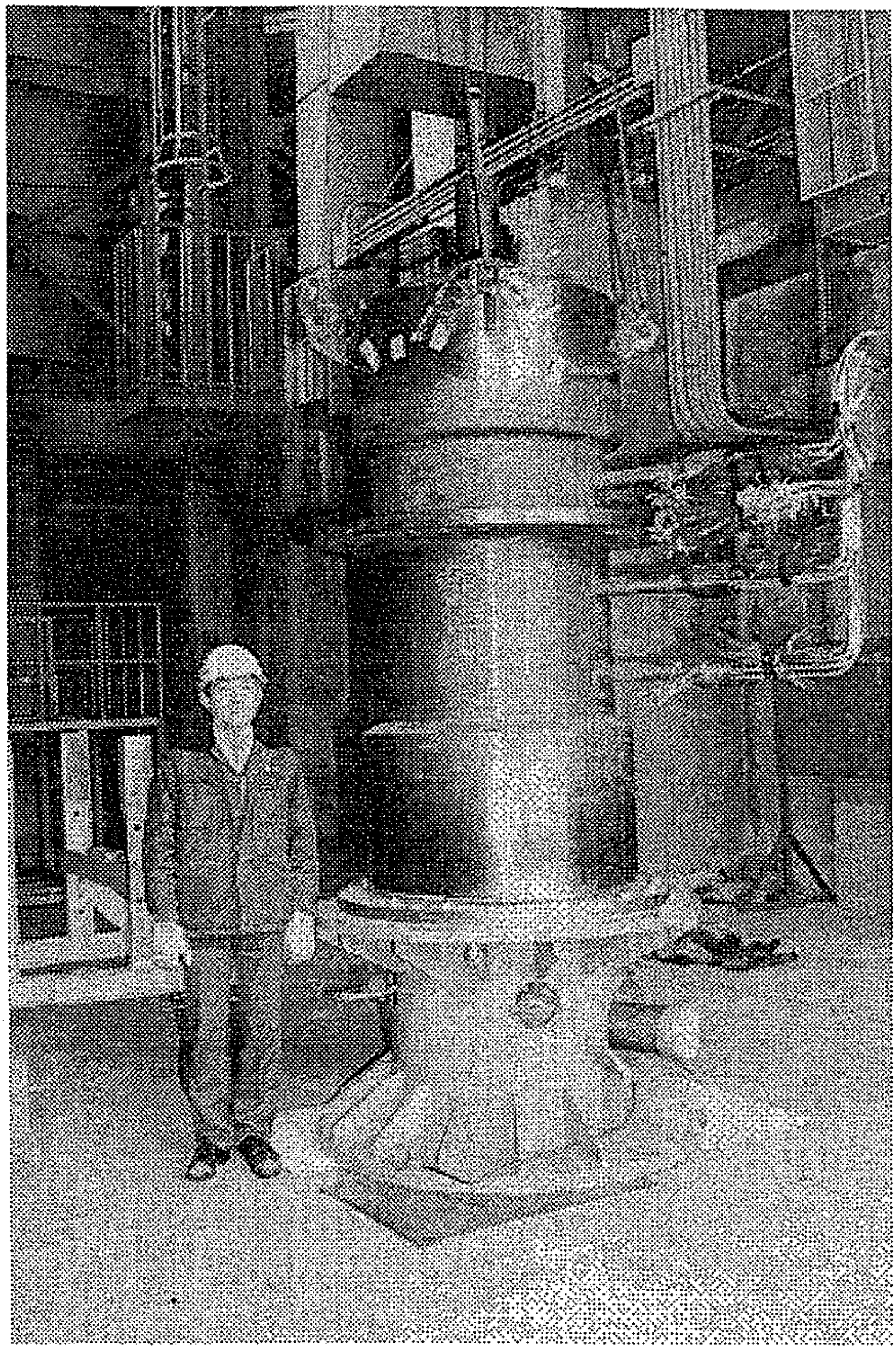

Fig.3 Welded vessel model

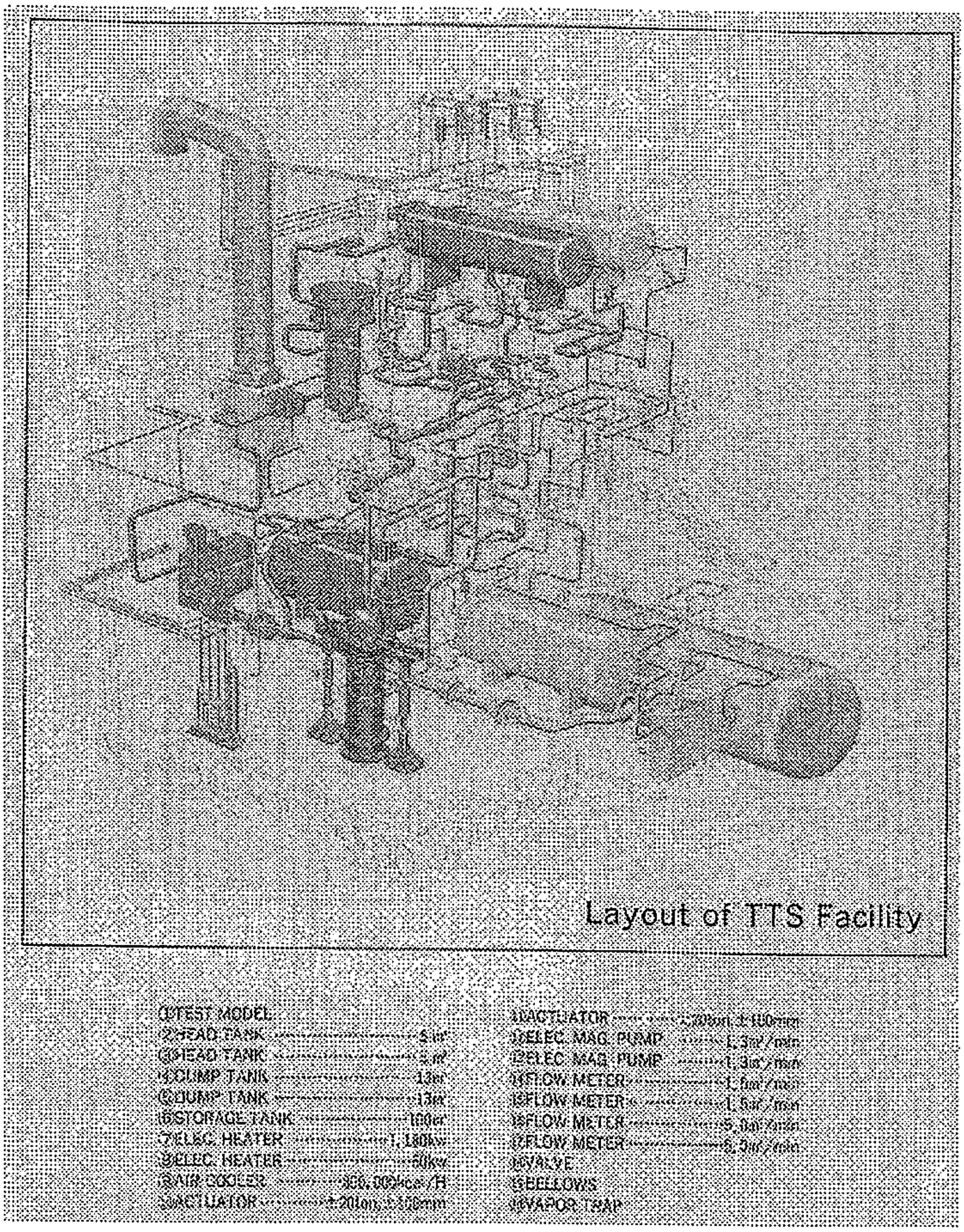

Fig.4 Thermal transient test facility for structure (TTS)

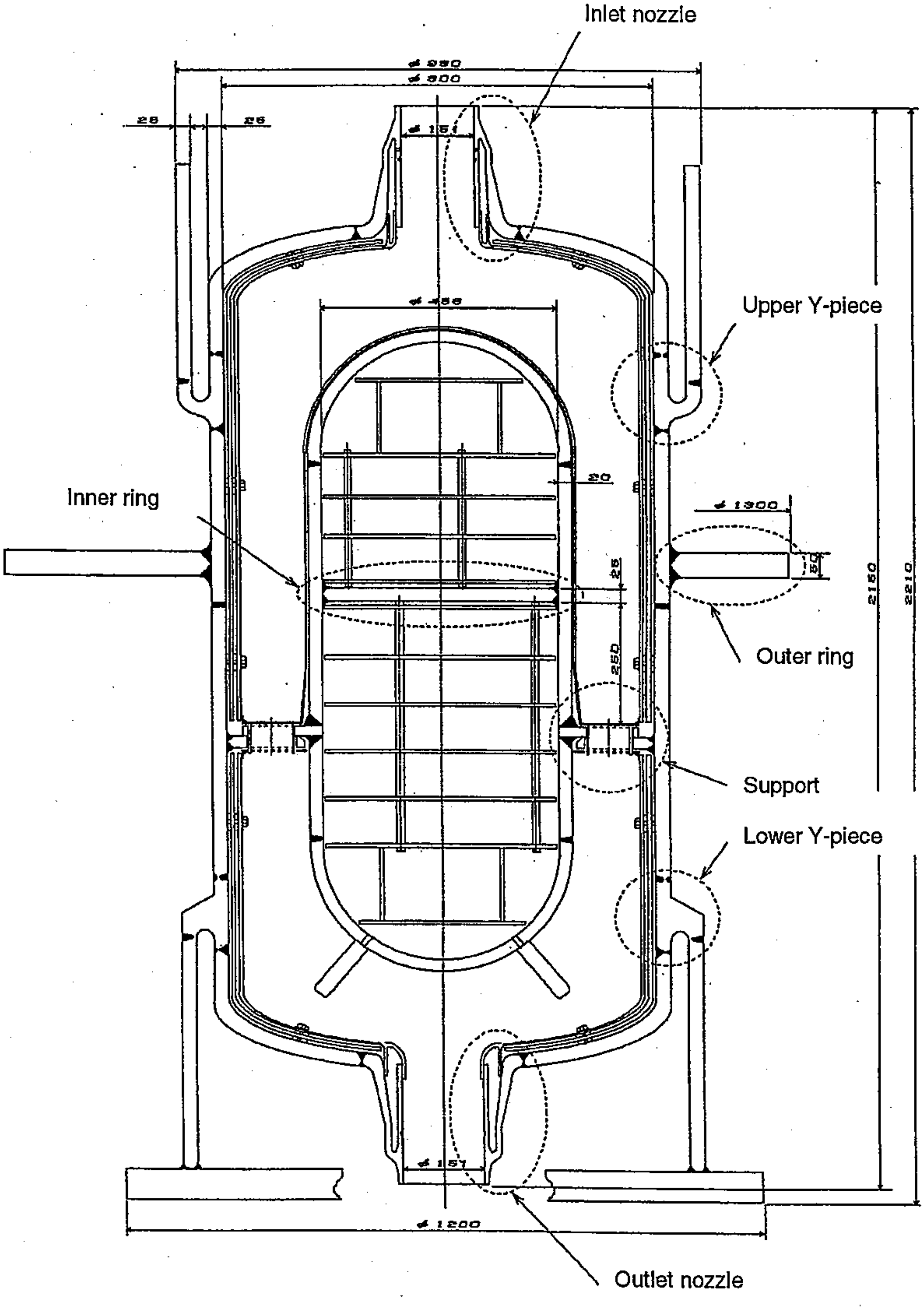

Fig.5 Dimension of welded vessel model

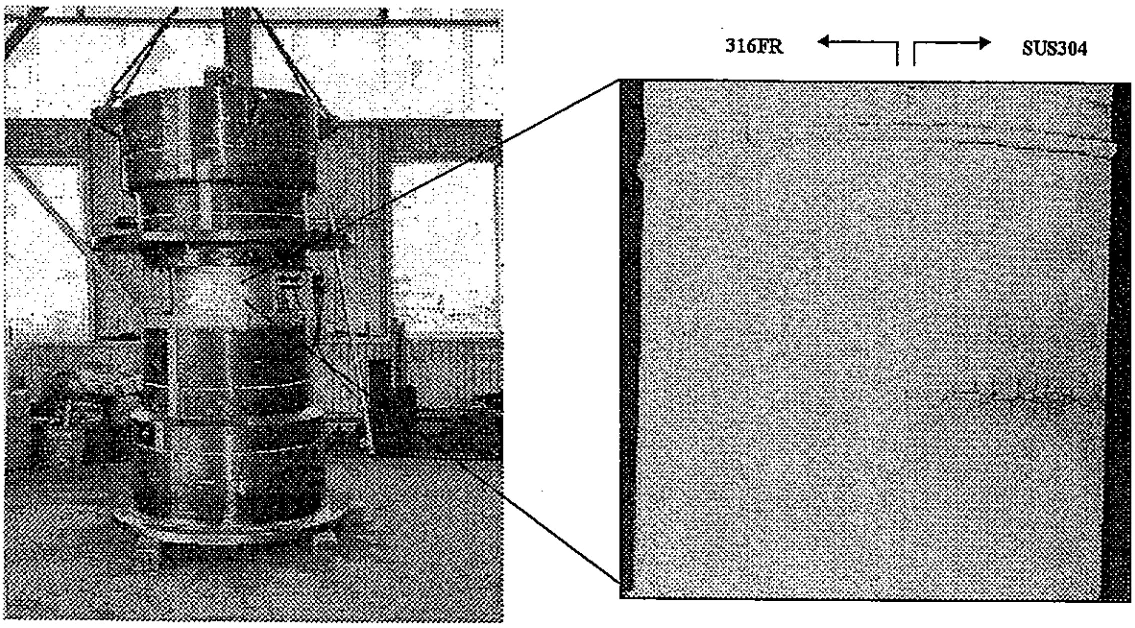

Fig.6 Thermal transient test result of inner vessel (316FR and SUS304)

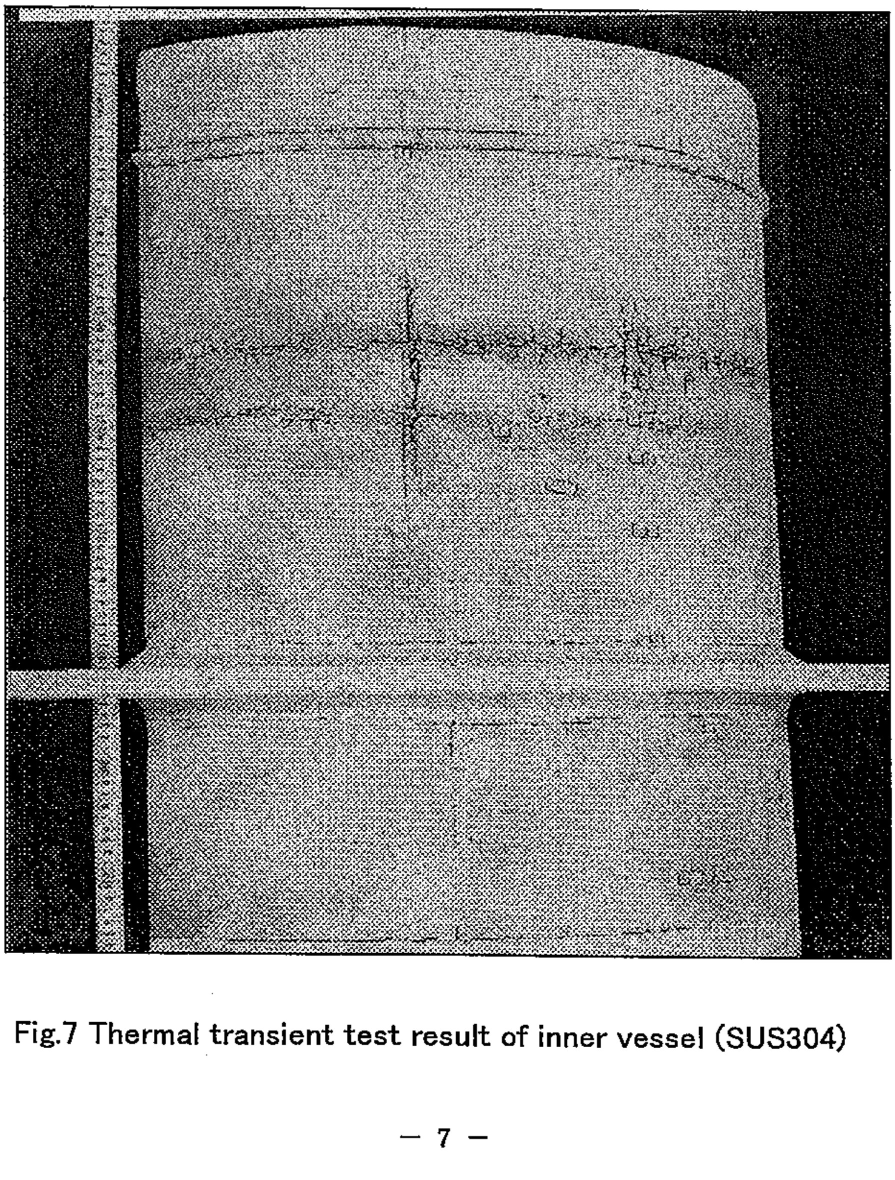

Fig.7 Thermal transient test result of inner vessel (SUS304)

3. SCOPE OF A BENCHMARK PROBLEM

In order to define a scope of the problem as the comparison of creep-fatigue evaluation procedures and to eliminate influences from differences of materials and structural analysis results, this benchmark program provides common material properties and structural analysis results as in Fig.8.

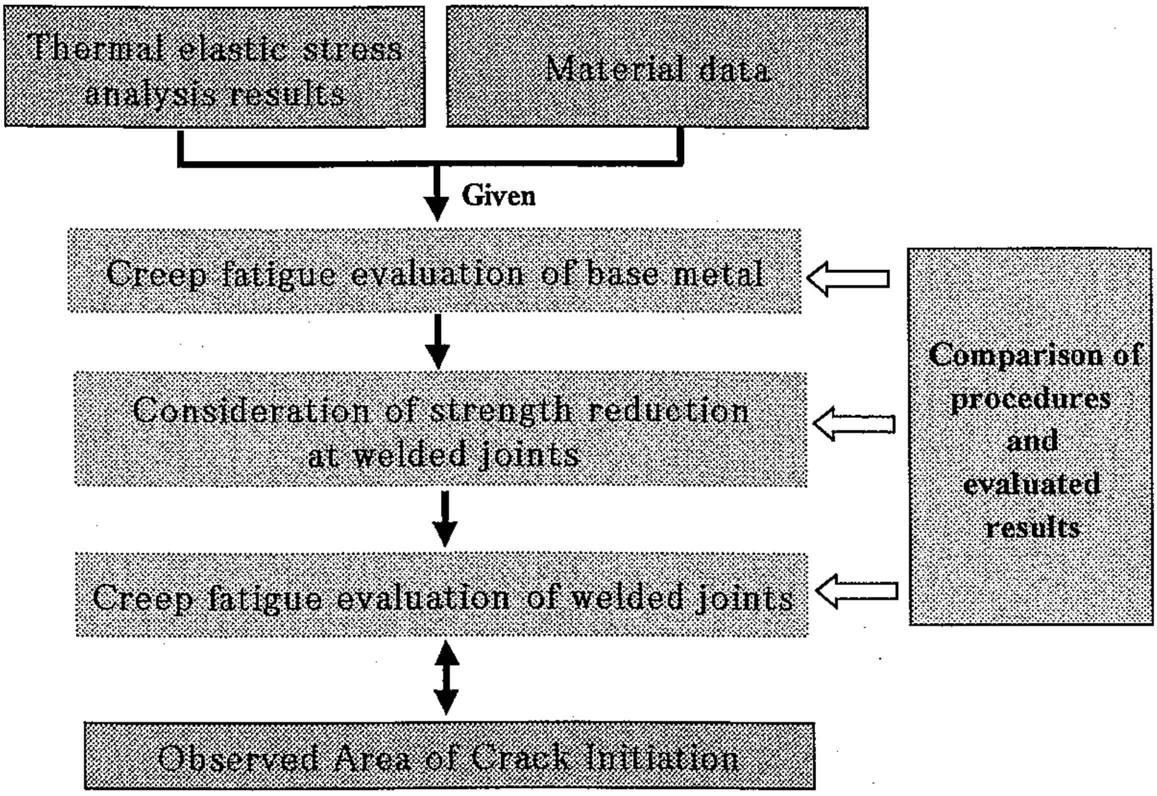

Fig.8 Scope of benchmark problem

Following material properties of SUS304 and 316FR are provided in Appendix1 and Appendix2.

- Fatigue curve
- Monotonic stress-strain curve
- Stress range-strain range relationship
- Creep strain

Above characteristics are average one of base metal obtained by regression analysis of material test results.

Material properties of a weld metal for SUS304 (Type308SS) are describes in literatures[3][4]. A fatigue curve of weld metal for SUS304 is equivalent to one of base metal. Yield stress of a weld metal for SUS304 is lower than base metal after sufficient cyclic loadings.

Properties of weld metal of 316FR are explained in a reference[5]. A fatigue curve is approximately the same as base metal. Difference of Yield stress between weld and base metals is smaller in 316FR than in SUS304.

Target area of benchmark in the welded vessel model is defined as 524mm length on the surface of the inner vessel as in Fig.9. This portion is made of SUS304 base metal, flash grained welded joint of SUS304, 316FR base metal, and flash grained welded joint of 316FR. All of these material parts have the same geometrical configuration.

For evaluation of structural strength against thermal transients, thermal stress analyses under thermal transient test conditions are required. To avoid complexities of structural analyses, a stress classification table obtained from thermal elastic analysis based on measured temperature data is provided in Fig.10 and by Appendix3. Both European and Japanese participants would apply the elastic route to evaluate creep-fatigue strength, based on the same stress classification table.

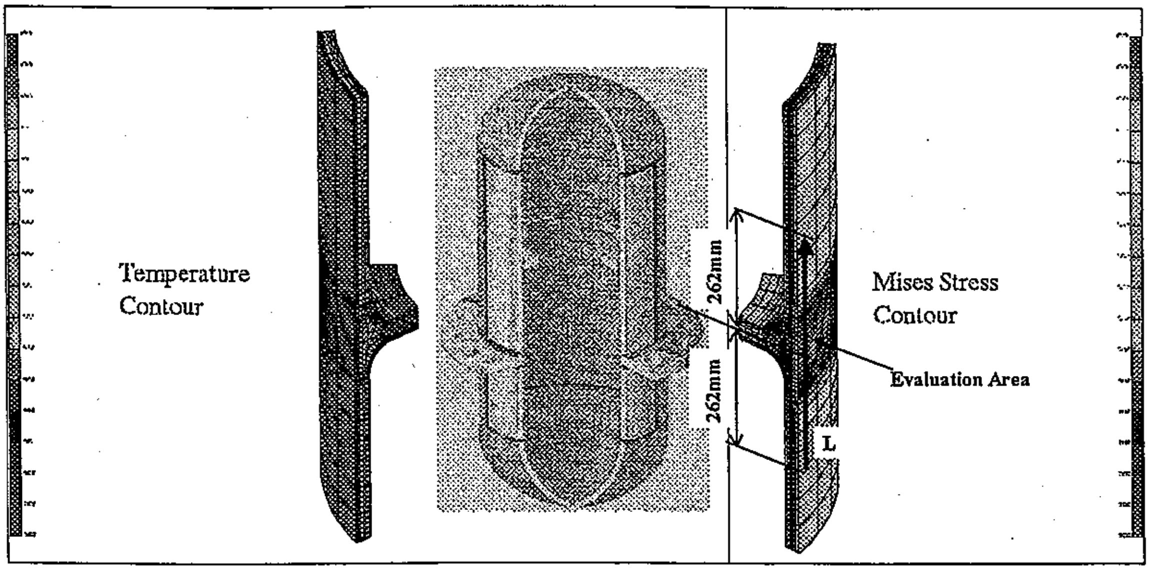

Fig.9 Thermal and thermal elastic analysis results

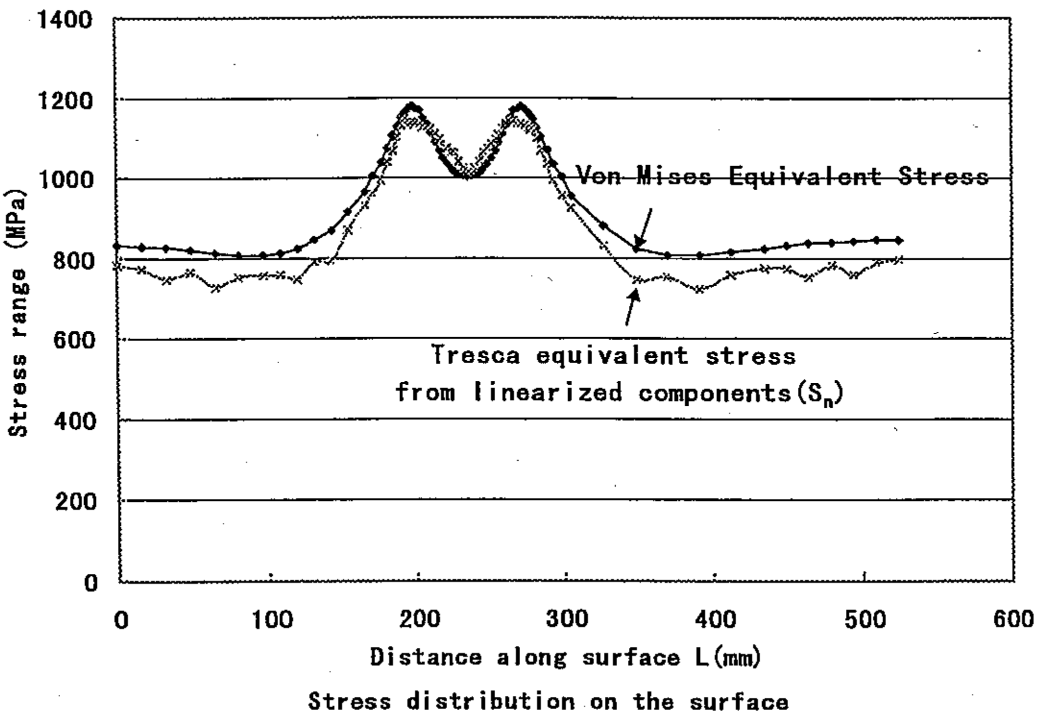

Fig.10 Thermal stress distribution along surface of inner vessel

4. BENCHMARK

The objective of this benchmark program is to evaluate creep-fatigue strength of the inner vessel in the welded vessel model which is made of SUS304, flash grained welded joint of SUS304, 316FR base metal, and flash grained welded joint of 316FR.

Both European and Japanese participants are expected to make a report with following items for SUS304, flash grained welded joint of SUS304, 316FR base metal, and flash grained welded joint of 316FR.

1. Creep-fatigue evaluation procedure
2. Criteria used for failure analysis
3. Total strain range
4. Fatigue strength reduction factor of welded joints
5. Fatigue damage factors
6. Creep damage factors

5. EXPERIMENTAL DATA

Photographs and sketches of initiated cracks on both 304SS and 316FR area of the inner vessel after 1055 cycles are provided in Appendix 4, which clarifies distribution and depth of cracks.

6. JNC CREEP-FATIGUE EVALUATION

6.1. CREEP-FATIGUE EVALUATION PROCEDURE

JNC creep-fatigue evaluation procedure for weldments is explained in literatures[6][7]. Concerning design factor, elastic follow-up parameter q for structural discontinuity is different from SOUFFLE test. Since geometries of SOUFFLE test specimens are flat plates without structural discontinuities, elastic follow-up parameter q is one. The inner vessel of a TTS welded vessel model is also a smooth cylinder, however, the surface becomes bi-axial field under severe thermal transients. Elastic follow-up parameter q of cylinders due to bi-axial bending stress was found to be q=1.67 by previous studies[8][9] and its value was adopted.

When parameter q_w and γ_y are equal to one, the creep-fatigue evaluation procedure for weldments becomes a procedure for base metal[8].

6.2. FATIGUE EVALUATION RESULTS

Distributions of total strain range on the surface of the inner vessel were estimated as in Fig.11 and Fig.12.

From fatigue curves of materials (304SS and 316FR) and calculated strain range, fatigue damage factors were evaluated by *Miner's* rule as in Fig.13 and Fig.14.

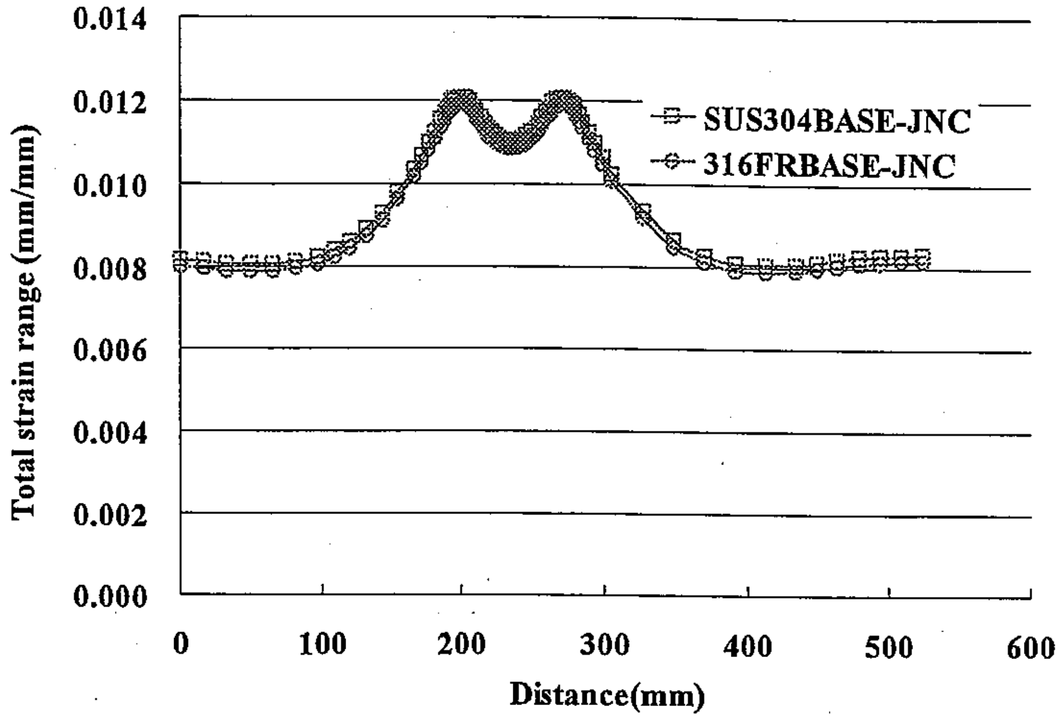

Fig.11 Distribution of total strain range on the surface of an inner vessel (Base metal)

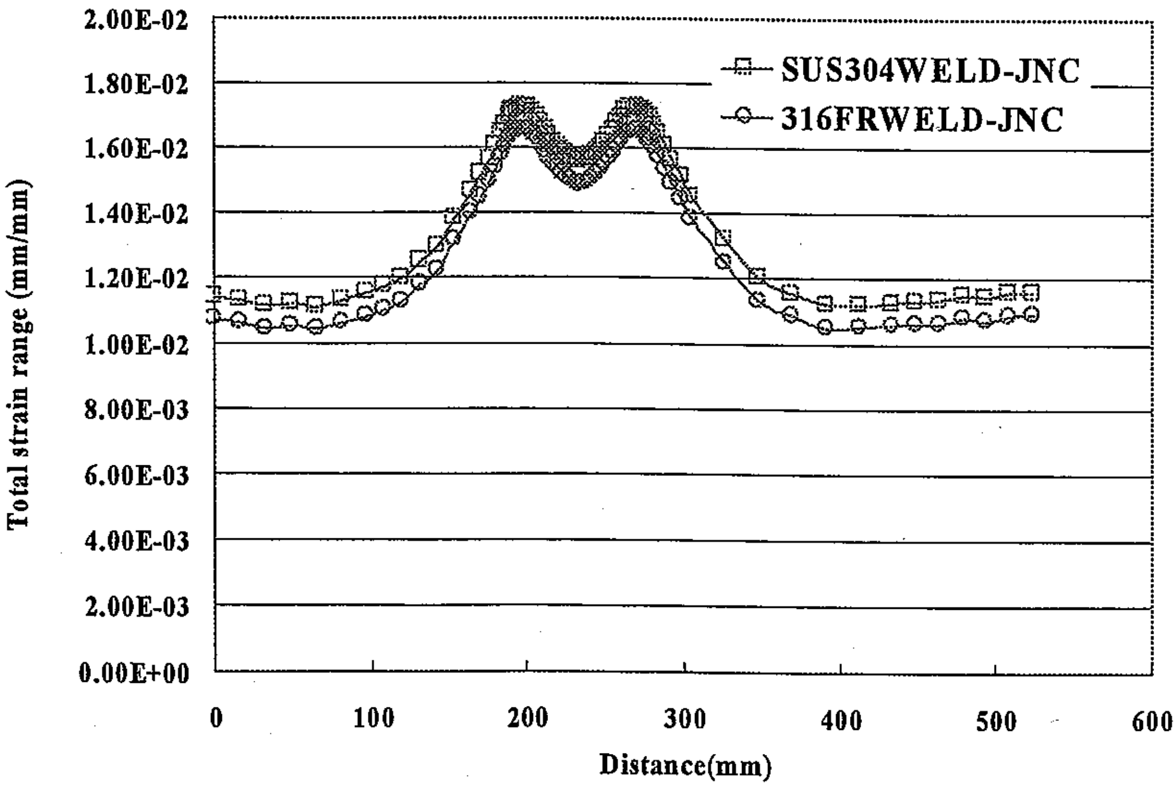

Fig.12 Distribution of total strain range on the surface of an inner vessel (Welded joint)

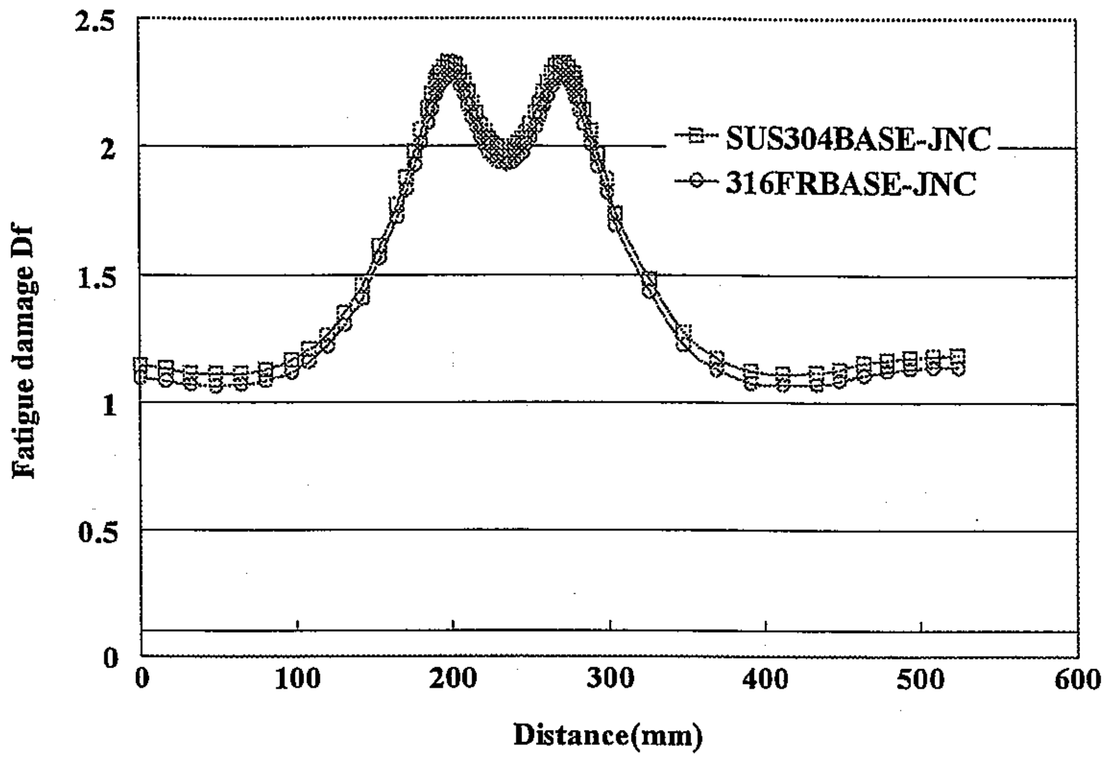

Fig.13 Distribution of fatigue damage factors on the surface of an inner vessel (Base metal)

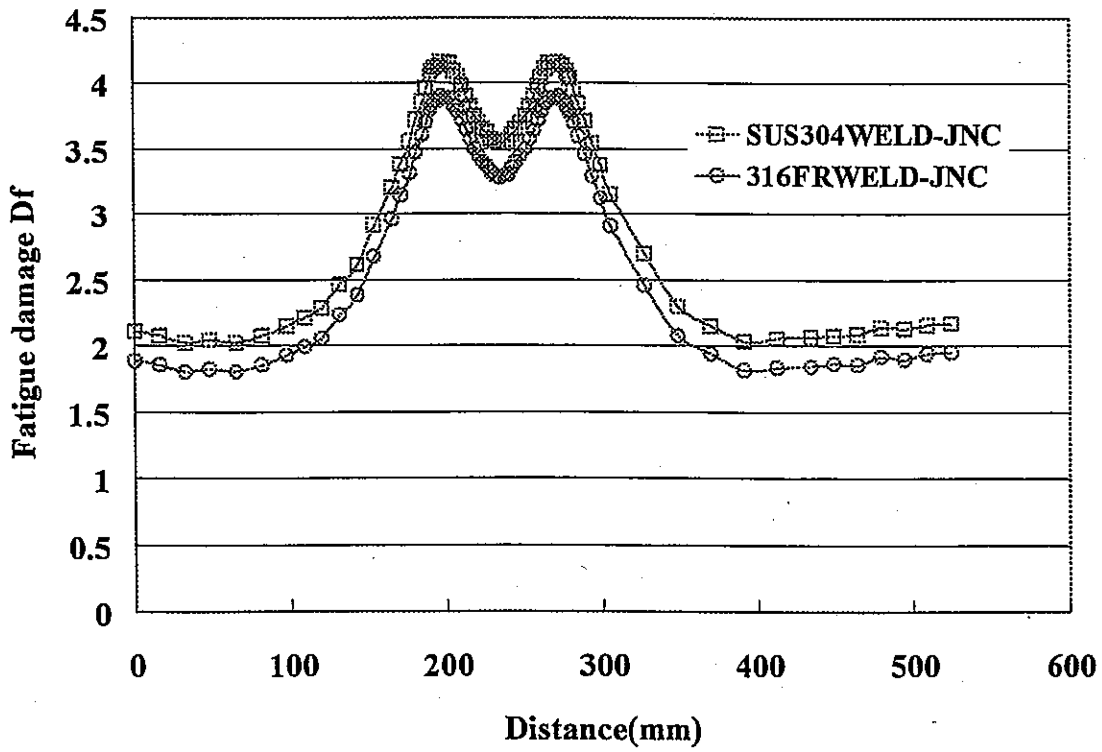

Fig.14 Distribution of fatigue damage factors on the surface of an inner vessel (Welded joint)

6.3. CREEP-FATIGUE EVALUATION RESULTS

From creep rupture curves of materials (304SS and 316FR) with estimated stress history, creep damage factors were calculated based on time fraction rule considering stress relaxation.

Predicted creep-fatigue damage on the inner vessel was as in Fig.15 and Fig.16. From these figures, creep-fatigue damage factors for all materials are beyond 1.0 at all of locations. It means that calculation results predicted possibility of crack initiation at all portions of the inner vessel after 1055 cycles of thermal transients.

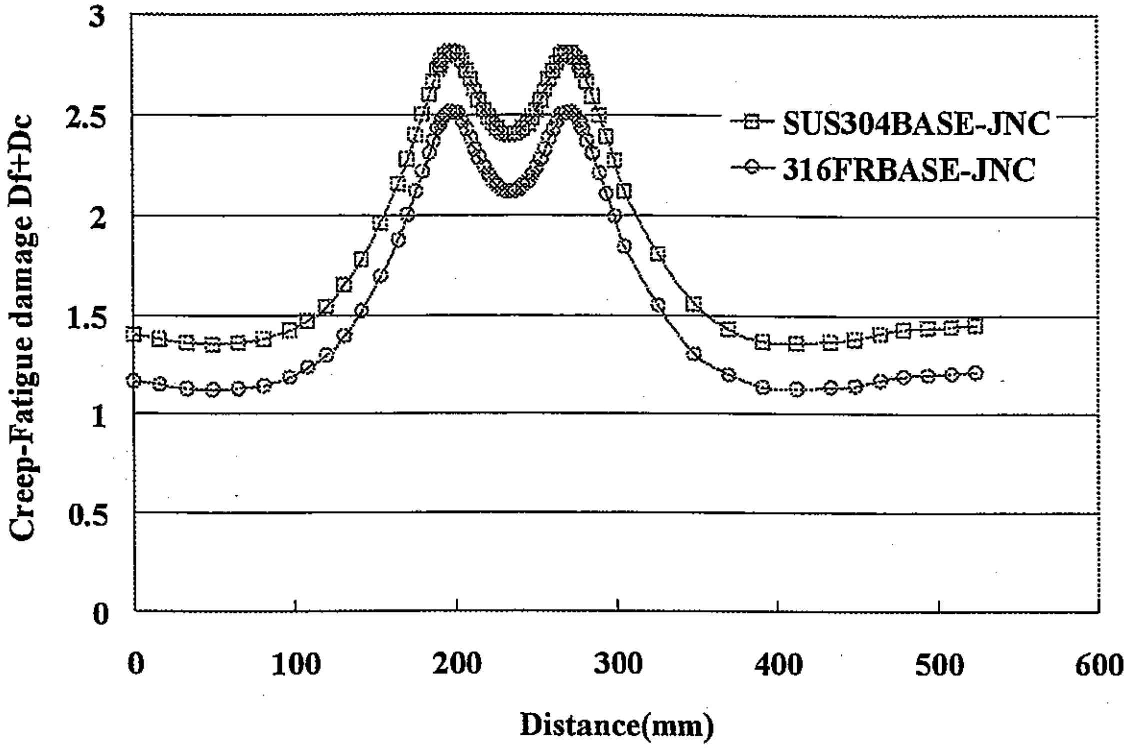

Fig.15 Distribution of creep-fatigue damage factors on the surface of an inner vessel (Base metal)

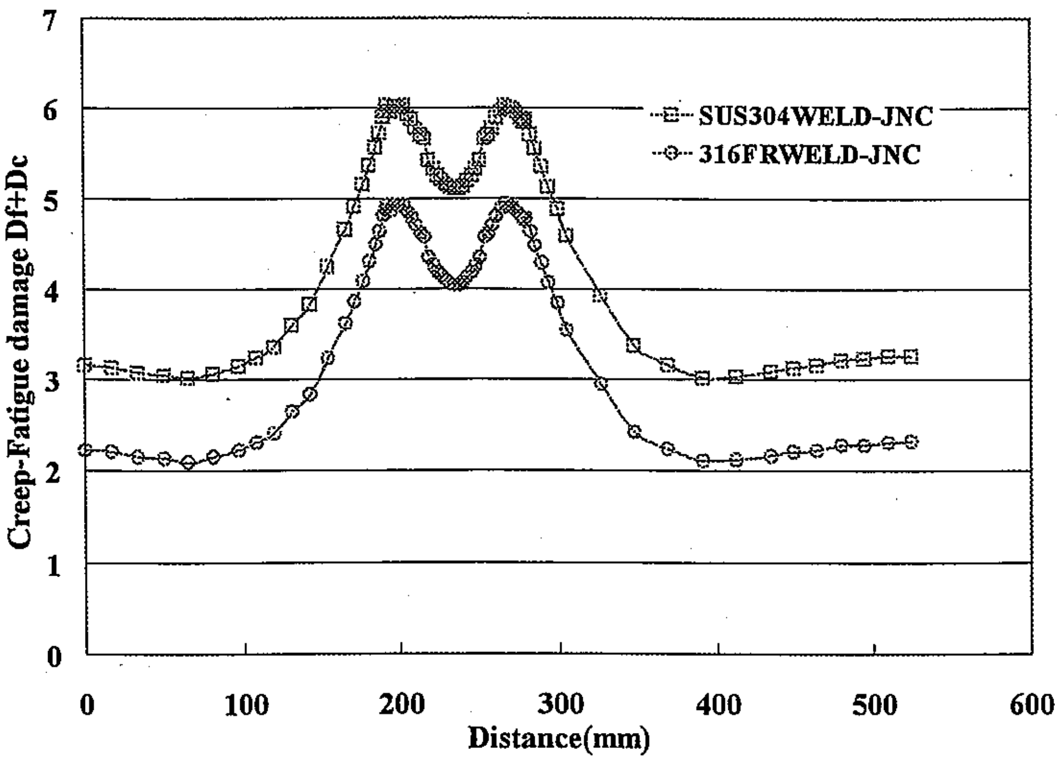

Fig.16 Distribution of creep-fatigue damage factors on the surface of an inner vessel (Welded joints)

7. DISCUSSIONS

Fig.17 is a sketch of initiated cracks on the surface of the inner vessel. Further sketches and photographs are attached in the Appendix 4. From comparison of calculated results with these experimental results, JNC procedure is considered to be conservative for 316FR. One of reasons is that yield strength difference between base and weld metals is less than γ_y=0.9 in the most of strain range of this test. Another reason is that α_R=10 is adjusted factor to the weakest heat. These reasons are common with uni-axial material tests and SOUFFLE test, however, evaluation results of TTS test are considered to be more conservative than other tests. It is possible that q_w caused by thermal stress is less than one of mechanical stress, even if value of γ_y is the same.

8. FUTURE PLAN

In the next step of benchmark program, thermal transient strength evaluation of un-finished welded joints with penetration beads is planned.

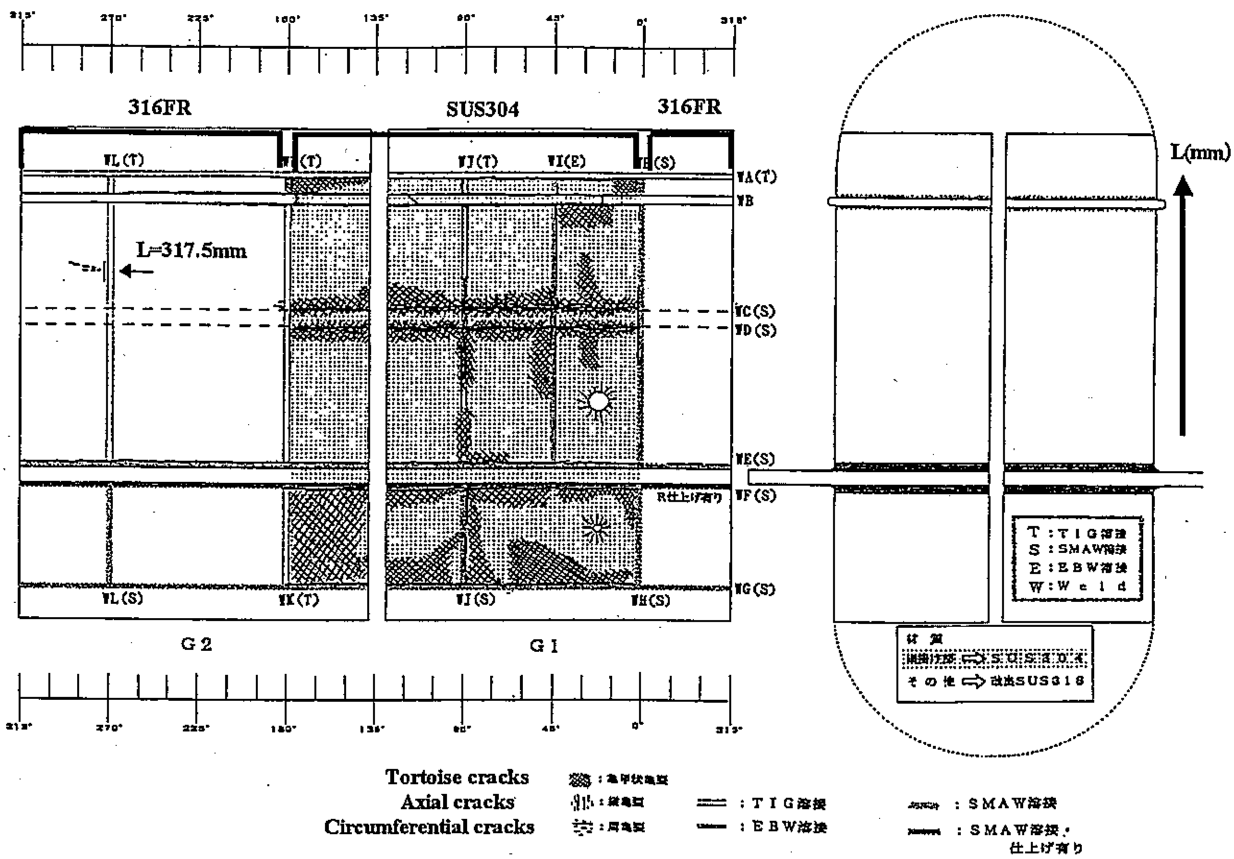

Fig.17 Distribution of initiated cracks on the surface of the inner vessel

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ANNEXE 1 : Material properties of Japanese 304SS(SUS304)

ANNEXE 2 : Material properties of Japanese 316FR

ANNEXE 3 : Stress classification table obtained by thermal elastic analysis of the inner vessel model

ANNEXE 4 : Photographs and sketches of initiated clacks on both surface and section area of the inner vessel after 1055 cycles

Appendix 1　Material properties of Japanese 304SS

SUS304, 316FR Fatigue Curve

$$\log_{10}(N_f)^{-\frac{1}{2}} = A_0 + A_1 \cdot \log_{10}\Delta\varepsilon_t + A_2 \cdot (\log_{10}\Delta\varepsilon_t)^2 + A_3 \cdot (\log_{10}\Delta\varepsilon_t)^4$$

Unit

T : *Temperatue* (℃)

ε : *StrainRate*(mm/mm/sec)

$\Delta\varepsilon_t$: Total Strain Range (mm/mm)

N_f : *Number* of Cycles to Failure

A_0	$1.621827 - 0.4567850 \times 10^{-7} \times T^2 \times R$
A_1	$1.131346 + 0.8665061 \times 10^{-8} \times T^2$
A_2	0.3439663
A_3	$-0.1374387 \times 10^{-1} + 0.4910723 \times 10^{-4} \times R$

Where $R = \log_{10}\varepsilon$

SUS304 Monotonic Stress-Strain Curve

(1)$\sigma \le \sigma_p$

$$\varepsilon_e = \frac{\sigma}{E}$$

$$\varepsilon_p = 0$$

(2)$\sigma > \sigma_p$

$$\varepsilon_e = \frac{\sigma}{E}$$

$$\varepsilon_p = \left(\frac{\sigma - \sigma_p}{K}\right)^{\frac{1}{m}}$$

<Unit>

ε_e(mm/mm), ε_p(mm/mm), σ(kg/mm^2)

<Limit of total strain>

Maximum total strain$(\varepsilon_e + \varepsilon_p)$max ≤ 0.03(mm/mm)

Parameter \ Temperature(°C)	$315 \le T \le 650$
$E(kg/mm^2)$	$315 \le T < 400$ $E = 2.040 \times 10^4 - 8.000T$ $400 \le T \le 650$ $E = 2.126 \times 10^4 - 10.125T$
$\sigma_p(kg/mm^2)$	$\sigma_y - K(0.002)^m$
$\sigma_y(kg/mm^2)$	$25.5655 - 5.58937 \times 10^{-2}T + 1.04384 \times 10^{-4}T^2 - 7.42535 \times 10^{-8}T^3$
$K(kg/mm^2)$	$44.3068 - 1.78933 \times 10^{-2}T$
m	$0.279395 + 7.749 \times 10^{-5}T$

SUS304 Stress Range – Strain Range Relationship

- $\Delta\sigma / 2 > \sigma_p$

$$\log_{10}(\Delta\sigma - 2\sigma_p) = A_0 + A_1 \cdot \log_{10}(\Delta\varepsilon_t - \Delta\sigma / E)$$

- $\Delta\sigma / 2 \leq \sigma_p$

$$\Delta\sigma = E \cdot \Delta\varepsilon_t$$

Unit

T : *Temperature* (℃) $425 \leq T \leq 650$

$\Delta\sigma$: *StressRange* (kg/mm^2)

$\Delta\varepsilon_t$: *TotalStrainRange* (mm/mm)

E : *ElasticModulus* (kg/mm^2)

σ_p : Pr*oportiolLimt*(*kg* / *mm*^{2})

A_0	$0.9772687 + 0.6446708 \times 10^{-2} \times T - 0.4675557 \times 10^{-5} \times T^2 - 0.3724201 \times 10^{-8} \times T^3$
A_1	$3.690128 - 0.1847969 \times 10^{-1} \times T + 0.3544927 \times 10^{-4} \times T^2 - 0.229\ 7822 \times 10^{-7} \times T^3$
E	$2.10236 \times 10^4 - 9.71895 \times T$
σ_p	$25.5655 - 5.58937 \times 10^{-2} \times T + 1.04384 \times 10^{-4} \times T^2 - 7.42535 \times 10^{-8} \times T^3$ $- (44.3068 - 1.78933 \times 10^{-2} \times T) \times (0.002)^{0.279395 + 7.749 \times 10^{-5} \times T}$

SUS304 Creep Strain

$$\varepsilon_C = C_1(1-e^{-r_1 t}) + C_2(1-e^{-r_2 t}) + \varepsilon_m \; t$$

Unit

T : *Temperture* (°C) $425 \le T \le 650$

σ : *Stress* (kg/mm^2) $0.1 \le \sigma$

t_R : *CreepRuptureTime* (hr)

ε_m : *Stationary* Creep Strain Rate (mm/mm/hr)

t : *Time* (hr)

t_R	$\log_{10}(\alpha_C t_R) = -17.54301 + \frac{26248.54}{T+273.15} - \frac{6104.579}{T+273.15}\log_{10}\sigma - \frac{425.0012}{T+273.15}(\log_{10}\sigma)^2$		
ε_m	$62.416 \cdot \exp[-\frac{40812}{8.31\cdot(T+273.15)}]\cdot t_R^{-1.1335}$		
C_1	$1.2692\cdot \varepsilon_m^{0.74491}/r_1$	C_2	$0.48449\cdot \varepsilon_m^{0.81155}/r_2$
r_1	$103.37\cdot t_R^{-0.72607}$	r_2	$17.255\cdot t_R^{-0.86775}$

Where $\alpha c=1$

SUS304 Creep Rupture Time

$$(T+273.15)\ \{\log_{10}(\alpha_R t_R)+C\} = A_0 + A_1 \log_{10}\sigma + A_2(\log_{10}\sigma)^2$$

Unit

T : *Temperature* (℃) $425 \le T \le 825$

σ : *Stress* (kg/mm^2) $2 \le \sigma$

t_R : *CreepRuptureTime* (hr)

C	17.54301
A_0	26248.54
A_1	−6104.579
A_2	−425.0012

α_R	*Average* : 1

Appendix 2 Material properties of Japanese 316FR

316FR Monotonic Stress-Strain Curve

(1)$\sigma \le \sigma_p$

$$\varepsilon_e = \frac{\sigma}{E}$$

$$\varepsilon_p = 0$$

(2)$\sigma > \sigma_p$

$$\varepsilon_e = \frac{\sigma}{E}$$

$$\varepsilon_p = \left(\frac{\sigma - \sigma_p}{K}\right)^{\frac{1}{m}}$$

<Unit>

ε_e(mm/mm), ε_p(mm/mm), σ(kg/mm^2)

<Limit of total strain>

Maximum Total Strain $(\varepsilon_e + \varepsilon_p)\max \le 0.03$(mm/mm)

Parameter \ Temperature (°C)	$315 \le T \le 650$
$E(kg/mm^2)$	$315 \le T < 400$ $E = 2.040 \times 10^4 - 8.000T$ $400 \le T \le 650$ $E = 2.126 \times 10^4 - 10.125T$
$\sigma_p(kg/mm^2)$	$\sigma_y - K(0.002)^m$
$\sigma_y(kg/mm^2)$	$26.8073 - 5.04547 \times 10^{-2}T + 8.03901 \times 10^{-5}T^2 - 5.11282 \times 10^{-8}T^3$
$K(kg/mm^2)$	$40.0909 - 9.69990 \times 10^{-3}T$
m	$0.326245 + 6.13276 \times 10^{-5}T$

316FR Stress Range – Strain Range Relationship

- $\Delta\sigma / 2 > \sigma_p$

$$\log_{10}(\Delta\sigma - 2\sigma_p) = A_0 + A_1 \cdot \log_{10}(\Delta\varepsilon_t - \Delta\sigma / E)$$

- $\Delta\sigma / 2 \leq \sigma_p$

$$\Delta\sigma = E \cdot \Delta\varepsilon_t$$

Unit

T : *Temperature* (℃) $425 \leq T \leq 650$

$\Delta\sigma$: *StressRange* (kg/mm²)

$\Delta\varepsilon_t$: *TotalStrainRange* (mm/mm)

E : *ElasticModulus* (kg/mm²)

σ_p : Pr*oportiolLimt*(*kg* / *mm*²)

A_0	$4.139556 - 0.4434273 \times 10^{-2} \times T + 0.1354228 \times 10^{-5} \times T^2 + 0.1593061 \times 10^{-8} \times T^3$
A_1	$2.171727 - 0.7045263 \times 10^{-2} \times T + 0.7832692 \times 10^{-5} \times T^2 - 0.2083600 \times 10^{-8} \times T^3$
E	$2.10236 \times 10^4 - 9.71895 \times T$
σ_p	$26.8073 - 5.04547 \times 10^{-2} \times T + 8.03901 \times 10^{-5} \times T^2 - 5.11282 \times 10^{-8} \times T^3$ $-(40.0909 - 9.69990 \times 10^{-3} \times T) \times (0.002)^{0.326245 + 6.13276 \times 10^{-5} \times T}$

316FR Creep Strain

$$\varepsilon_C = C_1(1-e^{-r_1 t}) + C_2(1-e^{-r_2 t}) + \varepsilon_m \ t$$

Unit

T : *Temperture* (℃) $425 \le T \le 650$

σ : *Stress* (kg/mm^2) $0.1 \le \sigma$

t_R : *CreepRuptureTime* (*hr*)

ε_m : *Stationary* Creep Strain Rate (mm/mm/hr)

t : *Time* (*hr*)

t_R	$\log_{10}(\alpha_C t_R) = -25.82042 + \frac{32232.27}{T+273.15} - \frac{39.74271}{T+273.15}\log_{10}\sigma - \frac{3481.803}{T+273.15}(\log_{10}\sigma)^2$		
ε_m	$241.33 \cdot \exp[-\frac{51222}{8.31\cdot(T+273.15)}]\cdot t_R^{-1.1032}$		
C_1	$1.2692\cdot\varepsilon_m^{0.74491}/r_1$	C_2	$0.48449\cdot\varepsilon_m^{0.81155}/r_2$
r_1	$103.37\cdot t_R^{-0.72607}$	r_2	$17.255\cdot t_R^{-0.86775}$

Where αc=1

316FR Creep Rupture Time

$$(T+273.15)\ \{\log_{10}(\alpha_R t_R)+C\}$$
$$= A_0 + A_1 \log_{10}\sigma + A_2(\log_{10}\sigma)^2$$

Unit

T : *Temperature* (°C) $425 \le T \le 825$

σ : Stress (kg/mm^2) $2 \le \sigma$

t_R : *CreepRuptureTime* (hr)

C	25.82042
A_0	32232.27
A_1	−39.74271
A_2	−3481.803

α_R	*A*verage : 1

Appendix 3 Stress classification table obtained by thermal elastic analysis of the inner vessel model

TN9400 2001-009

L	ΔVMS	Sn	TIME1	TEMP1	LTEMP1	MTEMP1	σr1	σz1	σθ1	τrz1	Lσr1	Lσz1	Lσθ1	Lτrz1	Mσr1	Mσz1	Mσθ1	Mτrz1	TIME2	TEMP2	LTEMP2	MTEMP2	σr2	σz2	σθ2	τrz2	Lσr2	Lσz2	Lσθ2	Lτrz2	Mσr2	Mσz2
202.6501	1168.969	1137.156	59.5	398.0557	407.0515	487.7256	0.040099	56.02271	57.58032	-0.05531	0.040099	52.64476	54.37715	-0.05531	-3.40037	-0.11004	10.43796	2.611888	3659.5	467.6152	460.2097	365.8674	-0.05576	-61.0716	-63.2323	0.060162	-0.05576	-61.001	-61.8091	0.060162	3.959399	0.162412
205.4402	1151.173	1125.603	55.75	402.6739	413.5496	494.5698	-0.01881	54.58072	57.07348	0.013606	-0.01881	51.44448	53.84978	0.013606	-3.35526	0.035607	9.625405	2.541780	3659.5	467.7022	459.1043	363.6848	0.017458	-60.3514	-62.7531	-0.0137	0.017458	-59.6438	-61.1798	-0.01165	3.982716	-0.01819
208.03	1132.517	1129.221	55.75	402.6079	415.4727	497.3716	0.0507	53.25685	56.63118	-0.07213	0.0507	51.24704	53.90387	-0.07213	-3.27204	0.047395	8.678095	2.510267	3659.5	467.7856	456.9467	360.4236	-0.05733	-58.6468	-62.301	0.078698	-0.05733	-58.6813	-61.4703	-0.02557	3.675622	-0.01034
210.6701	1111.155	1123.108	55.75	402.5474	417.312	500.3513	-0.01516	51.53426	56.05158	0.020707	-0.01516	50.25412	53.57305	0.012726	-3.03077	0.258592	7.757219	2.407714	3659.5	467.8652	454.8578	356.9805	0.015041	-56.9128	-61.6411	-0.07175	0.015041	-56.4126	-60.9994	0.007624	3.57965	-0.26945
213.21	1088.668	1110.850	55.75	402.4809	420.6663	504.9124	0.04641	49.08703	55.51901	-0.06080	0.044986	48.10287	53.07428	-0.01095	-2.85076	-0.02434	6.169238	2.342783	3659.5	467.9375	450.5093	351.6585	-0.05085	-55.0608	-61.0335	0.074973	-0.04839	-55.0608	-60.3729	0.007326	3.162779	0.073159
215.8702	1069.099	1097.276	55.75	402.4343	425.4265	509.72	-0.09264	48.22781	54.92442	0.076031	-0.02465	47.78638	52.37805	0.008798	-2.14059	0.091115	4.652047	2.111657	3659.5	468.0068	445.3853	346.0938	0.034944	-53.2096	-60.3636	-0.0272	0.026933	-53.2096	-59.5373	-0.00844	2.505138	-0.00235
218.6602	1050.452	1087.451	55.75	402.3655	431.4321	515.7002	0.027062	46.65273	54.39278	-0.05097	0.014619	46.49514	51.74404	-0.02638	-1.59955	0.024407	2.6813	1.260609	3655.75	462.9685	430.9148	333.5659	-0.03613	-51.8912	-59.0385	0.052189	-0.02057	-51.8912	-58.8474	0.027336	1.776164	-0.09779
221.3601	1036.448	1073.995	55.75	402.3472	439.4822	523.8708	0.002707	45.46768	53.95534	0.017317	0.001245	45.45768	51.29078	0.010757	-1.26731	0.265134	-0.09708	1.64323	3655.75	463.0081	421.1997	324.3972	-0.01335	-50.6451	-59.3718	-0.01727	-0.0066	-50.6451	-58.3069	-0.01115	1.44341	-0.29427
224.1101	1022.865	1056.921	55.75	402.3118	485.9114	550.5081	0.009752	44.33664	53.5499	-0.02971	0.005266	44.33664	50.97343	-0.0188	-1.46851	0.085177	-10.984	0.739716	3655.75	463.0435	366.7444	295.2944	-0.01637	-49.4499	-58.9358	0.030348	-0.00937	-49.4499	-57.3107	0.020076	1.785103	-0.09339
226.8301	1015.175	1067.248	55.75	402.2881	485.1499	552.0576	-0.00306	43.67596	53.2923	0.008429	-0.0019	43.67596	50.78037	0.005437	-2.40617	0.138669	-11.7443	0.584224	3655.75	463.0689	367.594	293.8823	-0.00393	-48.7618	-58.8632	-0.00797	-0.00254	-48.7618	-57.6329	-0.00539	2.794241	-0.15673
229.5501	1007.834	1040.48	55.75	402.2656	485.4666	553.2118	0.002148	43.06155	53.06575	-0.0096	0.001363	43.06155	49.73003	-0.00631	-2.3801	0.058730	-12.3411	0.411499	3655.75	463.0874	367.229	292.7480	-0.00085	-48.1238	-59.4244	0.000498	-0.00654	-48.1238	-56.4493	0.00507	3.411746	-0.06968
232.26	1005.238	1021.48	55.75	402.2598	485.1499	553.7642	0.021547	42.87684	52.9911	0.000565	0.01395	42.87684	48.84368	0.000378	-3.20737	0.151777	-12.5957	0.195072	3655.75	463.0969	367.5823	292.2168	-0.01081	-47.9369	-58.3472	-0.00011	-0.0206	-47.9369	-55.4235	[illegible]	3.741051	-0.16723
235	1003.527	1014.934	55.75	402.2551	485.5586	554.1545	-0.00937	42.68375	52.9133	-3.41E-05	-0.00607	42.68375	48.51306	-2.30E-05	-3.49068	0.064564	-12.8071	0.00112	3655.75	463.1043	367.0894	291.8308	0.001919	-47.7352	-58.2654	0.00028	0.001289	-47.7352	-55.0443	0.000199	3.944581	-0.06142
237.72	1005.218	1016.681	55.75	402.2519	485.1504	553.7649	0.022122	42.87801	52.9902	-0.00053	0.014547	42.87801	48.61762	-0.00035	-3.3079	0.151182	-12.5979	-0.19449	3655.75	463.0977	367.583	292.2371	-0.03077	-47.9354	-58.3457	-5.84E-06	-0.02088	-47.9354	-55.1606	-4.93E-06	3.742166	-0.16672
240.4502	1007.808	1023.746	55.75	402.2698	485.468	553.2097	0.001695	43.06308	53.06331	0.009775	0.001105	43.06308	49.94098	0.00655	-2.98855	0.060579	-12.3427	-0.41102	3655.75	463.0869	367.2788	292.7527	-0.00984	-48.1235	-58.4213	-0.00886	-0.00663	-48.1235	-55.5307	-0.00675	3.410077	-0.07137
243.1702	1015.085	1044.997	55.75	402.2801	485.147	552.0598	-0.00277	43.6787	53.28903	-0.0087	-0.00176	43.6787	49.94717	-0.00572	-2.40179	0.138886	-11.7547	-0.58185	3655.75	463.0686	367.5979	293.8801	-0.00511	-48.7637	-58.6598	0.008312	-0.00337	-48.7637	-56.6063	0.005746	2.789163	-0.15644
245.8701	1022.813	1056.762	55.75	402.3118	485.9055	550.5913	0.010742	44.34048	53.54575	0.028088	0.006656	44.34048	50.96964	0.018754	-1.46597	0.085095	-10.9972	-0.73744	3655.75	463.0435	366.75	295.292	-0.01745	-49.4527	-58.9308	-0.02365	-0.01126	-49.4527	-57.0815	-0.02007	1.792906	-0.09319
248.6201	1036.43	1075.245	55.75	402.3469	439.4834	523.8699	0.001251	45.47218	53.94922	-0.01615	0.000669	45.47218	51.37158	-0.01018	-1.26758	0.264488	-0.10392	-1.64321	3655.75	463.0083	421.2014	324.4002	-0.01173	-50.6487	-59.3653	0.01589	-0.00656	-50.6487	-58.3545	0.01054	1.443862	-0.29336
251.3401	1050.447	1083.33	55.75	402.3653	431.4253	515.7014	0.023781	46.65647	54.38443	0.052999	0.010189	46.65647	51.74949	0.032658	-1.59917	0.087589	2.673737	-1.85836	3655.75	462.958	430.9224	333.5657	-0.03266	-51.8945	-59.0298	-0.05455	-0.01535	-51.8945	-58.87	-0.035	1.775639	-0.10158
254.0701	1069.006	1095.135	55.75	402.4353	425.4319	509.7227	-0.02879	48.23555	54.91771	-0.03169	-0.01491	48.07649	52.29665	-0.01649	-2.1406	0.090481	4.642015	-2.11098	3659.5	468.0036	445.3787	346.0911	0.030015	-53.7219	-60.3572	0.033596	0.016394	-53.7219	-59.4205	0.017651	2.505157	-0.08145
256.79	1088.799	1108.474	55.75	402.4808	420.8898	504.6972	0.050951	49.69905	55.51234	0.069343	0.037856	49.43556	52.96652	0.024792	-2.67071	-0.03769	6.164703	-2.23075	3659.5	467.9375	450.552	351.6765	-0.05563	-56.0744	-61.0275	-0.07539	-0.04285	-55.0744	-60.7238	-0.07478	3.13751	0.009598
259.3801	1111.322	1122.848	55.75	402.5471	417.3088	500.3501	-0.03726	51.53612	56.03445	-0.01404	-0.03088	50.76342	53.56428	-0.00284	-3.09097	0.259753	7.745145	-2.40739	3659.5	467.8652	454.8552	356.9812	0.032712	-56.9151	-61.6734	0.014426	0.031397	-56.9151	-60.9498	0.00204	3.500379	-0.27061
261.97	1132.383	1137.652	55.75	402.6062	415.4731	497.3696	0.056484	53.26727	56.62181	0.070521	0.056484	52.54233	54.34139	0.047673	-3.27225	0.044047	8.661565	-2.51767	3659.5	467.7847	456.9431	360.4248	-0.0645	-58.8601	-62.2916	-0.07877	-0.0645	-58.8601	-61.6666	-0.04398	3.676107	-0.00637
264.5601	1151.098	1148.068	55.75	402.6738	413.5498	494.5691	-0.01633	54.59096	57.01175	-0.0153	-0.01633	53.63784	54.75022	-0.0153	-3.35621	0.056113	9.610277	-2.54144	3659.5	467.7007	459.1023	363.6648	0.015341	-60.3624	-62.7423	0.015552	0.015341	-60.2506	-62.3679	0.015552	3.903367	-0.01572
267.1401	1167.685	1144.936	55.75	402.7398	412.615	497.5563	0.04345	55.92508	57.41908	0.0548	0.04345	53.68197	54.60369	0.0548	-3.33037	-0.10432	10.20722	-2.56592	3659.5	467.6172	460.207	365.8669	-0.05335	-61.884	-63.2178	-0.06097	-0.05335	-61.347	-62.7671	-0.06097	3.959616	0.160376
269.73	1174.031	1126.051	59.5	398.1286	406.0101	485.9746	0.031616	56.56486	57.68914	-0.00111	0.031616	53.04164	54.31925	-0.00111	-2.70482	-0.01914	11.03978	-2.53469	3663.25	471.8715	466.9321	373.1804	-0.04597	-62.2904	-63.1959	0.001479	-0.04597	-61.3304	-61.6819	0.001479	3.813530	0.105427
272.3201	1179.273	1135.678	59.5	398.198	405.476	484.8691	0.038080	57.01193	57.71960	0.011397	0.026981	53.0866	54.29174	0.011397	-2.87284	-0.06625	11.41545	-2.47020	3663.25	471.7261	467.5864	374.4177	-0.0537	-62.6337	-63.2695	-0.01345	-0.0537	-61.4124	-61.6865	-0.01345	3.420763	0.132403
274.9102	1172.079	1130.971	59.5	398.2525	404.6421	484.01	-0.01285	56.50124	57.41948	0.008724	-0.01285	52.61106	54.00936	0.006724	-2.45165	0.034656	11.72512	-2.40057	3663.25	471.6394	468.4631	375.3573	0.004549	-62.2857	-62.9431	-0.00525	0.004549	-60.8756	-61.3602	-0.00525	2.91007	0.021609
277.5	1163.713	1125.076	59.5	398.322	405.0815	483.6925	0.045032	55.94743	57.12187	-0.01379	0.045032	52.09539	53.72924	-0.01379	-1.84602	0.141122	11.82293	-2.25634	3659.5	467.3066	462.5407	370.3225	-0.04995	-61.667	-62.7393	0.023528	-0.04995	-60.4481	-61.1695	0.023528	2.163581	-0.13347
279.6502	1155.85	1120.41	59.5	398.3457	404.8247	483.8602	0.027425	55.39739	56.87877	0.002246	0.027425	51.58127	53.50072	0.002246	-1.60279	0.095367	11.75166	-2.17887	3659.5	467.2835	462.8345	370.1211	-0.01773	-61.2168	-62.4291	0.000717	-0.01773	-59.8321	-60.867	0.000717	1.876657	-0.06124
279.8101	1146.853	1124.033	55.75	402.011	410.6062	488.8396	0.018178	54.74741	56.46405	-0.02789	-1.05708	50.76036	52.84233	-1.21397	-1.3835	0.138709	11.54766	-2.11569	3659.5	467.2534	462.4233	370.1033	-0.01509	-60.6743	-62.1662	0.030765	1.201469	-60.1574	-61.0973	1.316912	1.638759	-0.12707
282.5	1126.753	1100.854	55.75	403.0486	410.3865	488.9138	0.016841	53.39087	55.81944	0.015146	-0.95409	49.2706	52.0597	-1.52482	-0.96165	0.117921	11.38025	-1.94075	3659.5	467.2017	462.6494	369.9414	-0.01384	-59.1918	-61.4575	-0.016	1.093909	-58.3831	-60.4213	1.700913	1.136109	-0.08087
285.1802	1104.531	1067.765	55.75	403.0835	411.3708	488.8816	0.025327	51.9066	55.10985	-0.05994	-0.8787	47.33925	50.97815	-1.71244	-0.77292	0.133717	11.20632	-1.90787	3659.5	467.1506	461.5723	369.9729	-0.02141	-57.5495	-60.6749	0.066343	0.946869	-56.1461	-59.7249	1.923076	0.907672	-0.14731
289.4302	1071.527	1037.006	55.75	403.1206	410.8118	488.8933	0.000675	49.69175	53.95621	0.034109	-0.69014	45.41708	50.16162	-1.56362	-0.58907	0.108806	10.75113	-1.61381	3659.5	467.0952	462.3709	369.9779	0.005396	-55.111	-58.4071	-0.03666	0.788789	-53.8867	-58.3006	1.763386	0.692778	-0.07483
293.6602	1036.807	992.2349	55.75	403.146	411.9567	488.7554	0.022545	47.40199	52.75627	-0.06739	-0.61917	42.79547	48.49072	-1.55391	-0.52561	0.115003	10.31979	-1.57495	3659.5	467.044	460.8035	370.0024	-0.01929	-52.5923	-58.0305	0.074036	0.704896	-50.8466	-56.4424	1.75090	0.616375	-0.13309
299.4302	1007.597	957.9317	55.75	403.1611	410.7481	488.352	-0.01752	45.13467	51.28743	0.031687	-0.63417	40.86501	47.45429	-1.19874	-0.53102	0.09523	9.537685	-1.20876	3655.75	462.0867	455.8108	364.4443	0.016413	-50.3714	-56.6195	-0.03399	0.720093	-48.1758	-54.7446	1.313677	0.674733	-0.06874
305.2002	954.1554	924.7308	55.75	403.1665	410.4656	488.1843	0.247704	42.1504	49.65617	-0.0057	-0.20079	39.77808	46.56704	-1.12458	-0.49936	0.218591	8.067904	-1.14795	3655.75	462.0647	456.0872	364.8098	-0.26669	-47.2353	-54.8973	0.004963	0.233957	-46.3459	-53.7696	1.231156	0.567470	-0.20626
326.7002	881.1792	832.5762	55.75	403.1187	410.8721	487.8586	0.037815	38.62148	45.59634	0.125542	-0.34916	34.35727	41.70522	-0.22218	-0.5073	0.077195	5.947269	-0.22623	3655.75	462.0591	455.6619	364.9707	-0.04461	-43.4594	-50.637	-0.13024	0.630143	-40.6566	-48.6130	0.247044	0.599597	-0.04676
348.2002	824.2109	747.7780	52	408.4685	419.9285	493.4351	0.010111	36.35912	42.241	-0.03848	-0.53098	30.61557	36.92105	-0.22039	-0.47023	-0.15791	3.383609	-0.21528	3655.75	462.0886	452.1569	364.5063	-0.00372	-41.0601	-47.2694	0.041199	0.615098	-37.0377	-43.9081	0.240766	0.566566	0.164451
369.7002	808.576	753.7073	52	408.4348	416.949	492.627	0.030722	36.69485	40.69362	-0.04239	-0.53724	31.97513	35.41139	0.020075	-0.45900	0.05219	1.791398	0.019678	3655.75	462.1152	455.5786	365.3232	-0.02408	-41.4619	-45.6622	0.045916	0.626766	-38.6003	-43.5341	-0.02543	0.591723	-0.07606
391.2002	806.7778	722.1551	52	406.4131	419.9517	493.1213	0.023516	37.50949	39.89795	0.047897	-0.50731	31.35979	34.77379	0.210795	-0.47531	-0.1085	0.592122	0.718587	3655.75	462.1333	452.1111	364.7749	-0.02273	-42.3799	-44.0071	-0.05264	0.569050	-37.9429	-41.2162	-0.23009	0.573746	0.101267
412.7002	815.0176	750.2366	52	408.4021	418.9761	492.437	0.009258	38.48533	39.6707	-0.03781	-0.55816	33.70177	35.37427	0.058217	-0.50405	0.073104	0.900076	0.057369	3655.75	462.144	455.5369	365.4895	-0.00909	-43.4744	-44.8752	0.040303	0.651994	-40.6252	-42.5019	-0.06689	0.605996	-0.04743
434.2002	824.4989	775.6507	52	408.3843	416.1917	491.9724	0.04227	39.41574	39.75844	0.022735	-0.3885	35.20680	35.95491	0.121499	-0.44656	0.354012	0.39256	0.133191	3655.75	462.1509	456.3389	366.0403	-0.04459	-44.4727	-44.7076	-0.02386	0.459103	-42.20	-43.1127	-0.13547	0.535672	-0.3456
449.2002	831.5499	774.7236	52	408.3911	416.9898	492.3718	0.011973	39.8932	39.91295	-0.00549	-0.54907	35.08354	35.81871	0.062357	-0.50751	0.09073	0.154452	0.061522	3655.75	462.1531	455.52	365.5505	-0.01063	-44.9859	-44.9572	0.005835	0.614195	-42.2007	-42.7069	-0.06917	0.61366	-0.06579
464.2002	836.9566	751.0739	52	400.3877	411.8064	492.9011	0.023827	40.2841	40.07658	0.008109	-0.50757	34.13495	34.46095	0.084164	-0.48073	-0.16347	-0.04192	0.085472	3655.75	462.1528	452.2759	364.9956	-0.02457	-45.4067	-45.1349	-0.00858	0.580728	-41.1503	-41.4991	-0.09736	0.507245	0.171465

Appendix 4 Photographs and sketches of initiated cracks on both surface and section area of the inner vessel after 1055 cycles

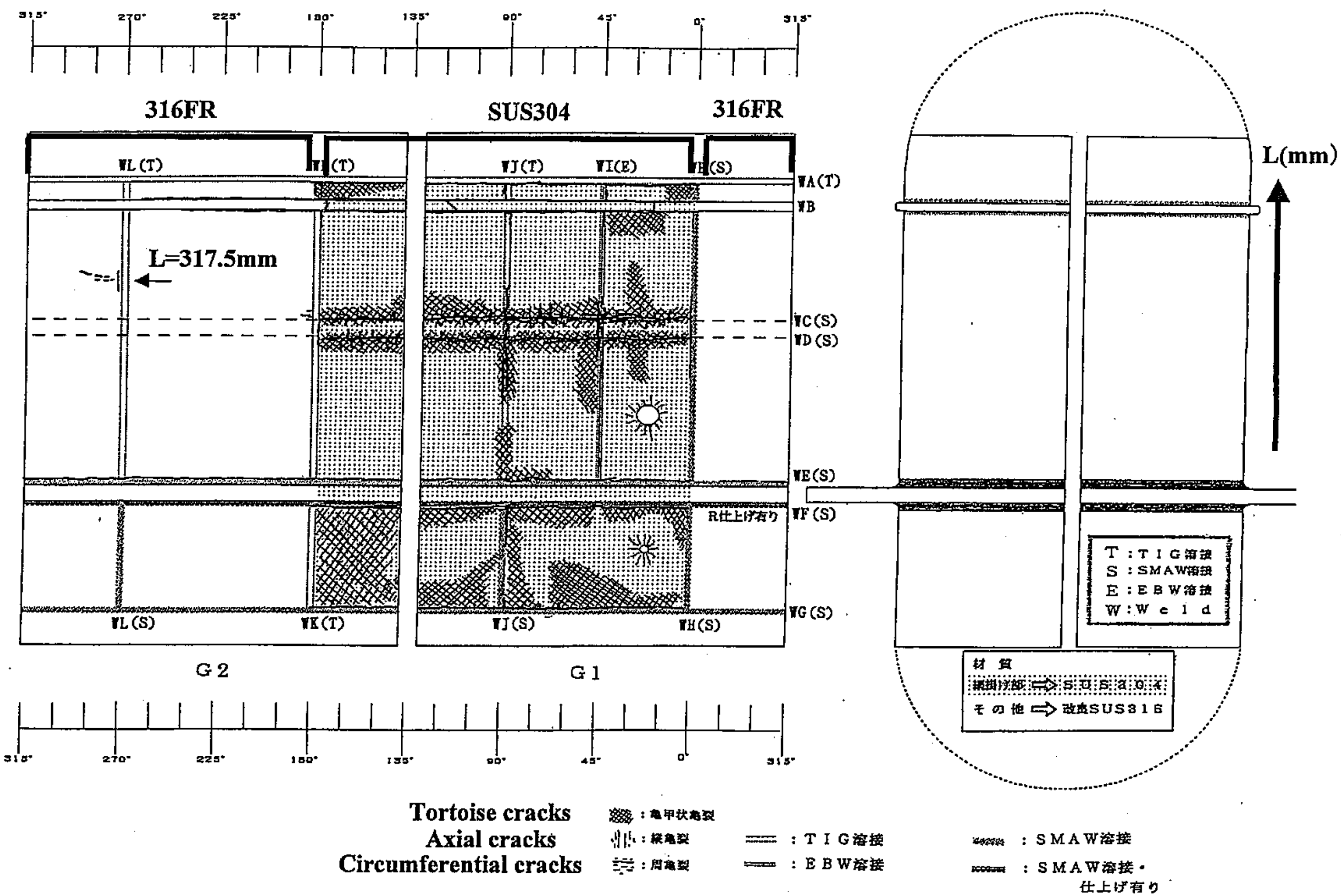

Fig.A4.1 Distribution of initiated cracks on the surface of the inner vessel

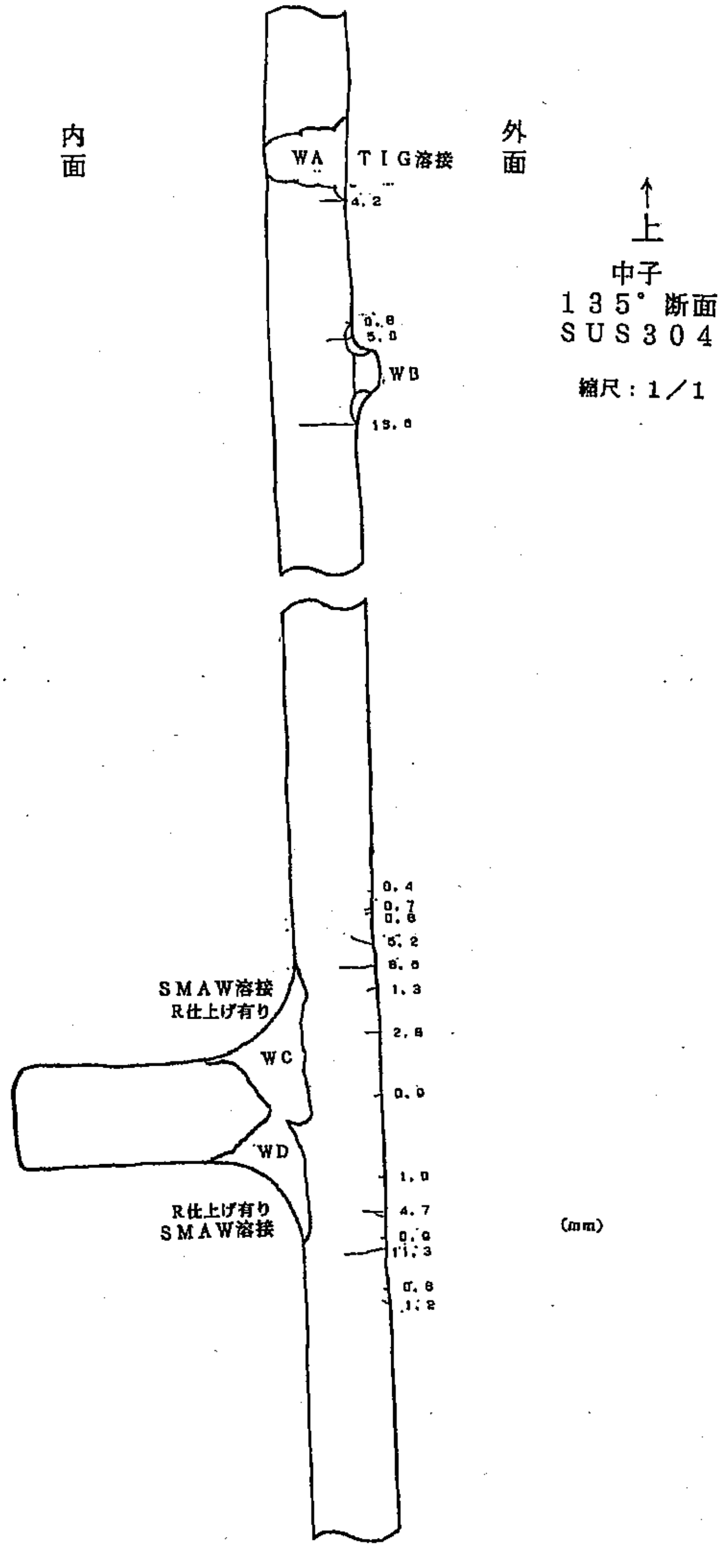

Fig.A4.2 Sketches of initiated cracks on a section area of the inner vessel after 1055 cycles (SUS304 135° ref : Fig.A4.1)

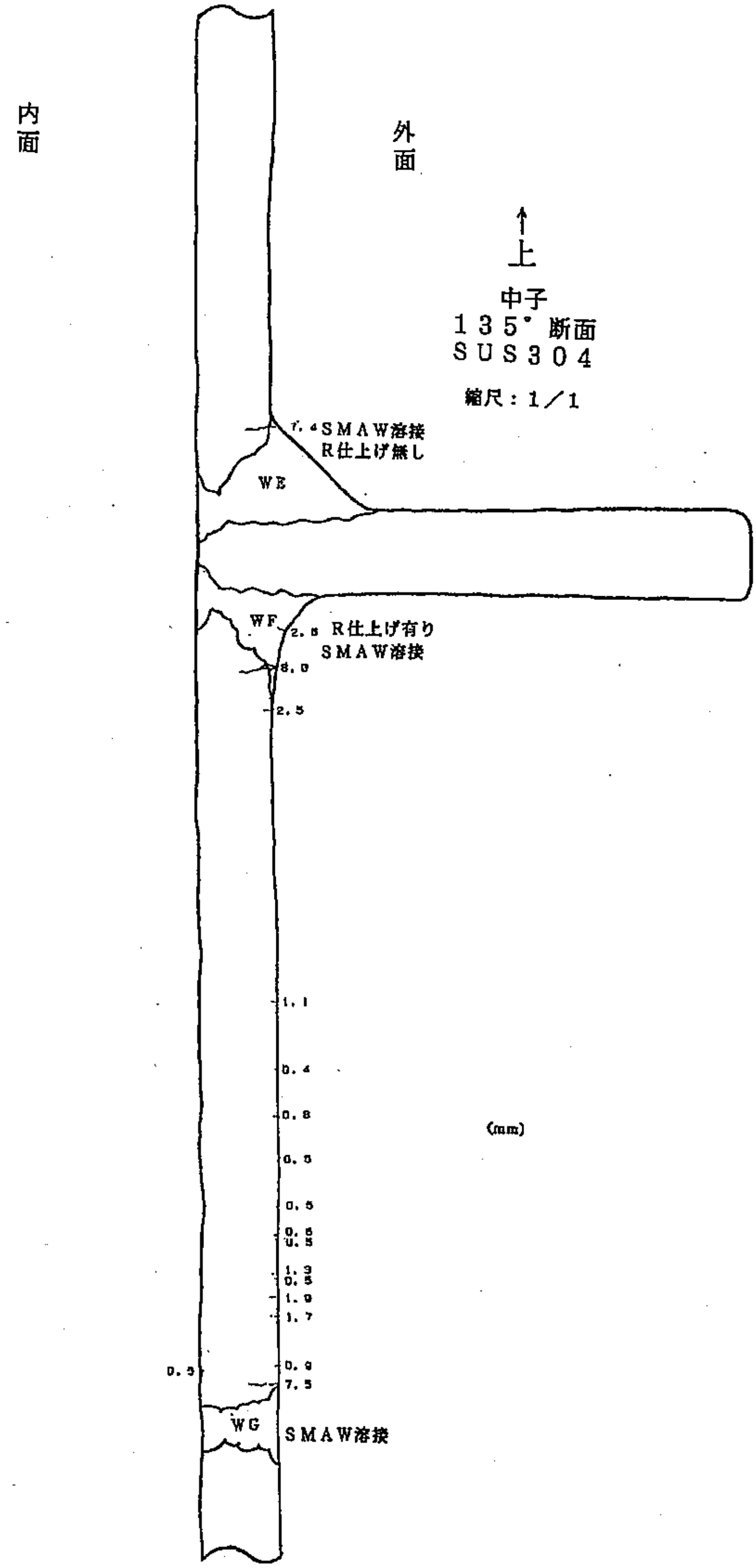

Fig.A4.3 Sketches of initiated cracks on a section area of the inner vessel after 1055 cycles (SUS304 135° ref : Fig.A4.1)

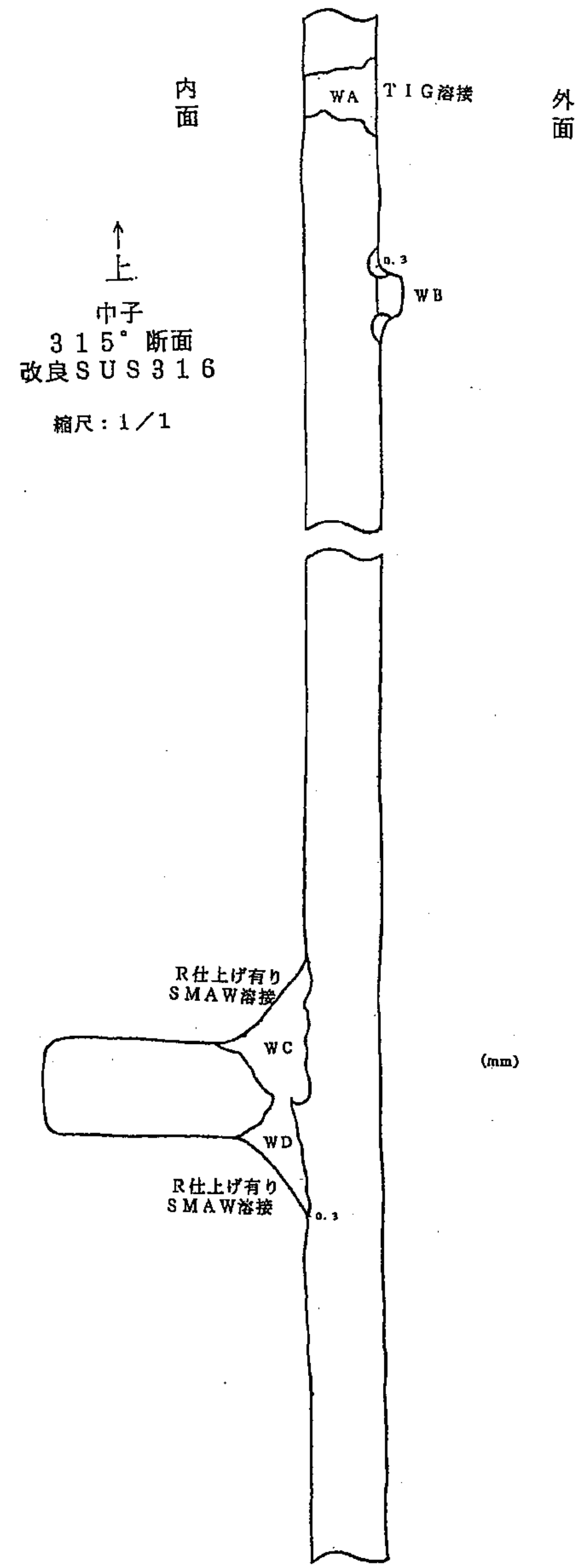

Fig.A4.4 Sketches of initiated cracks on a section area of the inner vessel after 1055 cycles (316FR 315° ref : Fig.A4.1)

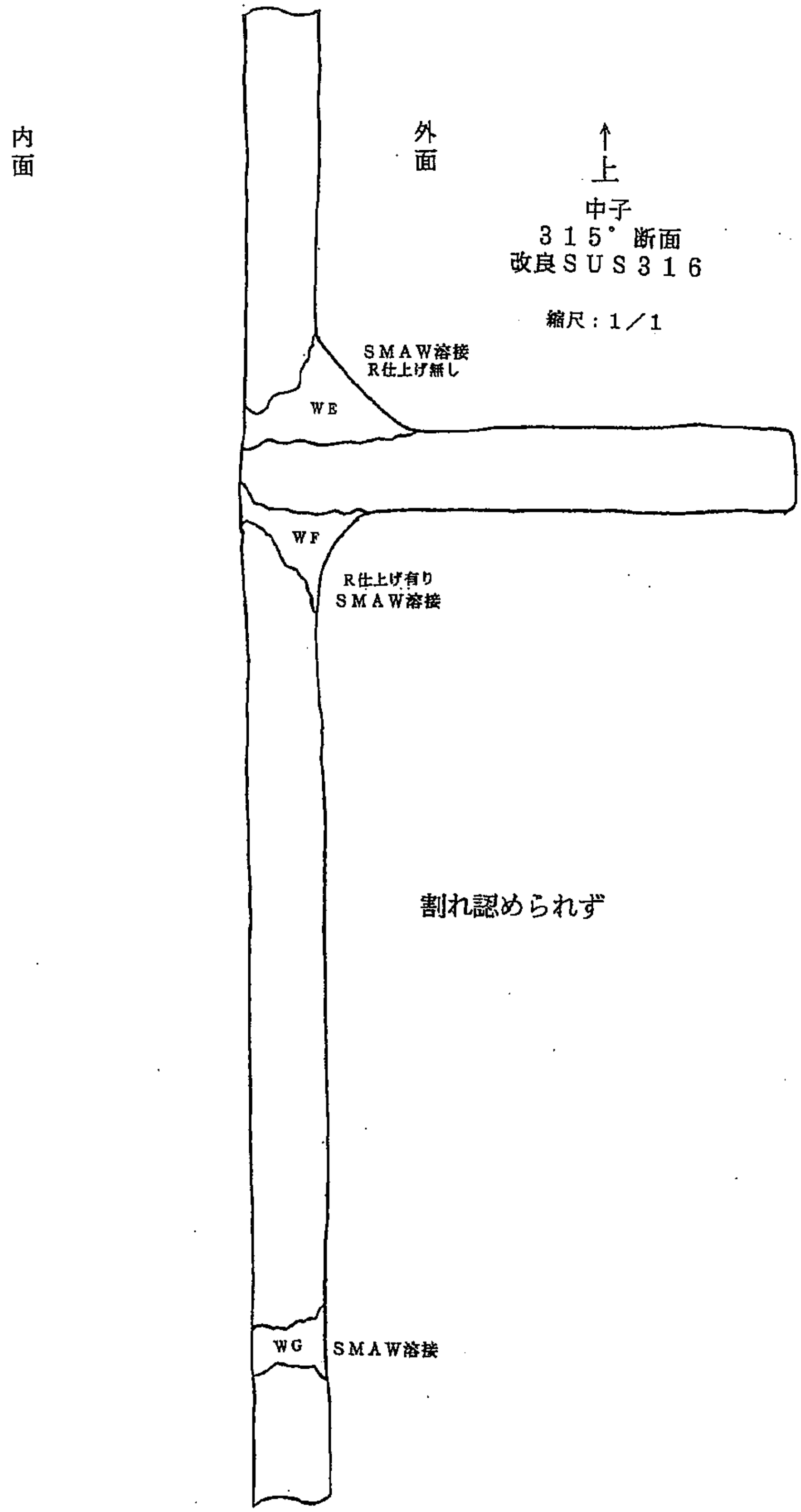

Fig.A4.5 Sketches of initiated cracks on a section area of the inner vessel after 1055 cycles
(316FR 315° ref : Fig.A4.1)

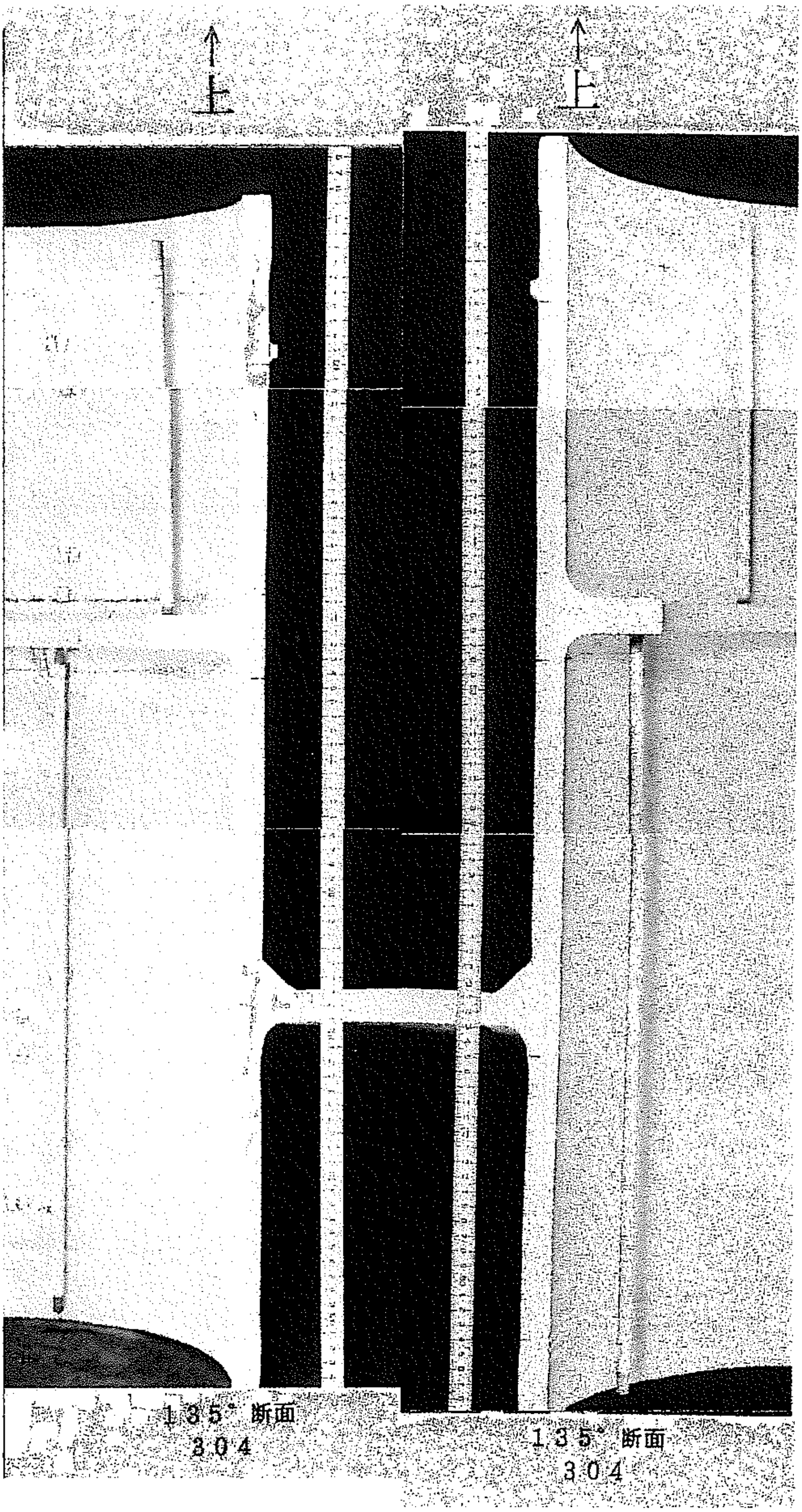

Fig.A4.6 Photograph of initiated cracks on a section area of the inner vessel after 1055 cycles
(SUS304 135° ref : Fig.A4.1)

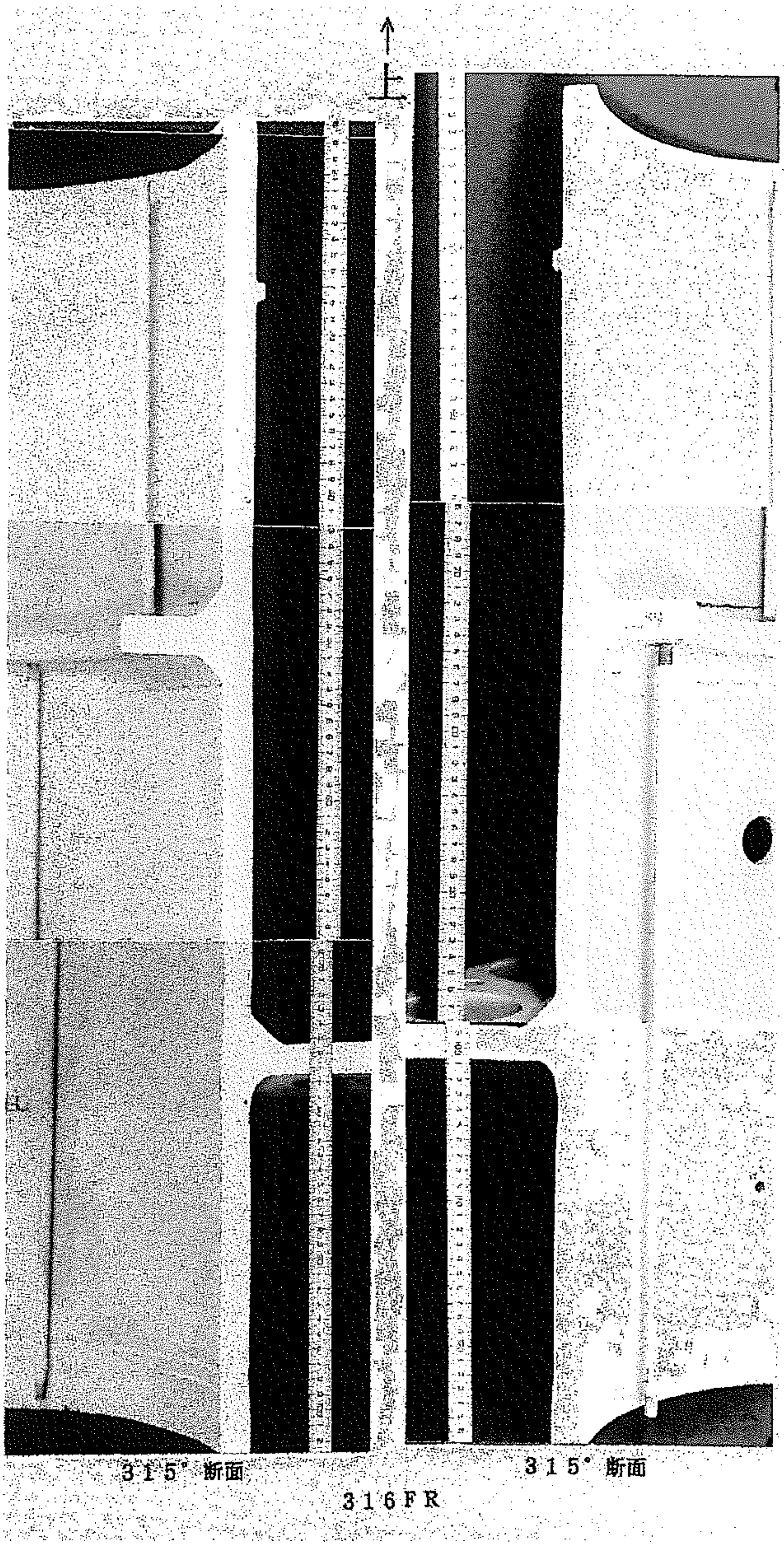

Fig.A4.7 Photograph of initiated cracks on a section area of the inner vessel after 1055 cycles
(316FR 315° ref : Fig.A4.1)

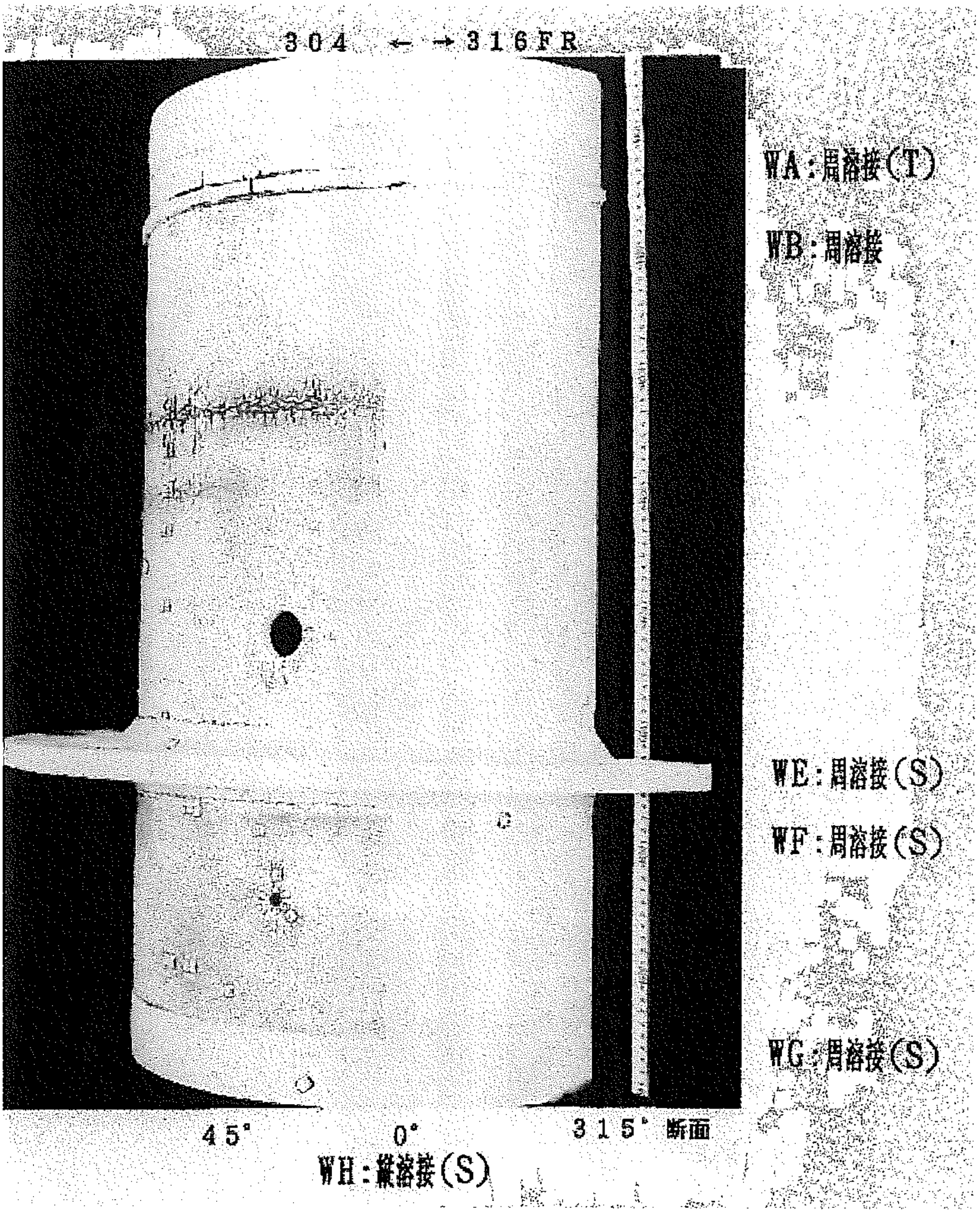

Fig.A4.8 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles (316FR-SUS304 315° - 45° ref : Fig.A4.1)

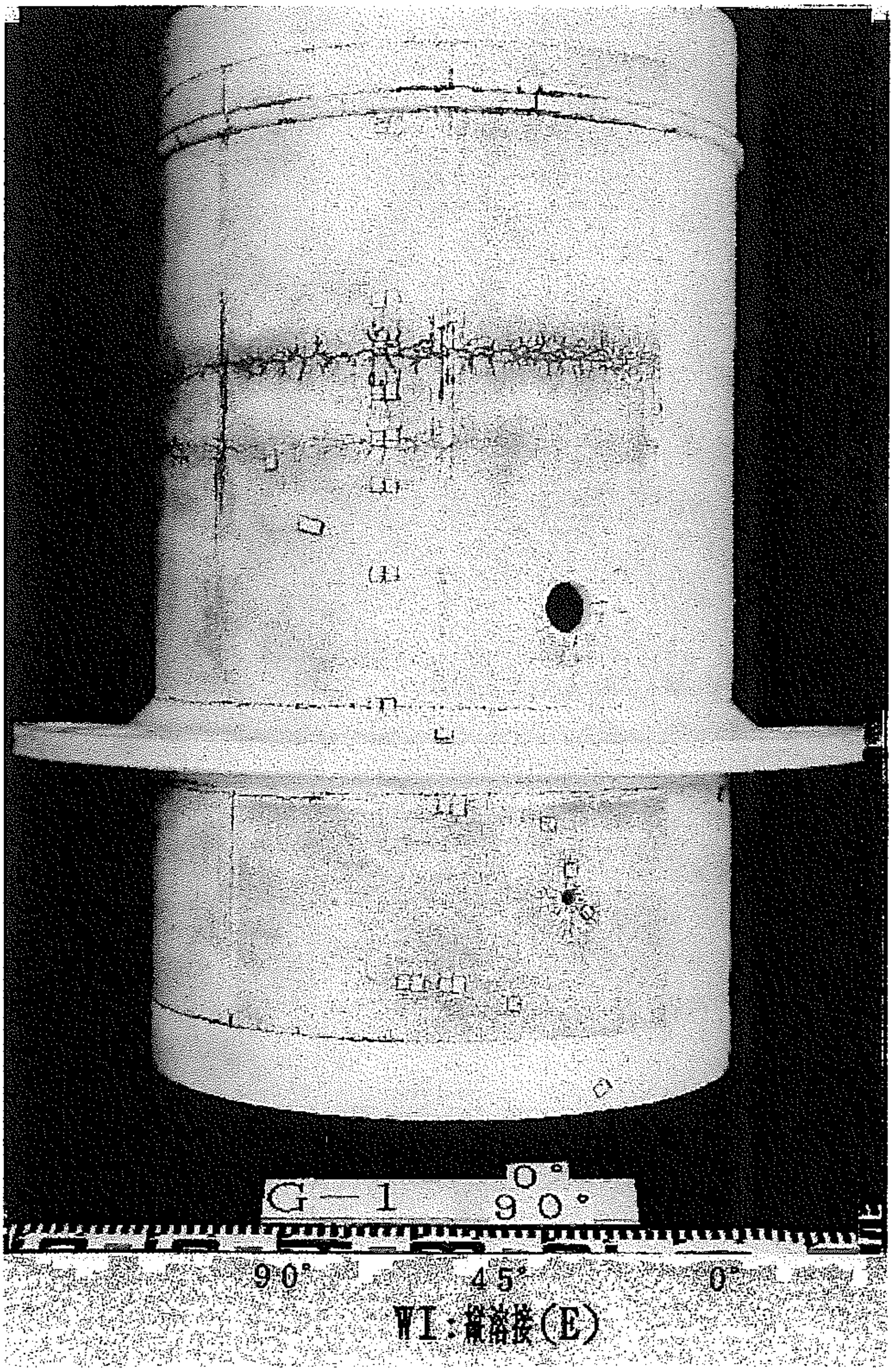

Fig.A4.9 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles
(SUS304 0° － 90° ref : Fig.A4.1)

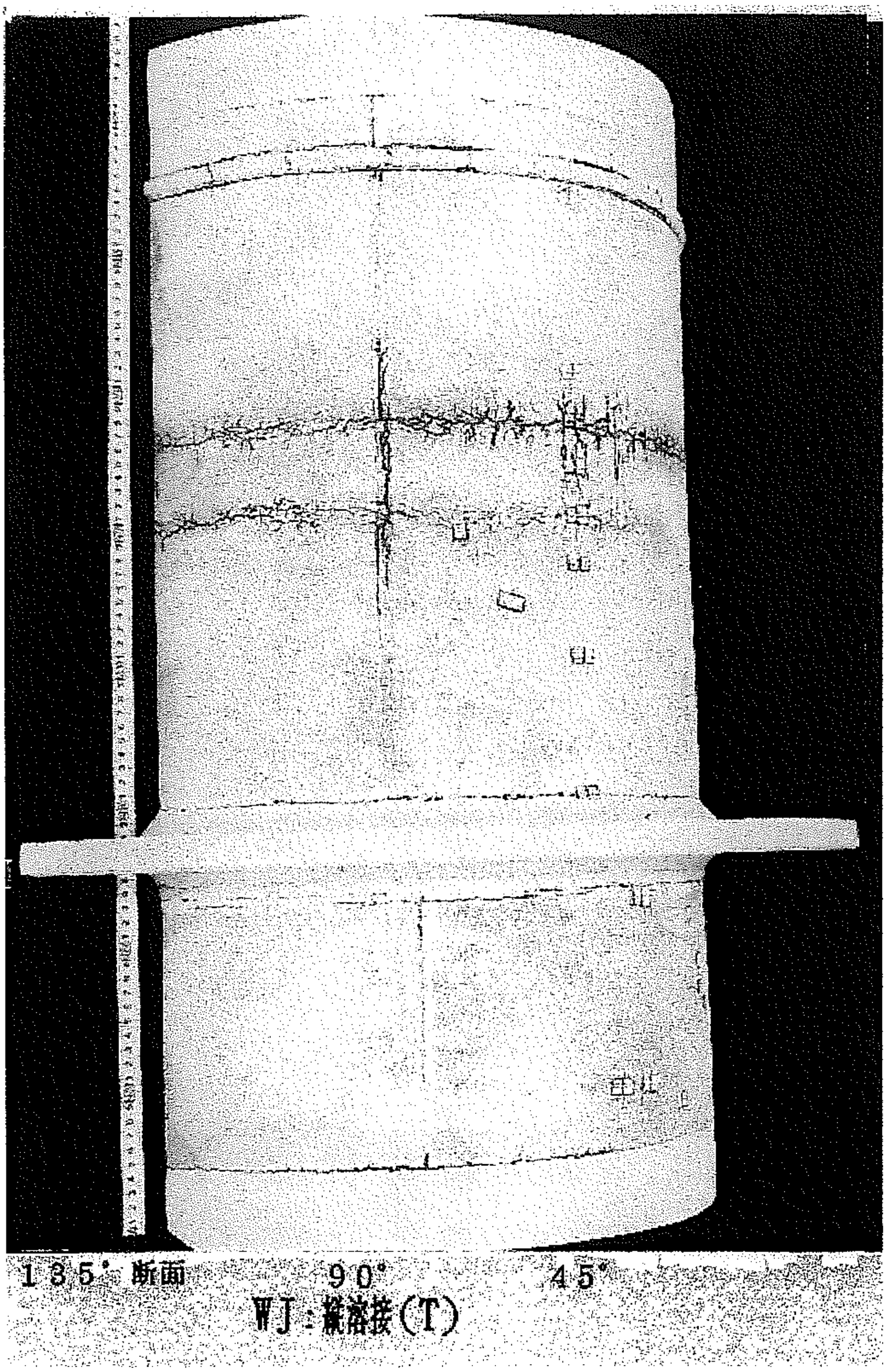

Fig.A4.10 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles (SUS304 45° - 135° ref: Fig.A4.1)

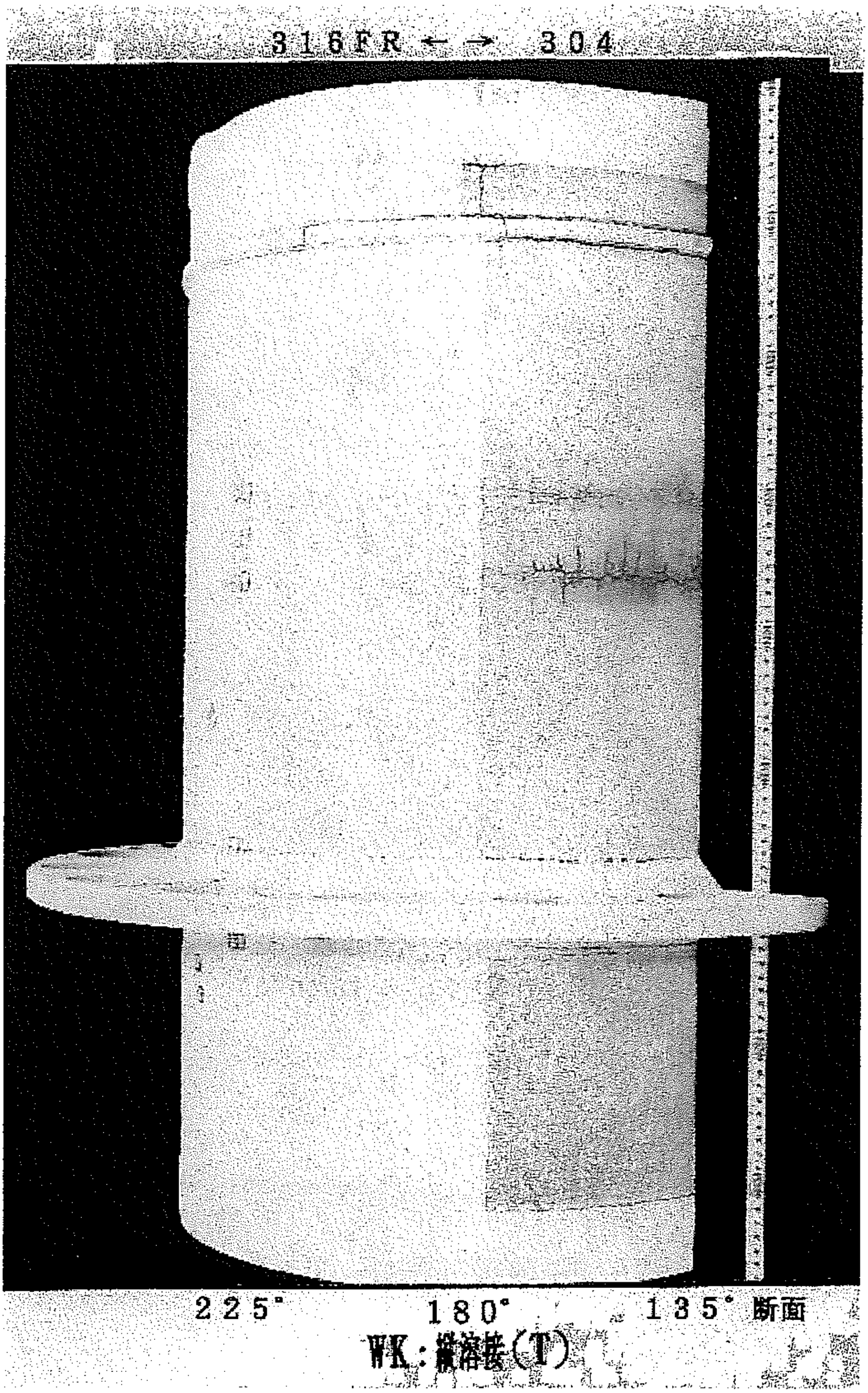

Fig.A4.11 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles
(SUS304-316FR 135° - 225° ref: Fig.A4.1)

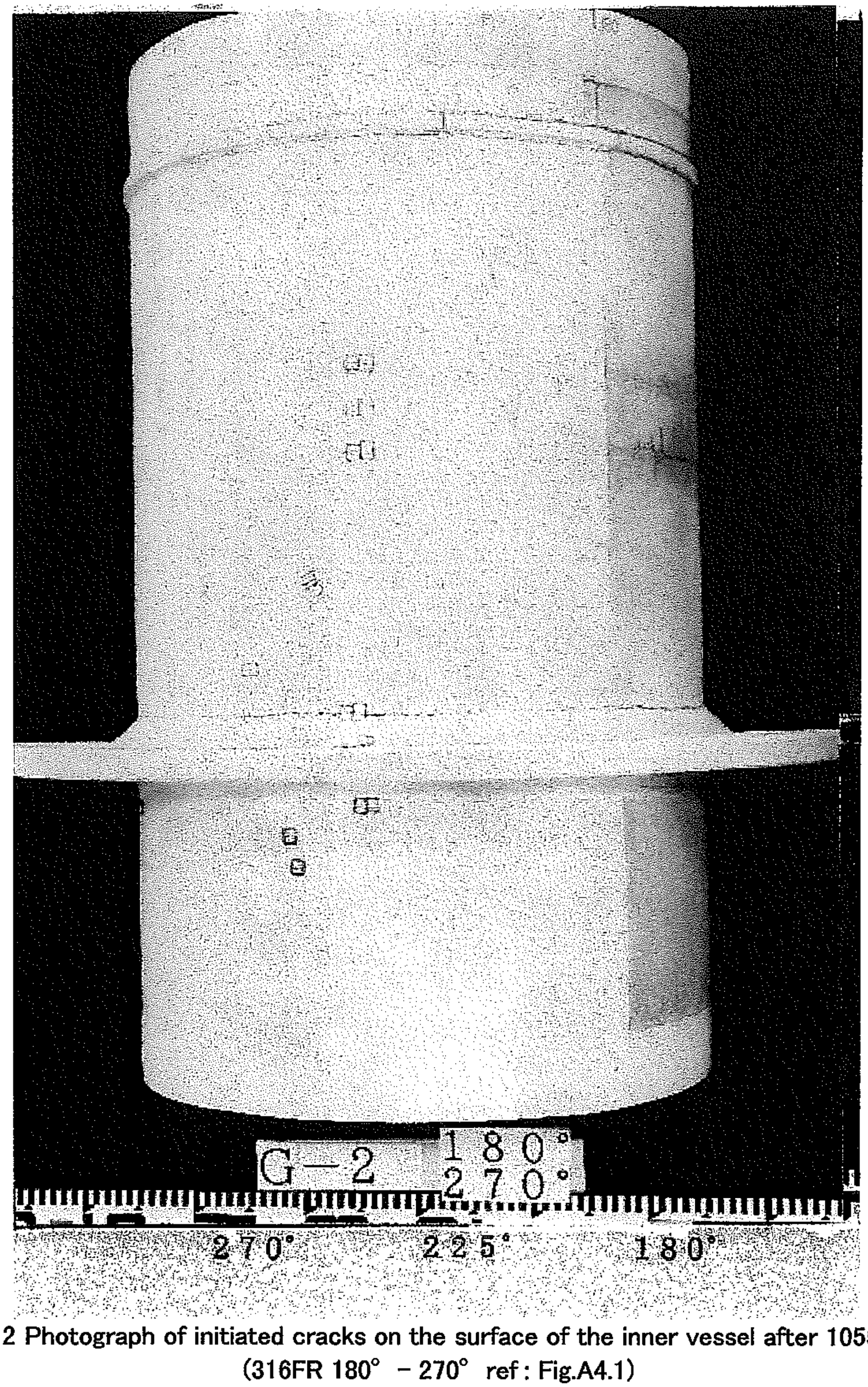

Fig.A4.12 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles
(316FR 180° - 270° ref: Fig.A4.1)

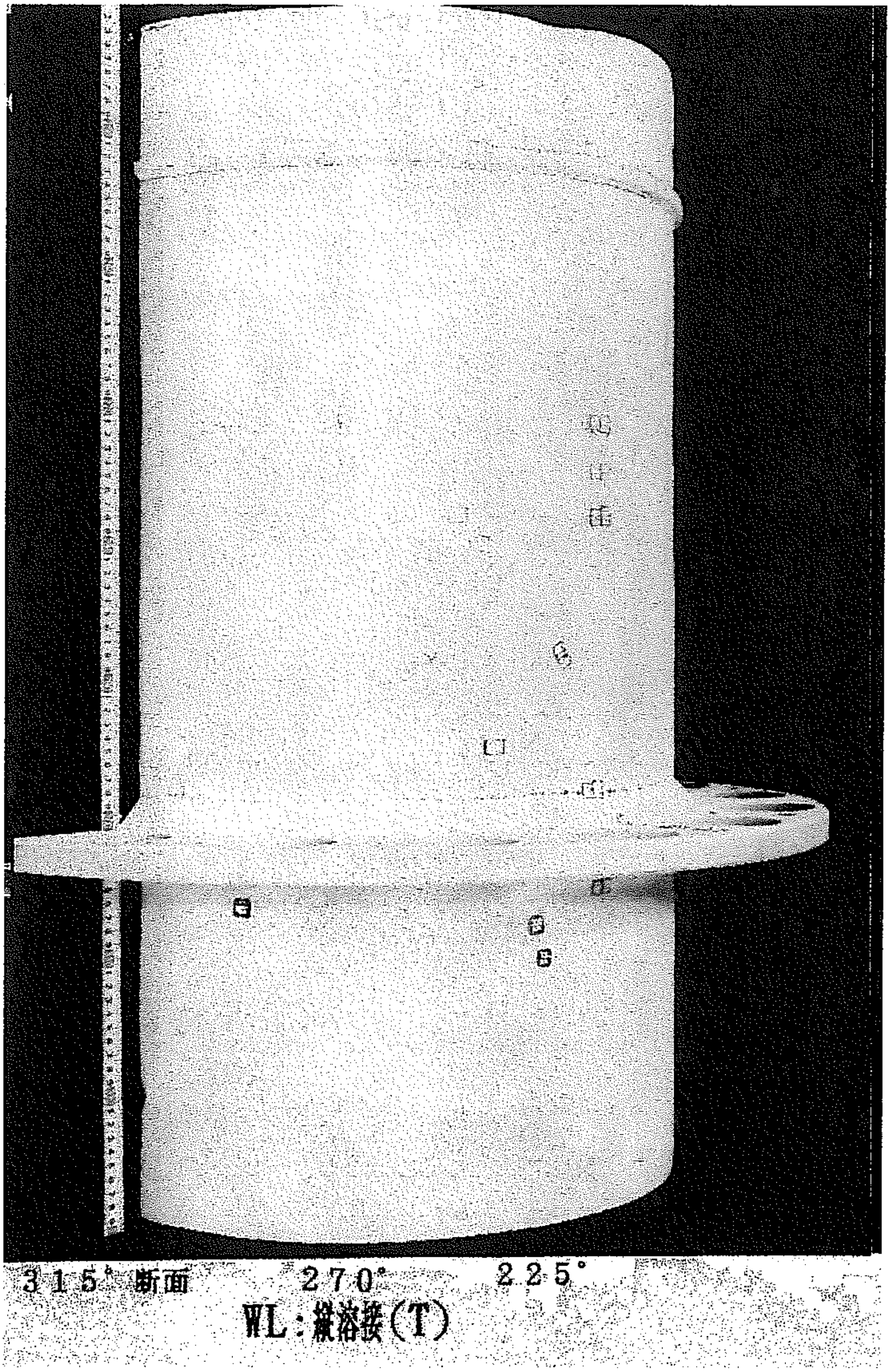

Fig.A4.13 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles
(316FR 225° － 315° ref : Fig.A4.1)

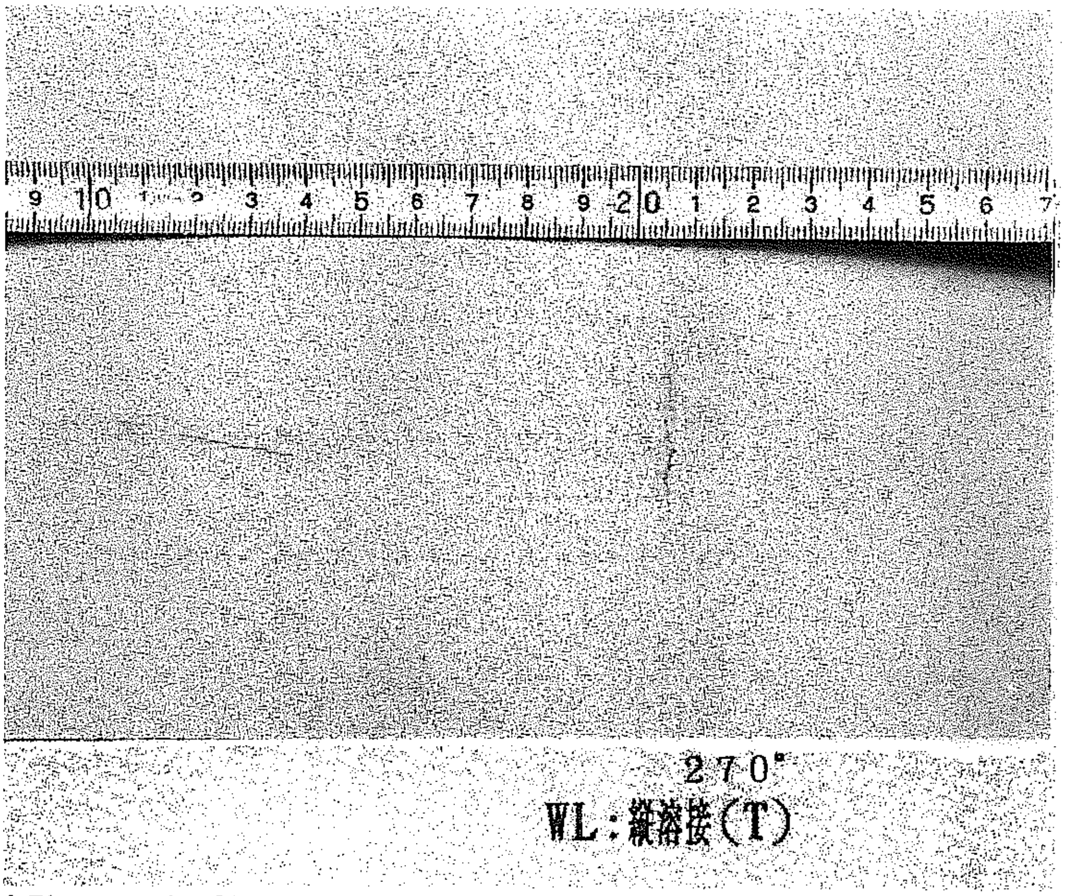

Fig.A4.14 Photograph of initiated cracks on the surface of the inner vessel after 1055 cycles
(316FR 270° ref : Fig.A4.1)