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Fatigue Behavior of Nozzles of Light Water Reactor Pressure Vessel Model

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ABSTRACT

In this paper, the experimental results of a cyclic internal pressure test are described on the pressure vessel model, in which three kinds of nozzle models were welded. In the inner corner surface of each nozzle two kinds of artificial cracks were machined perpendicular to the direction of maximum circumferential stresses, which occur at both the head and bottom sides.

Cyclic internal pressure was given from zero to 10.8 MN/m^2 by oil after the strain distribution of the inner and outer surface of each nozzle was examined by static internal pressure of 10.8 MN/m^2. In the cyclic internal pressure test, the fatigue crack length from the artificial cracks at any pressure cycles imposed was measured by an electrical resistance method and crack gages.

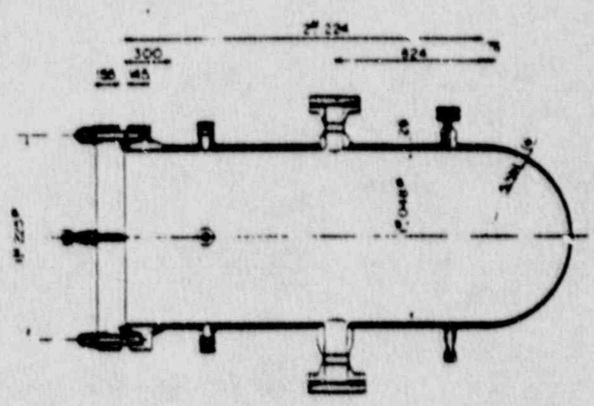

FIG. 1 CROSS SECTION OF NO. 5 PRESSURE VESSEL MODEL

INTRODUCTION

In the assessment of integrity for light water reactor pressure vessels, it is very important to study experimentally and theoretically the initiation life and propagation behavior at the inner corner surface of the nozzles where the maximum circumferential stress is induced by internal pressure.

In the Japan Atomic Energy Research Institute, cyclic internal pressure tests have been so far performed to experimentally investigate the initiation life and propagation rate of crack of some artificial cracks at the inner corner using five steel models of light water reactor pressure vessels [1], [2], [3]. In this paper, the experimental results of a cyclic internal pressure test are described mainly on the fifth pressure vessel model, in which three kinds of nozzle models were welded. The pressure vessel model was designed based on the criteria of Sec. III, ASME Boiler and Pressure Vessel Code [4] and nearly 2,000-mm length, 1,000-mm diameter and 23-mm thickness, as shown in Fig. 1, while three nozzle models were respectively selected from the nozzles of the primary circuit of boiling water reactor pressure vessels which are being now constructed or operated in Japan. In the inner corner surface of each nozzle two kinds of artificial cracks (notches) were machined perpendicular to the direction of maximum circumferential stresses, which occur at both the head and bottom sides. The artificial cracks were machined by a thin grinder of 0.3-mm thickness and 30-mm diameter as follows: one was of nearly 20-mm surface length and 3-mm depth with a straight crack front (A-type), while another was of nearly 8-mm surface length and 3-mm depth with a crack front of a circular

arc (B-type). Cyclic internal pressure was given from zero to 10.8 MN/m^2 by oil after the stress distribution of the inner and outer surface of each nozzle was obtained by static internal pressure of 10.8 MN/m^2 and then each artificial crack was machined. In the cyclic internal pressure test, the fatigue crack length was measured by an electrical resistance method and crack gages.

After 29,200 cycles of internal pressure, this test was stopped since one of six artificial cracks propagated to the outer surface and oil leaked from it. From the experimental results, any remarkable differences of crack initiation were not recognized between the A- and B- type artificial cracks and it was determined that the propagation rate of both cracks was the order of 10^{-3} mm/cycle.

PRESSURE VESSEL MODEL

The pressure vessel model used in this experiment is shown in Fig. 1. The chemical and mechanical properties of the materials of the shell and nozzle are described in Tables 1 (1) and (2). This pressure vessel model was designed based on the criteria of Sec. III, ASME Boiler and Pressure Vessel Code and three nozzle models were respectively designed being selected from the nozzles of the primary circuit of the pressure vessels of boiling water reactors of 800 ~ 1,100 MWe grade, which are being now constructed or operated in Japan and they were nearly 1/6 scale nozzle models of their prototype. As shown in Table 1 the shell was made of a low carbon steel, ASTM Type A302 Grade C and the nozzles were made of a forging steel, ASTM Type A336 Modified. The cross sections of three nozzle models of N1, N2 and N3 are shown in Figs. 2, 3 and 4 in detail and they were welded at 45°, 135° and 225° of the A-A section of the pressure vessel model as described in Fig. 1, respectively.

STATIC INTERNAL PRESSURE TEST

The strain distribution of the inner and outer surface of each nozzle was examined by strain gages when a static internal pressure was given to the pressure vessel model before two kinds of artificial cracks were machined at the inner corner surface of each nozzle. The

Table 1. Performance Testing Results on Shell Materials of No. 5 Pressure Vessel Model (1)

Production No. \ Specification	Extracted Position	Yield Strength (MN/m^2)	Ultimate Tensile Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)	Charpy V-Notch Impact Test (N.m)
		343	549/686	17	180° R = 1.25t	Average 33.3(N.m) Minimum 26.5 (at −12° C)
4K 1623 1/13	Top Bottom	587	685	20	Good	Longitudinal Average 110 115, 106, 110 Transverse Average 60.8 60.8,57.9,63.7

Chemical Composition (%)

Shell ASTM A302GradeC	Elements	C	Si	Mn	P	S	Ni	Cr	Mo
	Specifdication	0.20	0.15/0.30	1.15/1.50	0.035	0.040	0.40/0.70		0.45/0.60
	Ladle Analysis	0.19	0.29	1.28	0.014	0.015	0.57		0.51

Table 1. Performance Testing Results of Nozzle Materials of No. 5 Pressure Vessel Model (2)

Specification / Material number	Yield Strength (MN/m^2)	Ultimate Tensile Strength (MN/m^2)	Elongation (%)	Reduction of Area (%)	Bend Test	Charpy V-Notch Impact Test (N.m)
	343	549	20			Average 33.3 Minimum 26.5 (at −12° C)
45 E 253 2/3 2-5	453	608	27.9	69.4		Average 155.9 160.8,143.2,163.8

Chemical Composition (%)

Nozzle N1, N2, N3	Elements	C	Si	Mn	P	S	Ni	Cr	Mo
ASTM A336 modified ASME Case 1236-3	Specification	0.27	0.15/0.35	0.50/0.80	0.040	0.050	0.50/0.90	0.25/0.45	0.55/0.70
	Ladle Analysis	0.18	0.32	0.69	0.008	0.013	0.88	0.32	0.62

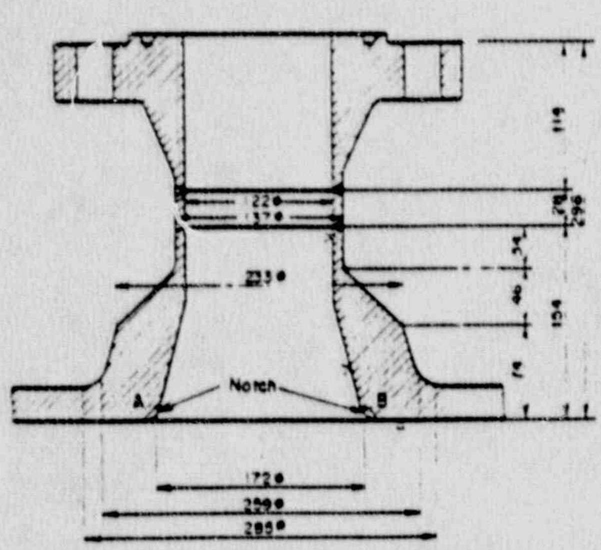

FIG. 2 CROSS SECTION OF N1 NOZZLE MODEL

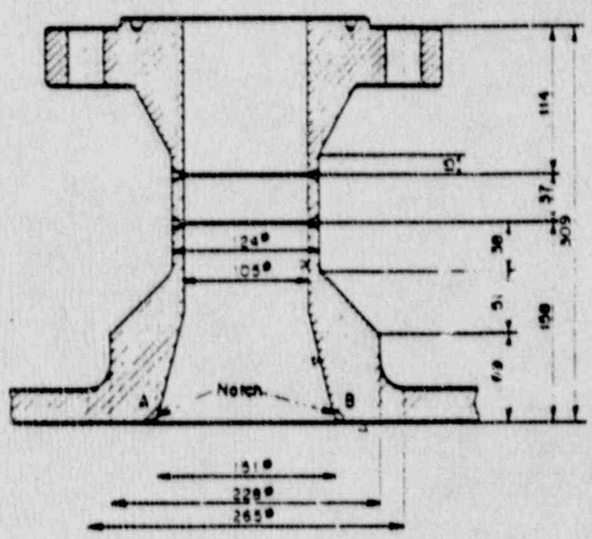

FIG. 3 CROSS SECTION OF N2 NOZZLE MODEL

static internal pressure test was carried out step by step to a maximum internal pressure of 10.8 MN/m^2 which was selected as nearly 1.5 times of operating pressure of boiling water reactors. In this internal pressure test a kind of machine oil was used as the pressurizing material.

All the stresses of the inner and outer surfaces of each nozzle were calculated from the strain values obtained experimentally by strain gages with an assumption of elastic stress concentration, where as Young's modulus and Poisson's ratio were used at 2.06×10^5 MN/m^2 and 0.3 respectively. The stress distributions of inner surface of each nozzle are shown in Figs. 5, 6 and 7, in which the experimental results of N3 nozzle are compared with the calculated values and they are consistent comparatively as shown in Fig. 7.

The circumferential stresses of the inner corner surface of each nozzle are maximum and their results are denoted in Table 2. The stress concentration factors of

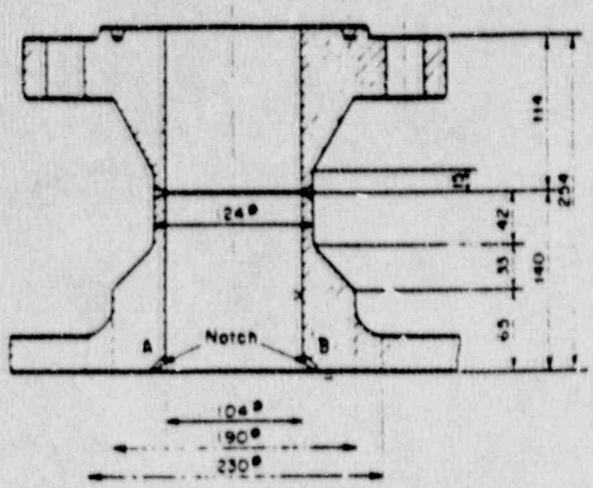

FIG. 4 CROSS SECTION OF N3 NOZZLE MODEL

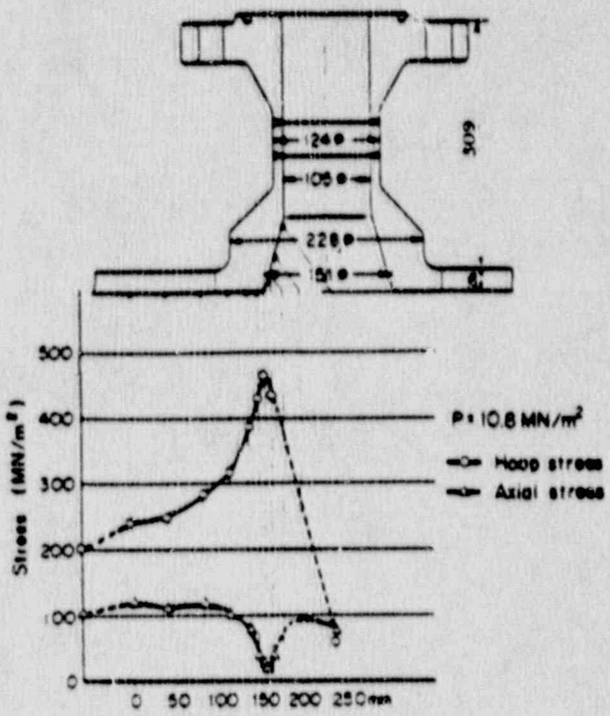

FIG. 6 STRESS DISTRIBUTION OF INNER SURFACE OF N2 NOZZLE

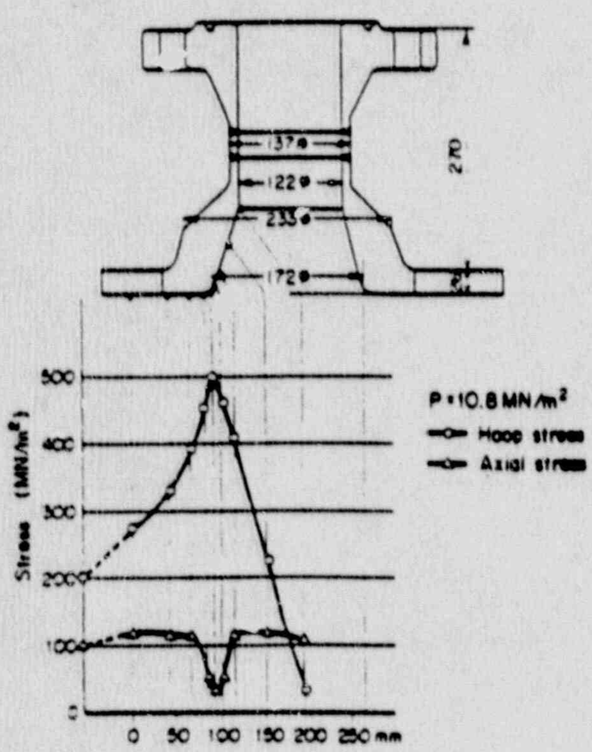

FIG. 5 STRESS DISTRIBUTION OF INNER SURFACE OF N1 NOZZLE

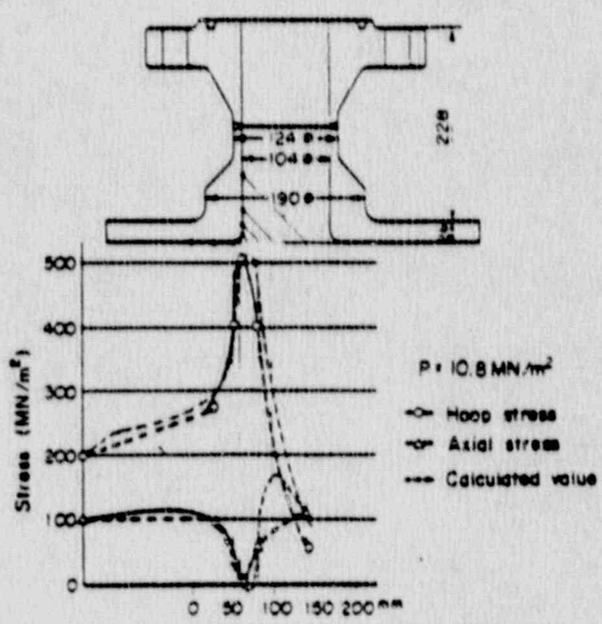

FIG. 7 STRESS DISTRIBUTION OF INNER SURFACE OF N3 NOZZLE

Table 2. Stress Concentration Factor of Inner Corner Surface of Nozzle

Nozzle	N1	N2	N3
Circumferential Stress of Inner Surface of Shell (MN/m^2)	202	202	202
Circumferential Stress of Inner Corner Surface of Nozzle (MN/m^2)	495	456	517
Stress Concentration Factor of Inner Corner Surface of Nozzle	2.5	2.3	2.6

the inner corner surface of each nozzle are 2.5, 2.3 and 2.6 of N1, N2 and N3 nozzle respectively as shown in Table 2. It has been determined from these experimental results that three are not any remarkable differences of stress concentration factors of circumferential stress among the three nozzles.

CYCLIC INTERNAL PRESSURE TEST

After the static internal pressure test, in order to investigate the effect of crack geometry on the initiation life and propagation rate, two kinds of artificial cracks, A-type and B-type, were machined. These artificial cracks are depicted in Figs. 2, 3 and 4 respectively. They were machined at the symmetrical places of the inner corner surface of each nozzle, which were the flange and bottom side of the pressure vessel model.

Cyclic internal pressure was given to the pressure vessel model with a cycling rate of 5 cpm from 0 to 10.8 MN/m^2. The fatigue crack length from the artificial cracks at any pressure imposed was measured to the direction of the depth ($\theta = 45°$) by an electrical potential method and at the inner surface of the shell ($\theta = 0°$) and nozzle side ($\theta = 90°$ or $\theta = 105°$) by crack gages, where θ is defined as the circumferential angular coordinate, as shown in Fig. 8. The cyclic internal pressure had been applied to the leakage of oil from one of six cracks.

The oil leaked out from the outer surface of A type notch of N1 nozzle after cyclic internal pressure of 29,200 cycles. In Fig. 8, for example, is shown the relationship between number of cycles and crack length from the tip of A type notch of N1 nozzle. The crack initiation life of c-direction was smaller than one of a- and b-direction, which are the inner surface of shell and

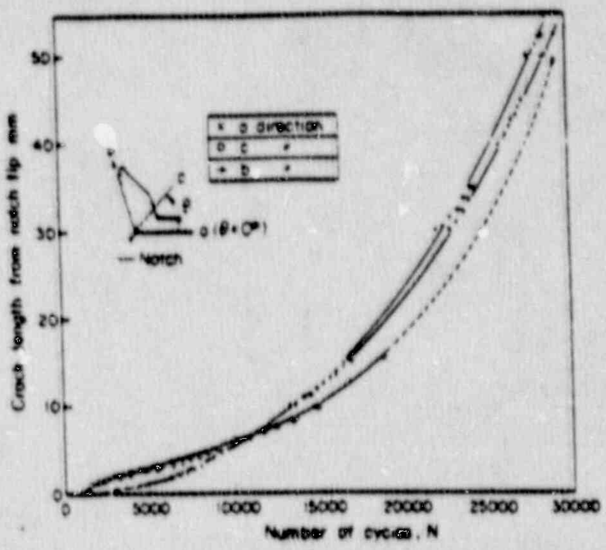

FIG. 8 CRACK LENGTH FROM NOTCH TIP OF N1 NOZZLE A TYPE NOTCH

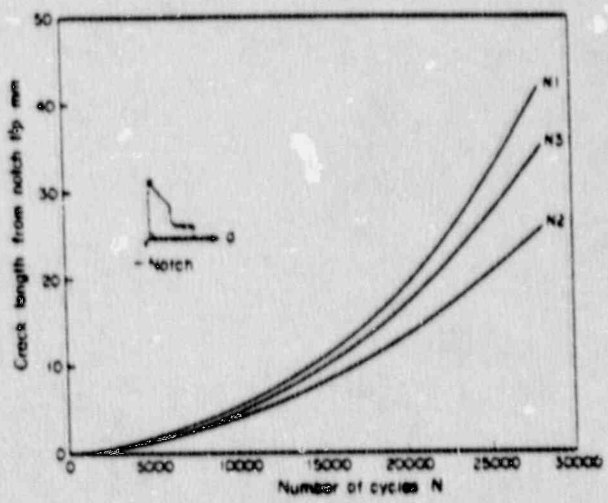

FIG. 9 CRACK LENGTH FROM NOTCH TIP OF A-DIRECTION (SHELL SIDE) OF N1, N2 AND N3 NOZZLE

nozzle side respectively. It is seen that the crack propagation rate of a- and b-directions are higher than one of c-direction except for the earlier stage. In Fig. 9, as an example, is denoted the relationship between the crack length from the notch tip of a-direction (shell side) of N1, N2 and N3 nozzle and number of cycles, obtained about B-type notch by crack gages. As shown in this figure, there are some differences of the crack propagation rate among three nozzles of N1, N2 and N3. Figure 10 shows the experimental results of the crack length from each notch tip of the a-, b- and c-directions, which were obtained by measuring the crack length of the fracture surface of N1, N2 and N3 nozzle respectively after each cross section was cut from each nozzle part. The crack length of N1 nozzle is the largest for both A and B type

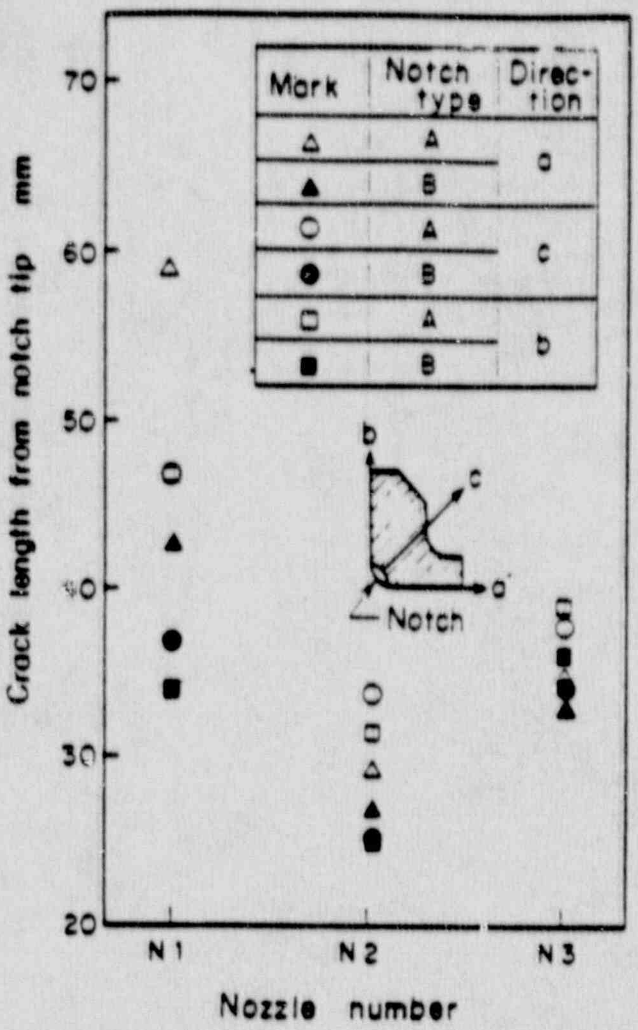

FIG. 10 CRACK LENGTH FROM NOTCH TIP OF A-, B- AND C-DIRECTION OF N1, N2 AND N3 NOZZLE

notch, while one of N2 nozzle is the smallest for both notches and one of N3 nozzle lies between N1 and N2 nozzles. It can be presumed from Figs. 5, 6, 7 and Table 2 that the crack propagation behavior of the nozzle is dependent on the stress distribution and stress concentration factor of the circumferential stress in its inner surface. As one reason, it seems that the stress concentration factors of the N1 and N3 nozzles are larger than one of the N2 nozzle. As shown in Fig. 10, the crack length of A type notch is larger than one of B type notch for each nozzle of N1, N2 and N3. It is supposed that this difference depends on the geometry of both notches.

In Fig. 11 are shown the macroscopic appearance of fracture surface of N1 nozzle (A type notch) and its fractographs, which were taken at four locations of the surface of fatigue failure. As denoted in this figure, the striations caused each cycle by cyclic internal pressure can be observed from the fractographs of S2, S7, S8 and S10 respectively. In Fig. 12 are compared the experimental results of crack propagation rates which have been obtained by an electrical potential method, crack gages and measurement of striation spacing for a-, b- and c-direction. The crack propagation rate obtained by measuring the striation spacing of the fractography is consistent with the rate obtained by the electrical potential method and crack gages, as shown in Fig. 12. The crack propagation rate was the order of 10^{-3} mm/cycle and increased with the crack length.

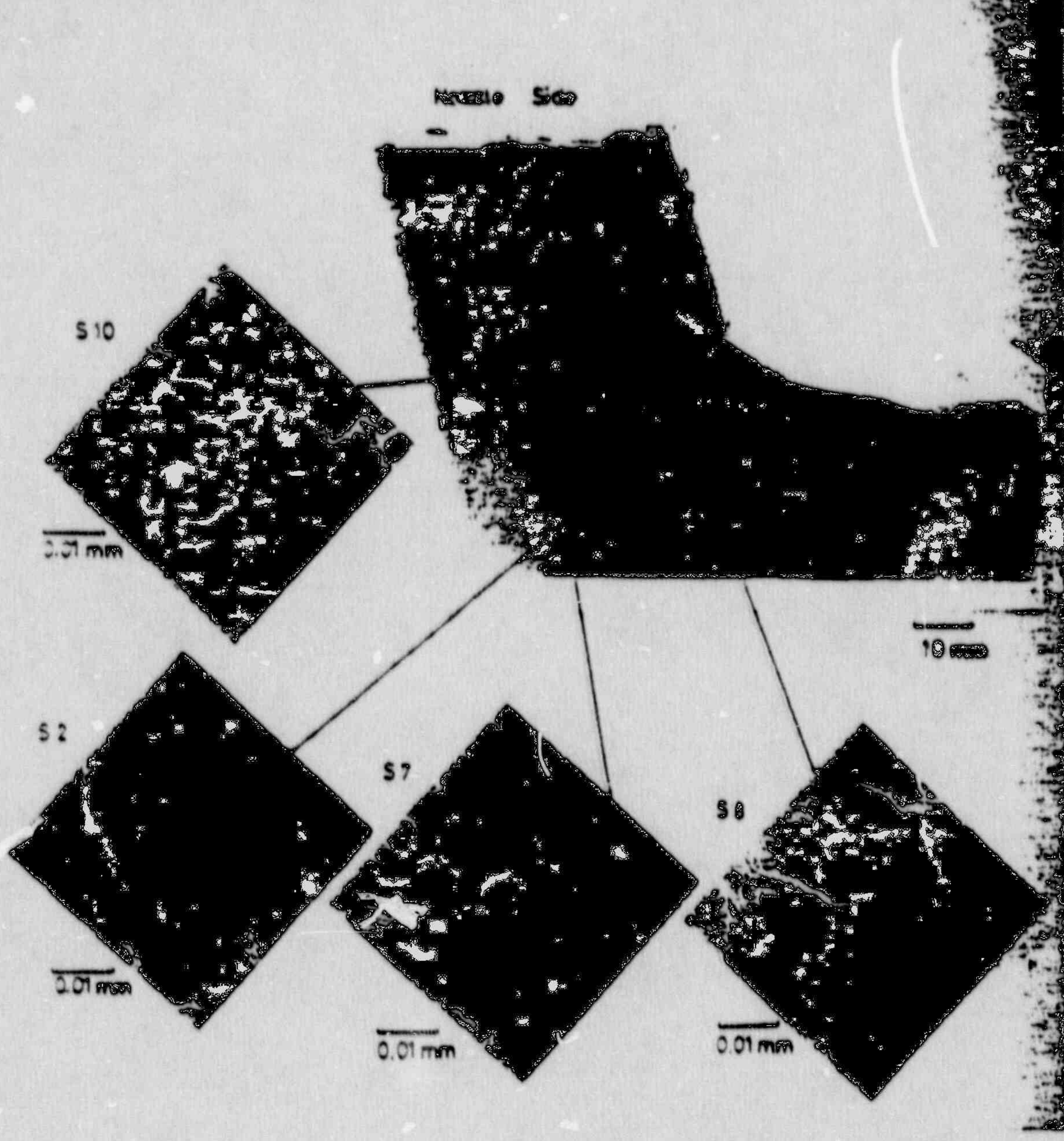

FIG. 11 FRACTURE SURFACE OF N1 NOZZLE (A TYPE NOTCH) AND ITS FRACTOGRAPHS

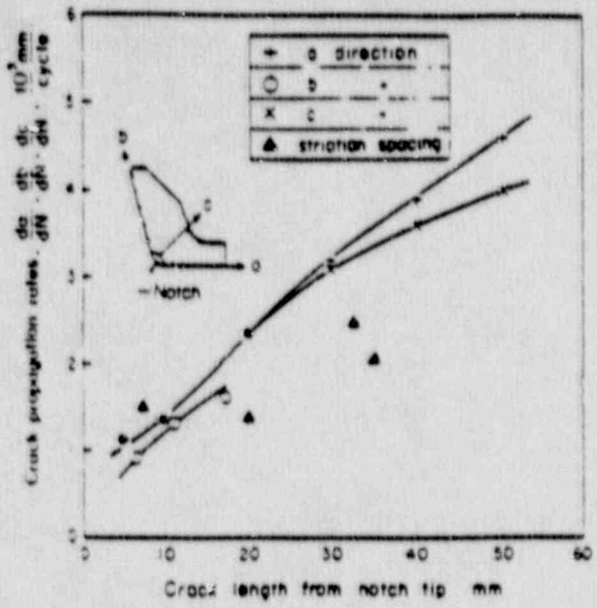

FIG. 12 CRACK PROPAGATION RATE N1 NOZZLE CROSS SECTION (A TYPE NOTCH)

CONCLUSIONS

The conclusions obtained from the experimental results of the static and cyclic internal pressure tests of the fifth pressure vessel model are as follows:

1) There are not any remarkable differences of stress distributions and stress concentration factors of circumferential stress at the inner corner surfaces among three nozzles of N1, N2 and N3, but it is, if anything, seen that the stress concentration factors of N1 and N3 nozzle are a little larger than one of N2 nozzle.

2) The crack propagation rate of the nozzle of the pressure vessel is dependent on the stress concentration factor of the inner nozzle corner.

3) The crack propagation rate of the nozzle is influenced by the geometry of notches at the inner nozzle corner.

4) The crack propagation rate of nozzle obtained by the electrical potential method and crack gages is consistent with the measurement of striation spacing and the order of the crack propagation rate is 10^{-3} mm/cycle under the environment of oil and room temperature. The experimental result is consistent with the results which were obtained by the cyclic internal pressure tests of the 3rd and 4th pressure vessel models [2], [3].

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REFERENCES

[1] Fujimura, T., Miyazono, S., and Ueda, S. *et al.*, "Characteristics of Crack Propagation in Overlaid Nozzles of a Nuclear Reactor", *Proceedings of the 1st International Conference on Pressure Vessel Technology*, Delft, Netherlands, September 29-Oct. 2, 1969, Part II, pp. 1213-1220.

[2] Fujimura, T., Miyazono, S., Kodaira, T. and Shibata, K., "Integrity Assessment of Structural Models of a Reactor Vessel with Notched Nozzles under Cyclic Pressure Loading", *Proceedings of the 2nd International Conference on Pressure Vessel Technology*, San Antonio, Texas U.S.A., October 1-4, 1974, 2-58, pp. 801-819.

[3] Miyazono, S. and Shibata, K. "Crack Propagation Characteristics in the Nozzle Corners of a Pressure Vessel Steel Model of Light Water Reactor", *Proceedings of the 3rd International Conference on Structural Mechanics in Reactor Technology*, London, United Kingdom September 1-5, 1975, G4/8.

[4] "Rules for Construction of Nuclear Vessels", ASME Boiler and Pressure Vessel Code, Sec. III, 1968 Ed.

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