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Benchmark problems on thermal striping evaluation of FAENA and TIFFSS sodium experiments

(Research Report)

June 2000

JAPAN NUCLEAR CYCLE DEVELOPMENT INSTITUTE

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Benchmark problems on thermal striping evaluation of FAENA and TIFFSS sodium experiments

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Naoto KASAHARA* and Yves LEJEAIL**

Abstract

Since thermal striping is a coupled thermohydraulic and thermomechanical phenomenon, sodium mock-up tests were usually required to confirm structural integrity. CEA and JNC have developed evaluation procedures of thermal striping to establish design-by-analysis methodology for this phenomenon. Attenuation of temperature and stress amplitude was one of the most important factors in the integrity assessment. Since this attenuation depends on frequencies of temperature fluctuation, benchmark problems based on frequency control tests were planned to confirm above procedures. One of benchmarks provided by CEA is temperature and fatigue evaluation of tubes and plates due to channel flows. Another problem from JNC is the same evaluation of plates subjected to vertical jets. This report explains details of both experiments and defines the benchmark problems.

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FAENAとTIFFSSナトリウム試験データを用いたサーマルストライピングベンチマーク問題

（研究報告書）

笠原 直人*、Yves LEJEAIL**

要　旨

流体温度ゆらぎによる構造物の熱疲労現象は熱流動と構造の両分野に亘る複雑な問題であり、従来その評価にはナトリウムモックアップテストが必要であった。本問題に対する解析による設計法を確立するため、CEAとJNCは評価法の開発を行ってきている。流体温度ゆらぎに対する構造健全性に対して、流体から構造への伝達過程で生じる温度ゆらぎの減衰作用が重要な役割を果たすことが知られている。その減衰の大きさは周波数に依存することから、評価法検証のために周波数制御ナトリウム試験データを用いたベンチマーク問題を計画した。一つはCEAから出題されたもので、温度が周波数制御された平行流を受ける管と平板の温度および疲労評価に関する問題である。もう一つのJNC出題の問題は、周波数制御された垂直ジェットを受ける平板の評価に関するものである。

本報告書は両者の実験の詳細を説明し、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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1 INTRODUCTION

At an incomplete mixing area of high and low temperature fluids near the structural surface, temperature fluctuation of fluid gives thermal fatigue damage on the wall structures. This coupled thermohydraulic and thermomechanical phenomenon is called thermal striping, which has so complex mechanism and sometimes causes crack initiation on the structural surfaces that sodium mock-up tests are usually required to confirm structural integrity of components.

In order to establish design-by-analysis methodology for thermal striping, CEA and JNC have developed evaluation procedures of this phenomenon. Under EJCC framework, intercomparison of both procedures is planned through application to the same benchmark problems. The background of benchmarks are as followings.

Thermal hydraulics and structural analysis has been conducted concerning a tee junction of the PHENIX secondary circuit due to thermal striping phenomenon, in the IAEA coordinated research program on Harmonization and validation of Fast Reactor thermomechanical and thermohydraulic codes and relations using experimental data [1] [2]. Through investigation of mechanism of thermal striping phenomenon and sensitive factors of structural integrity at a Tee junction of LMFR piping system, author paid attention to a sensitivity of induced stress amplitude to frequency of temperature fluctuation. High frequency components of fluctuation are attenuated in the boundary layer and are partially transferred to structures. Low frequency components of fluctuation can be transferred to structures, however they induce small amplitude of stress, since average temperature of wall thickness fluctuates. In the intermediate regime, there is the most damageable frequency, such as ~0.1 Hz in the case of the Phenix mixing tee. As the result, induced stress histories are not proportional to time series of temperature fluctuation of fluid. It means that attenuation factors of stress amplitude can be rationally evaluated with considering frequency of temperature fluctuation.

Attenuation mechanism of temperature fluctuation was investigated through sodium experiments and their analysis [3] [4]. From above work, attenuation mechanism was understood to be (1) turbulent mixing, (2) molecular diffusion, (3) non-stationary heat transfer, and (4) thermal homogenization.

Since this attenuation depends on frequencies of temperature fluctuation, CEA and JNC planned two kinds of complementary benchmark problems based on frequency control tests.

One of benchmarks provided by CEA is temperature and fatigue evaluation of tubes and plates due to channel flows. Another problem from JNC is the same evaluation of plates subjected to vertical jets. This report explains the details of both experiments and defines the benchmark problems.

The objective of the benchmark is comparison of temperature and thermal fatigue evaluation methods with relation to frequency of fluid temperature fluctuations.

2. FAENA EXPERIMENT

2.1. FAENA SODIUM LOOP

FAENA is a sodium loop mainly devoted to fast thermal shock experiments. The principle of the tests is very simple : hot and cold sodium jets are injected alternatively with electromagnetic pumps inside the channel of the specimen, which produce cracks at the surface. Possibilities of the sodium rig are as follows :

- heating power : 22 kW
- mean flow rate is between 0-1600 l/h (~700 l/h was used for FAENA experiments)
- domain of frequencies : 0.07 Hz - 0.3 Hz
- fluid temperature variations from 0 to ~300 °C

A classical air cooler was sufficient to ensure the sodium cold temperature. A schema of the loop is given in Fig.2.1, as well as of the sodium injection system in Fig.2.2. An overview of the FAENA completed programs is given thereafter

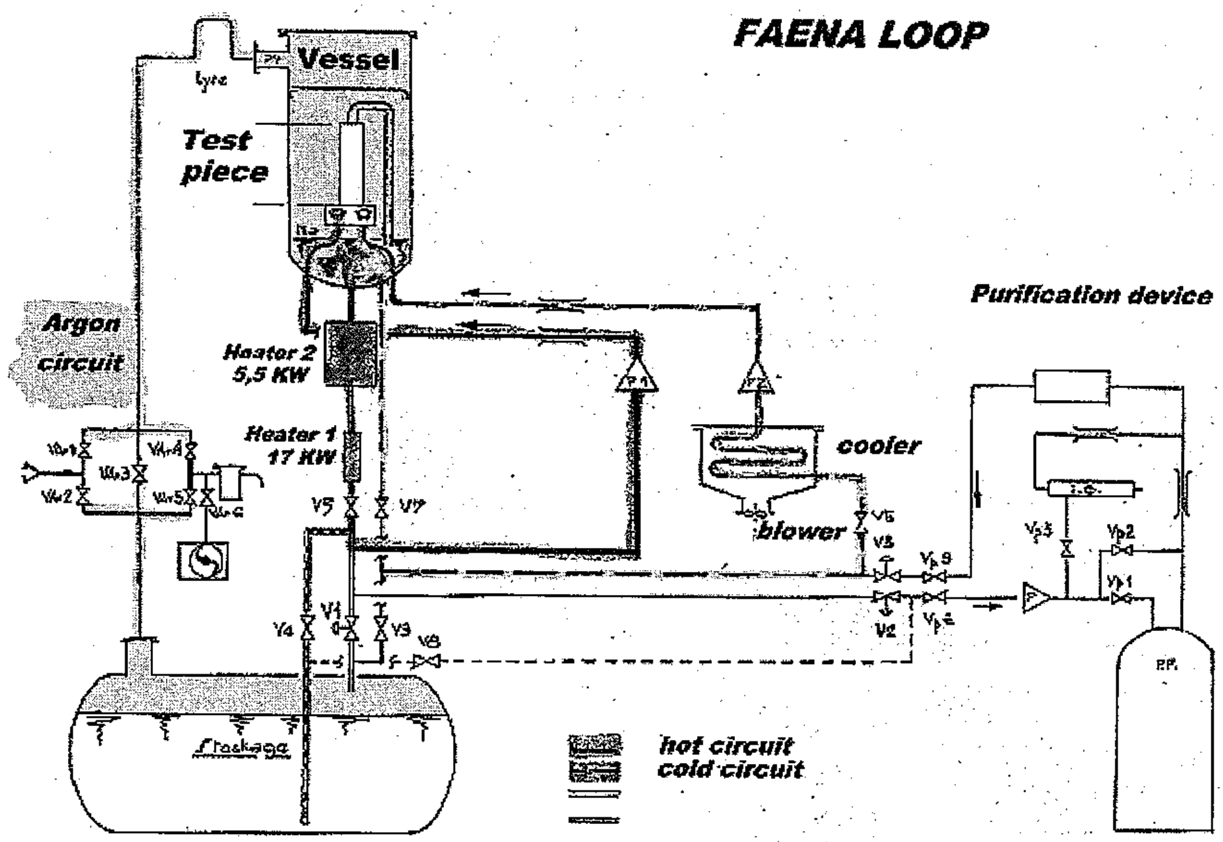


Fig.2.1 FAENA sodium loop.Total power available 22.5 KW, maximum flow rate for P1 and P2 electromagnetic pumps 1.6 m^3/h; nominal flow condition 0.7 m^3/h

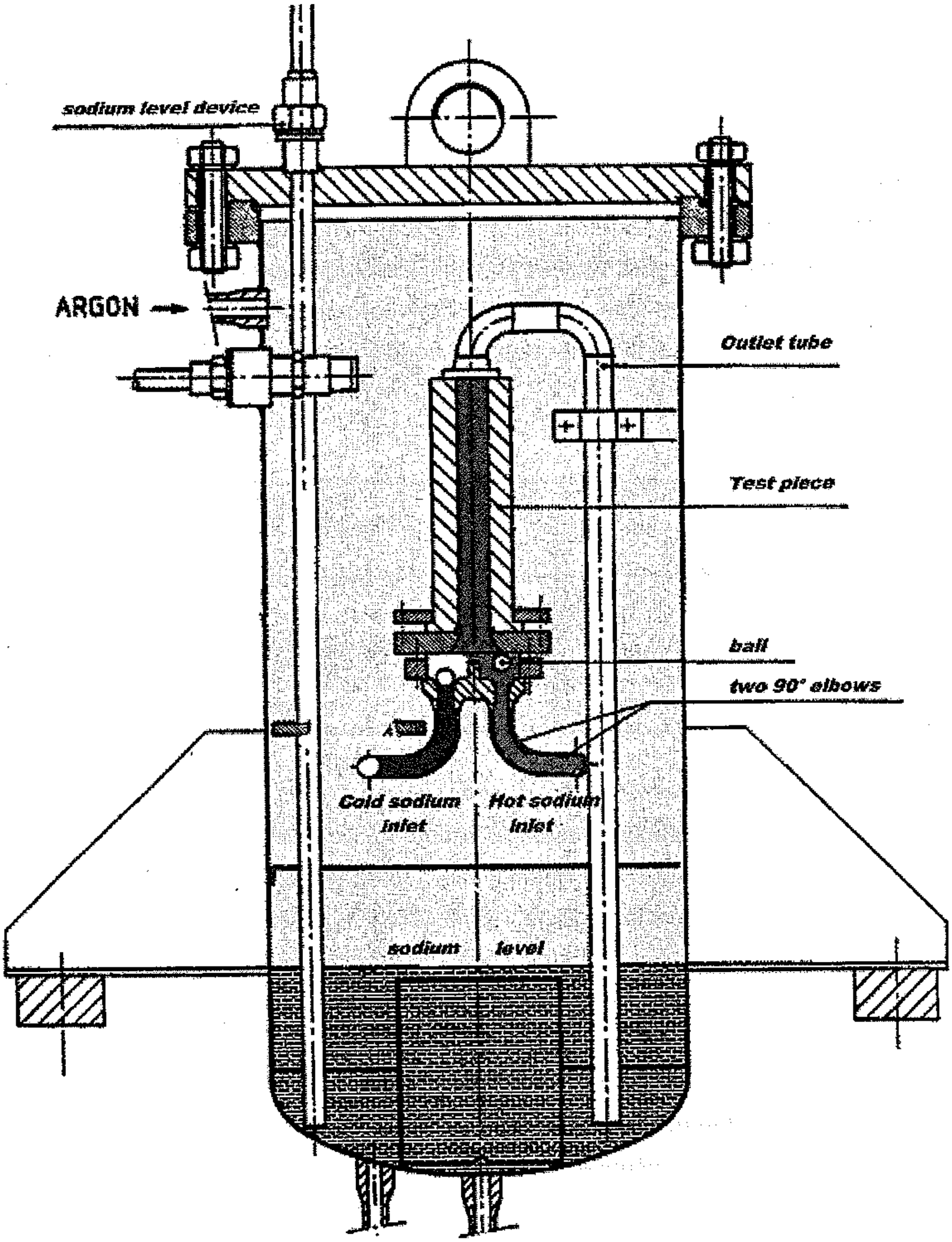


Fig.2.2 Detail of FAENA test piece feeding system

2.2. FAENA EXPERIMENTAL RESULTS (COMPLETED PROGRAM)

2.2.1 GENERAL PURPOSE

In Sodium FAENA fatigue tests were performed during period 1988-1997. Data were acquired in several conditions. For each configuration described below, a thermal specimen was used with type K thermocouples placed in sodium and at different depth in the specimen wall, and for the thermomechanical tests we performed metallographic and Scanning Electron Microscope examinations with a view to determine the level of the last crack corresponding to our initiation criteria. The table below roughly describes the conditions of the different tests including thermal specimens :

Geometry	Steel	Number of Tests	Frequency (Hz)	Inlet Sodium Temperature Variation (°C)	Maximum Number of cycles
Tube	9Cr1Mo mod	3	0.07	281	215000
Tube	316L	9	0.07 / 0.3	~ 281 / 200	18000 / 10^6
Tube	316L	3	0.07 / 0.3	281 / 200	12000 / 2 10^6
Welded Plates	316L	5	0.125	285	210000

Note that for the Welded Plates configuration, we studied influence of ageing and ground flush on fatigue life. Additionnally, some temperature measurements were performed at frequencies 0.25, 0.166, 0.125, 0.1, 0.07, 0.05 Hz and are available for determination of convection heat exchange coefficient (for statement of damaging frequencies purpose).

For the benchmark between CEA/JNC, we decided to choose Welded plates results for the thermal benchmark ; the reason was that more measurements were available for that configuration. But due to the complex fatigue analysis of this geometry which includes weldments, we prefered to study the tubular 316L specimens for the fatigue benchmark.

Both of them are described in the following.

2.3. DEFINITION OF THERMAL BENCHMARK ON 316L WELDED PLATES (FOURTH SERIES)

2.3.1 OBJECTIVE OF THE BENCHMARK

The aim of this benchmark is to validate theoritical diagrams of temperature attenuation from fluid to structure surface, by the mean of experimental data. The problem is that convection heat exchange coefficient is well defined in permanent flow but only a few validation is available for transient flows. Data needed are surface temperature variations, fluid temperature variations, geometry of the specimens, frequency of cycles, material data. We need also heat exchange coefficient determination.

2.3.2 DESCRIPTION OF EXPERIMENTAL DATA

Five Experiments were carried out during 1996-1997. The geometry was an assembly of a plate with a holder (see Fig.2.3 and Fig.2.4). The aim was to study influence of ageing and ground flush on weld fatigue life. A specimen was instrumented with 40 ϕ 0.5mm type K thermocouples at several positions in sodium flow and in plate depth (see Figs 2.5 to 2.7 describing thermocouple locations). The table below displays the thermocouple location inside plates, comparing theoritical and measured after test positions (d distance means distance from tip of thermocouple to the surface of the plate).

n° TC	*measured distance d*	*theoritical distance d*	*remarks*
	(mm)	*(mm)*	
8,9,10	0.925;2.125;3.35	1,2,3	TC9,10 partial contact
18,19,20	1.075;4.675;3	1,2,3	
28,29,30	1.45;1.95;2.95	1,2,3	TC 19 insufficiant depth
38,39,40	1.075;1.95;2.975	1,2,3	
3,4	2.088;1	2,1	TC13,33 measurements not valids
13,14	/;1.08	2,1	
23,24	2.45;1	2,1	
33,34	/;1.075	2,1	

Temperature measurements were performed at frequencies 0.25, 0.166, 0.125, 0.1, 0.07, 0.05 Hz (Fig 2.8 shows an example of temperature measurement) and are available for determination of convection heat exchange coefficient (for statement of damaging frequencies purpose). More details are given in the following table :

flow rate (l/h)	frequencies (Hz)	inlet temperature variation in sodium (peak to peak) (°C)	time acquisition (s)
730	0.25, 0.166, 0.125, 0.1, 0.07, 0.05	~ 255, ~255, ~285 ~ 295,~ 295 , ~305	10, 10, 13, 13, 22, 25

In fact, surface temperatures were measured with thermocouples 5,6,7,15,16,17,25,26,27,35,36,37 (Fig.2.5 and Fig.2.6). Here, the section at Z=43mm (Fig.2.6) was chosen because of less scatters in the measurements, in addition distance of the section from the inlet is sufficient to avoid inlet perturbations.

Tables thereafter give the ratio of surface temperature to fluid temperature variations :

f (Hz)	FAENA-4th (L=15mm,d=5mm)
0.050	0.817
0.070	0.793
0.100	0.754
0.125	0.727
0.166	0.667
0.250	0.554

f (Hz)	FAENA-4th(L=15mm,d=2mm)
0.050	0.942
0.070	0.939
0.100	0.915
0.125	0.889
0.166	0.872
0.250	0.838

L is the thickness of the plate

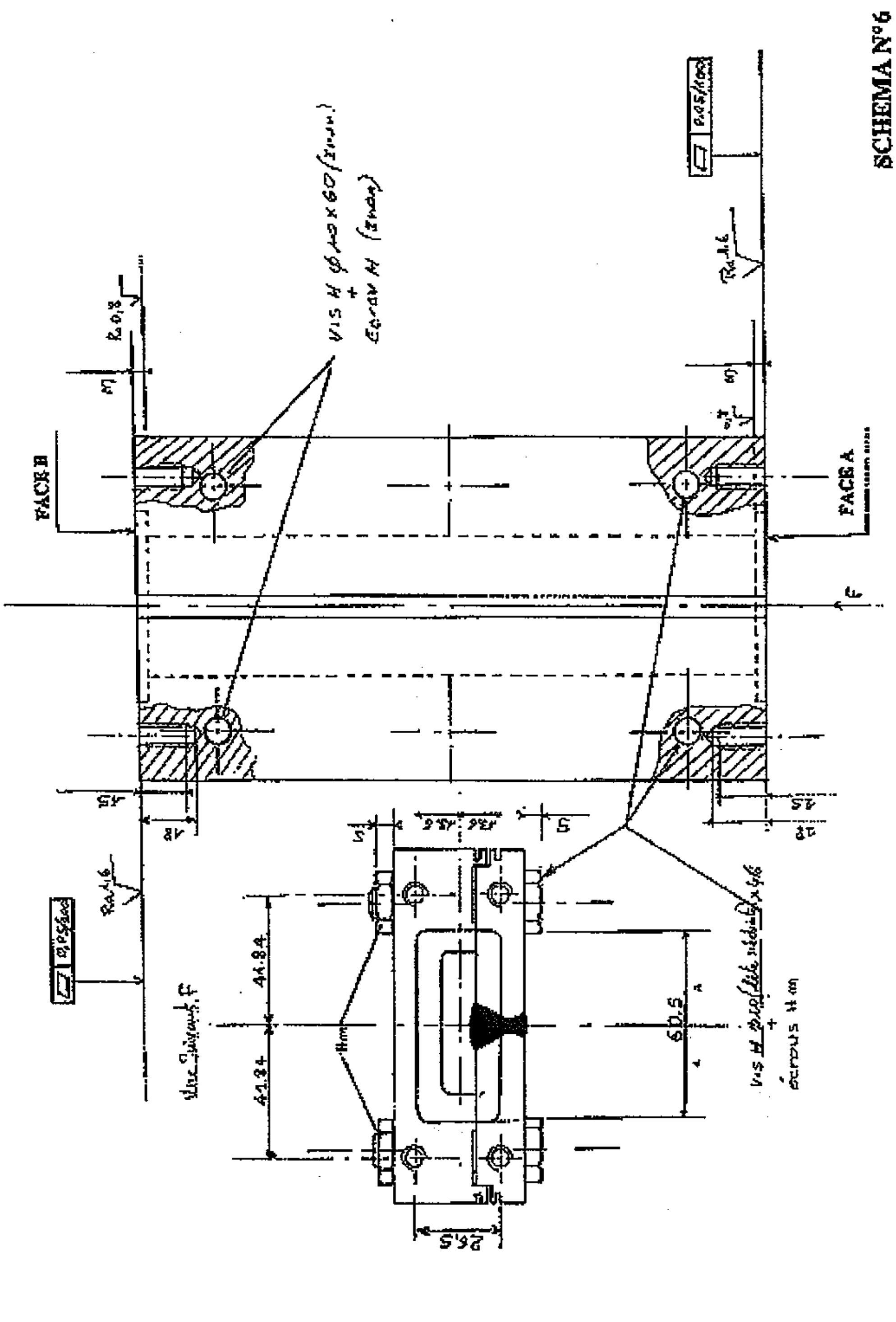


Fig.2.3 Plate of 316L steel (VIRGO) with weldment, details of whole geometry (plate + holder)

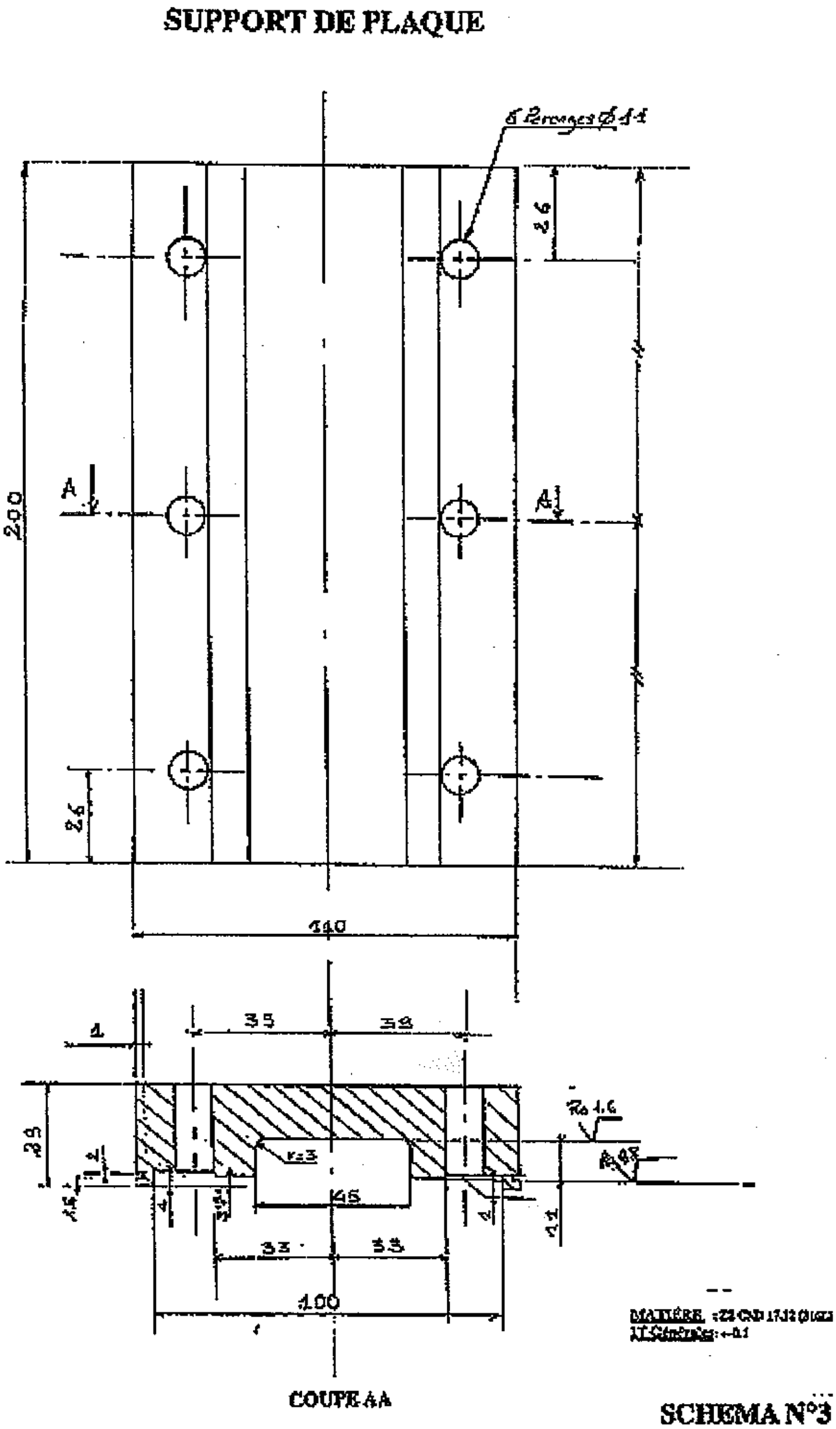


Fig.2.4 Plate of 316L steel (VIRGO) with weldment, details of holder geometry

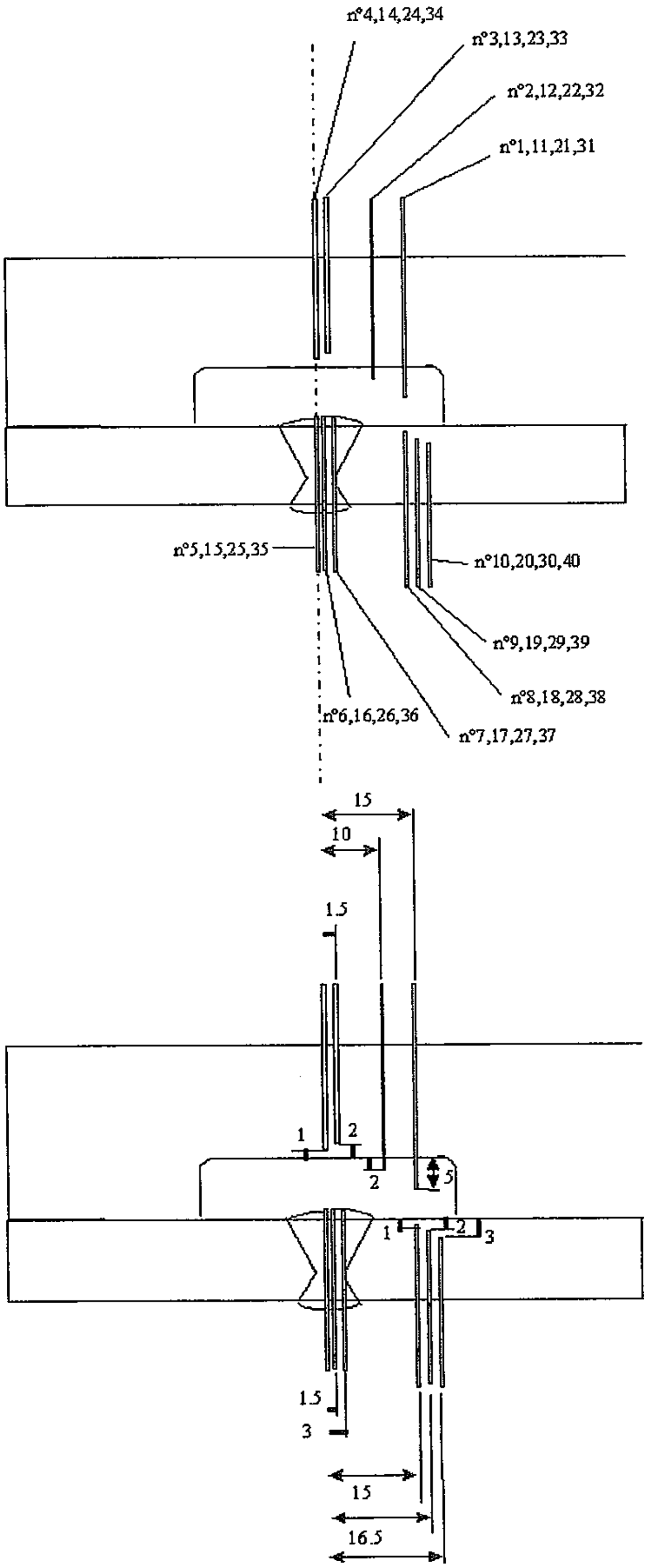


Fig.2.5 Plate of 316L steel (VIRGO) with weldment, details of thermocouple locations

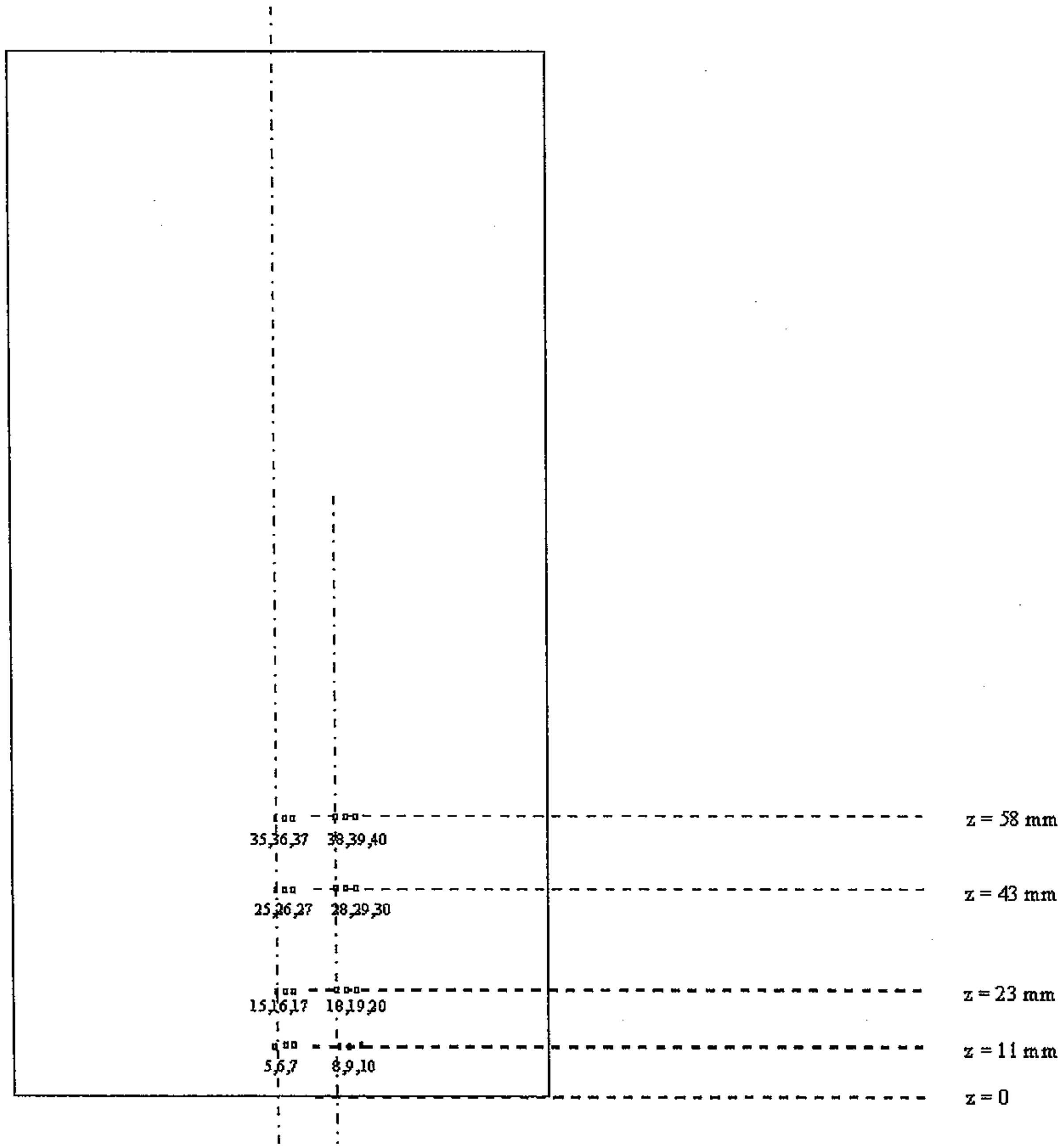


Fig. 2.6 Plate of 316L steel (VIRGO) with weldment, details of thermocouple locations in the welded plate

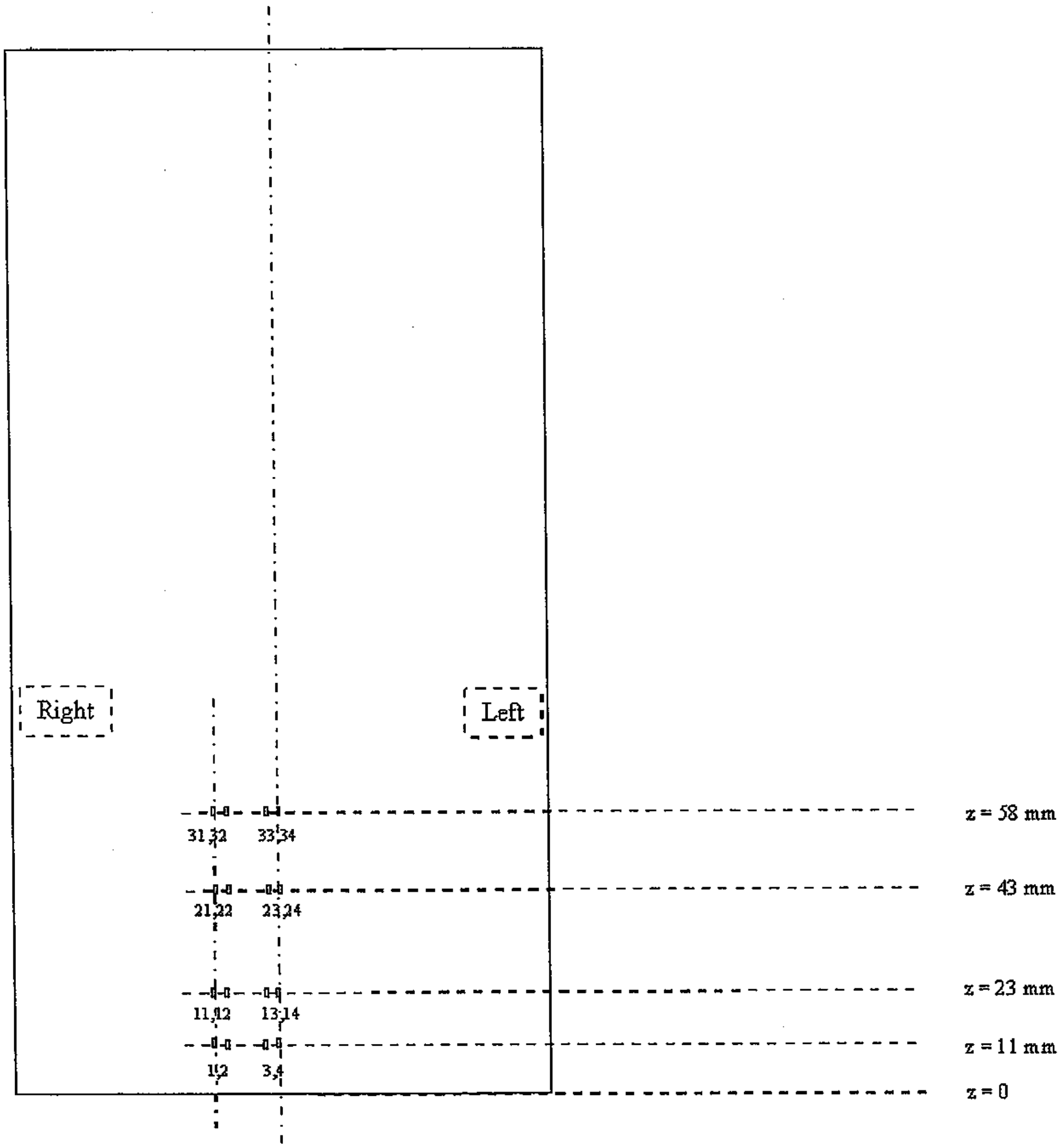


Fig. 2.7 Plate of 316L steel (VIRGO) with weldment, details of thermocouple locations in the holder

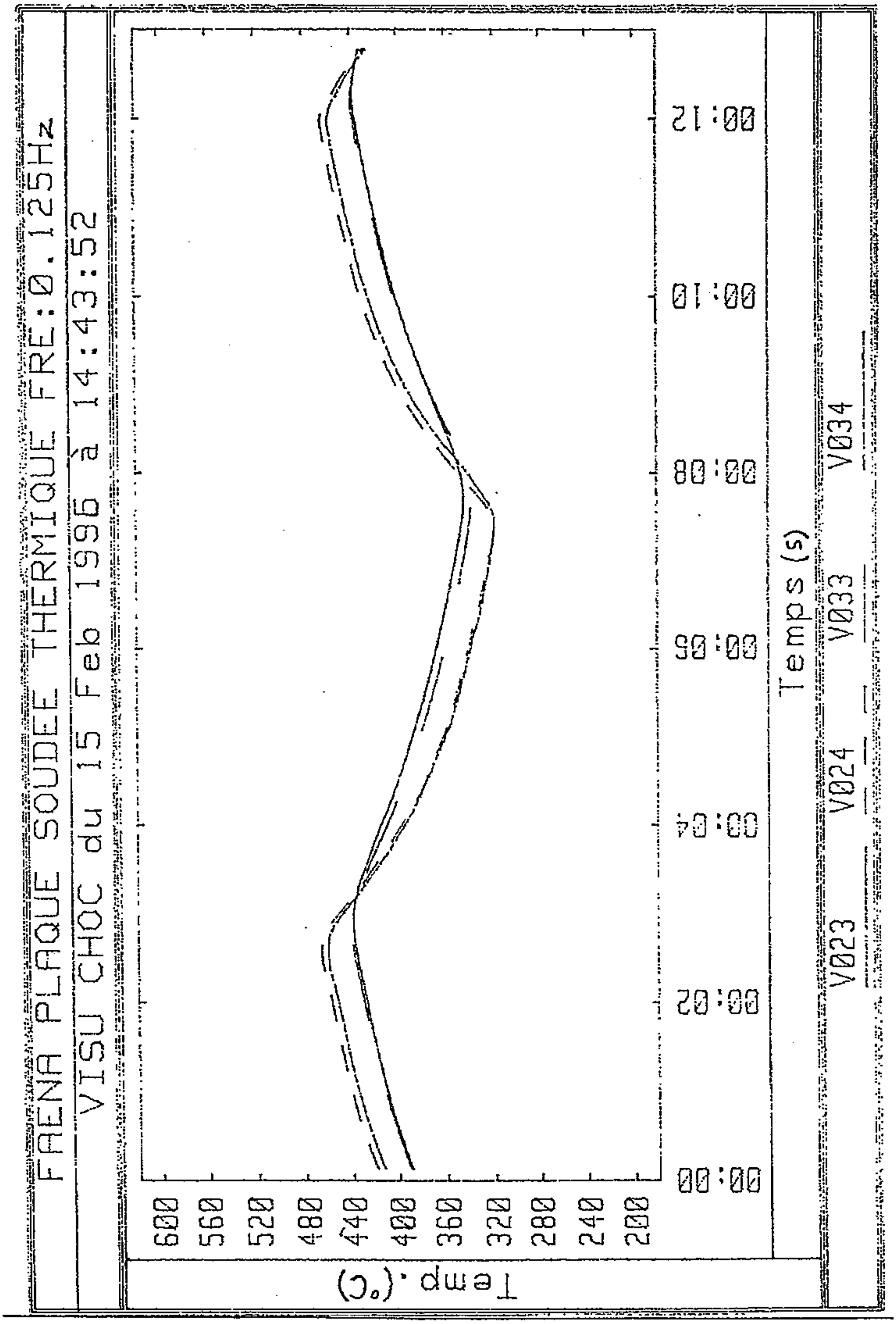


Fig.2.8 Plate of 316L steel (VIRGO) with weldment, example of temperature measurement inside the holder during 0.125 Hz frequency test (level of section 3 and section 4)

2.4. DEFINITION OF FATIGUE BENCHMARK ON 316L(N) CYLINDRICAL TEST PIECE (FAENA THIRD SERIES))

2.4.1 OBJECTIVE OF THE BENCHMARK

The objective is to compare French and Japanese thermal fatigue analysis. The following experimental data are necessary for FAENA fatigue analysis :

- thermal loading inside specimen channel (fluid temperature variation versus z coordinate, time history of fluid temperature variation, sodium velocity)
- material data including expansion coefficient, Young's modulus, stress strain cyclic curves, and fatigue curves. These data are not shown in this paper since they are available in the RCC-MR design code. We only have to take care that mean fatigue curves have to be used for a best fit analysis.
- position of the last crack corresponding to initiation in the internal channel is required to determine precisely the level of strain variation in this location

2.4.2 DESCRIPTION OF EXPERIMENTAL DATA

(1) Thermal loading

The test piece was made of 316L(N) steel, with the geometry described on Fig. 2.9. Figs 2.10 and 2.11 show the thermocouple locations for the thermal specimen. Thermocouples were K type, 0.5 mm diameter, insulated and in hole brazed (thermocouple diameter was 1 mm for fluid measurements).

Temperature measurements were performed for the following conditions :

flow rate (l/h)	frequency (Hz)	inlet temperature variation in sodium (peak to peak) (℃)	outlet temperature variation in sodium (peak to peak) (℃)	time acquisition (s)
712	0.3	200	100	10
727	0.07	289	202	32

An example of temperature measurement is given on the Fig.2.12. For the precise definition of fluid thermal loadings, basic functions have been determined :

$$\Delta T_f(z) = (z + 152592.6) / (z + 527) \qquad \text{(z in mm , frequency 0.07Hz)}$$

$$\Delta T_f(z) = (z + 45398.7) / (z + 227.4) \qquad \text{(z in mm , frequency 0.3Hz)}$$

Time history functions can be defined for each frequency. For f = 0.07Hz :

t (s)	0	1.29	2.245	3.946	6.806	7.918	8.98	10.748	14.42	15.23
F(t)	0	0.669	0.786	0.903	1.	0.	-0.619	-0.826	-1.	-0.

For f = 0.3Hz :

t (s)	0	0.63	1.41	1.61	2.21	2.70	3.31	3.56	4.
F(t)	0	0.5	1.	1.	0..	-0.4375	-1.	-1.	0.

Finally, in sodium temperature can be evaluated by $T_f(z,t) = \Delta T_f(z)\ F(t)$

(2) Crack initiation

Principle of interpretation of FAENA tests is rather complex due to axial gradients of loading. The highest position of crack must be determined by several techniques (dye penetrant inspection, Scanning Electron Microscope examination, and finally Optical Microscope observation of metallographic cuts in order to verify that the last crack depth is less than initiation depth criteria (200 μm))

Two mechanical tests were performed in that configuration :

flow rate (l/h)	frequency (Hz)	inlet temperature variation in sodium (peak to peak) (℃)	outlet temperature variation in sodium (peak to peak) (℃)	CLA (μm)	axial position (z in mm) for the last crack	number of applied cycles
712	0.3	200	100	0.1 - 0.3	60	$2.1\ 10^6$
727	0.07	289	202	0.1 - 0.3	no crack	12100

The crack pattern obtained at 0.3Hz is shown on Fig.2.13. Note that no crack was found in 0.07Hz test after application of 12100 cycles. CLA means Center Line Average which is equivalent to the mean surface roughness R_a.

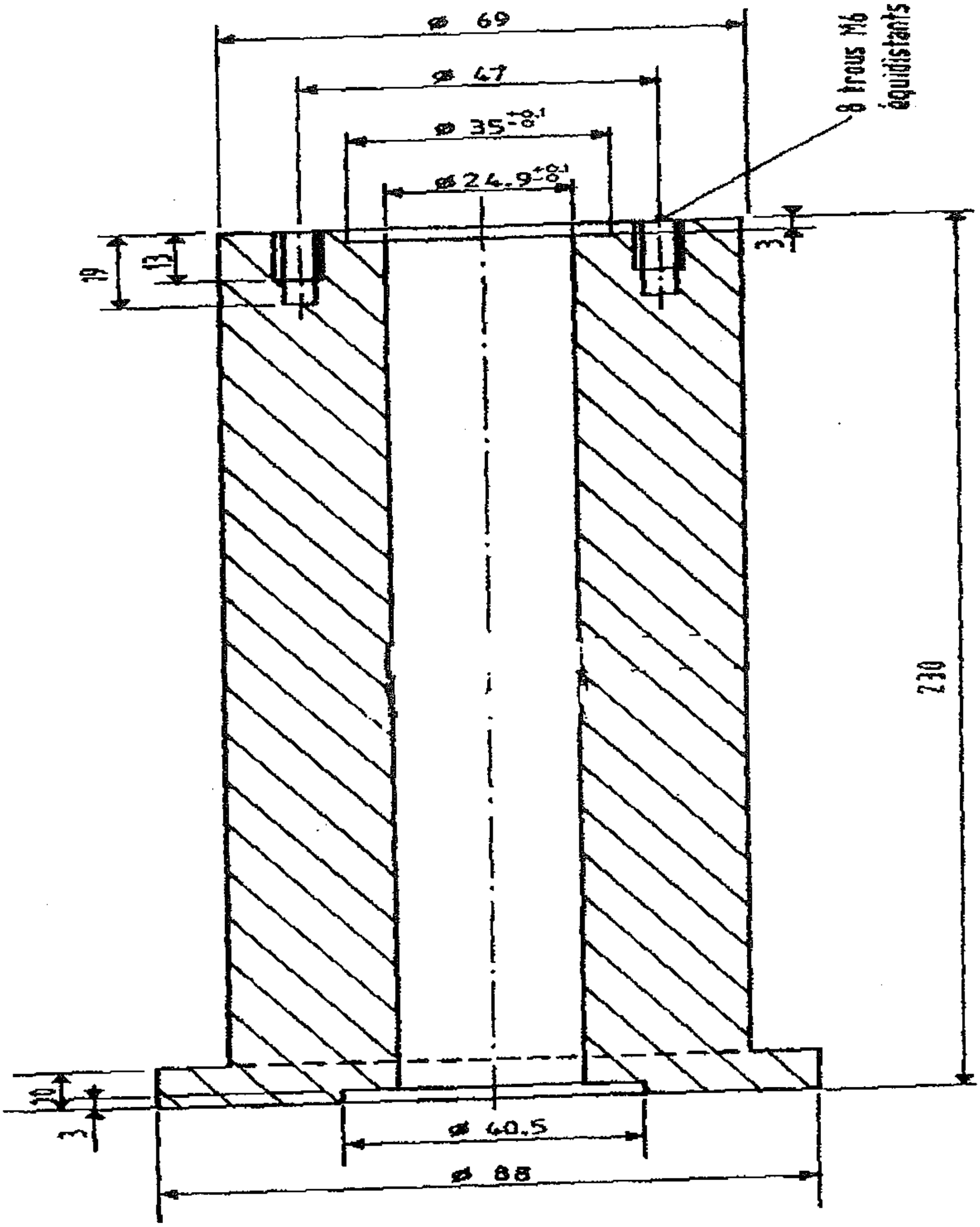


Fig.2.9 Cylindrical geometry for 316L(N) tests

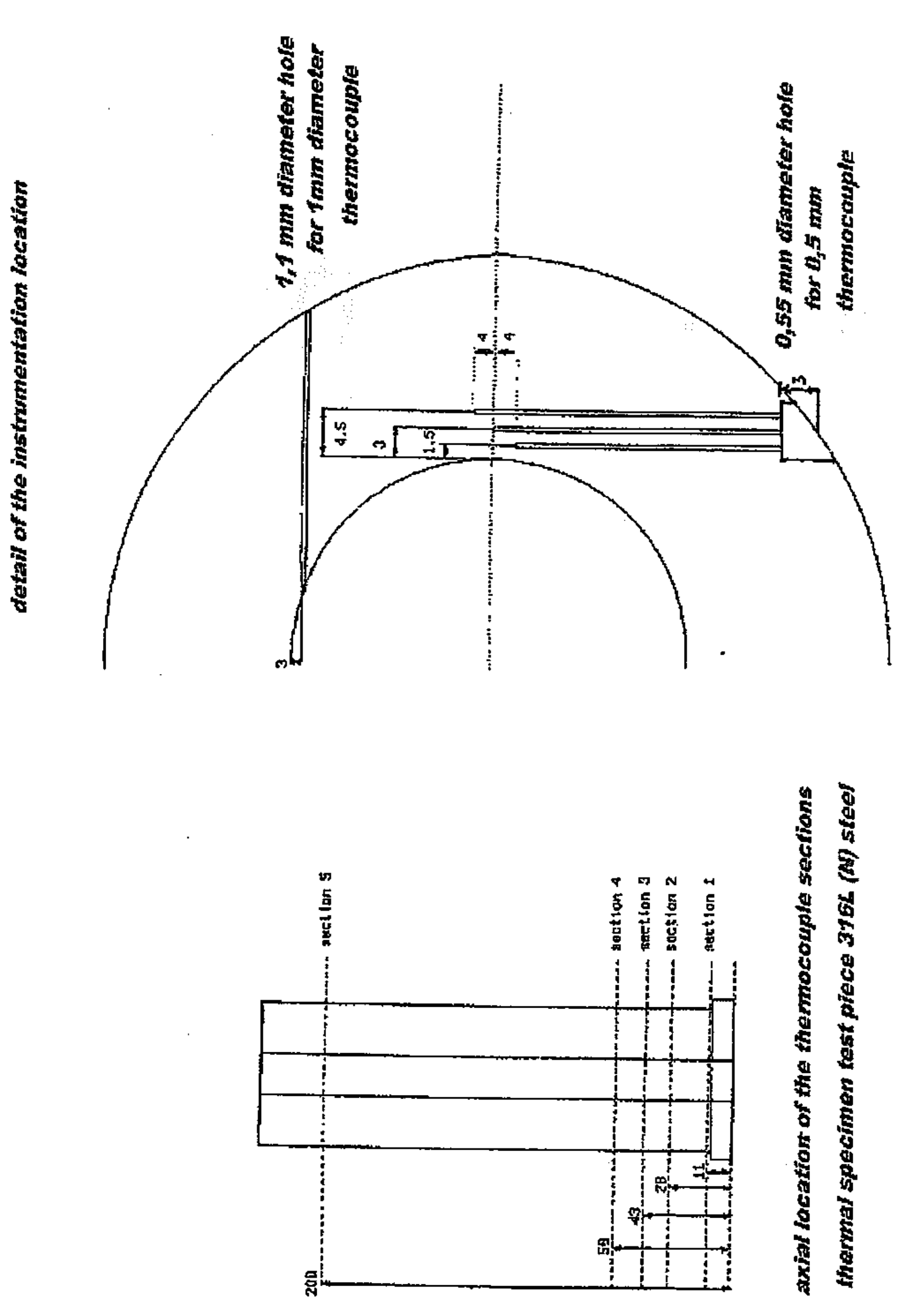


Fig.2.10 Cylindrical test piece made of 316L(N) steel, locations of thermocouples of the thermal specimen

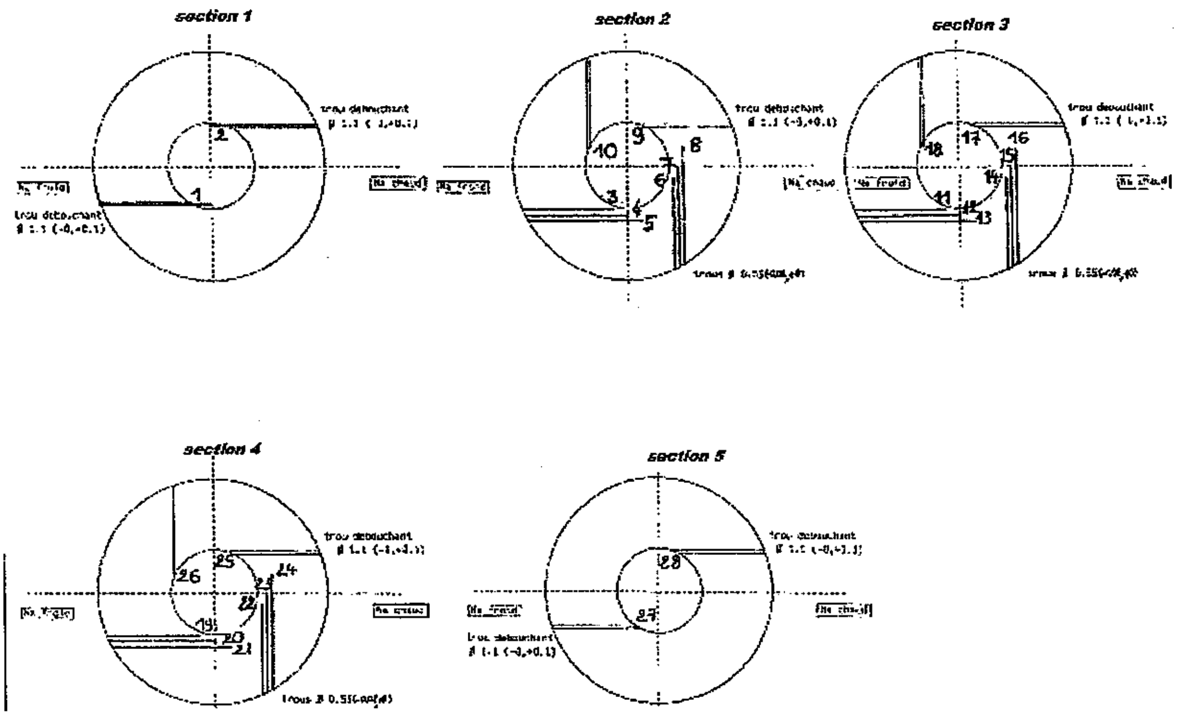


Fig.2.11 Cylindrical test piece made of 316L(N) steel, locations of thermocouples of the thermal specimen

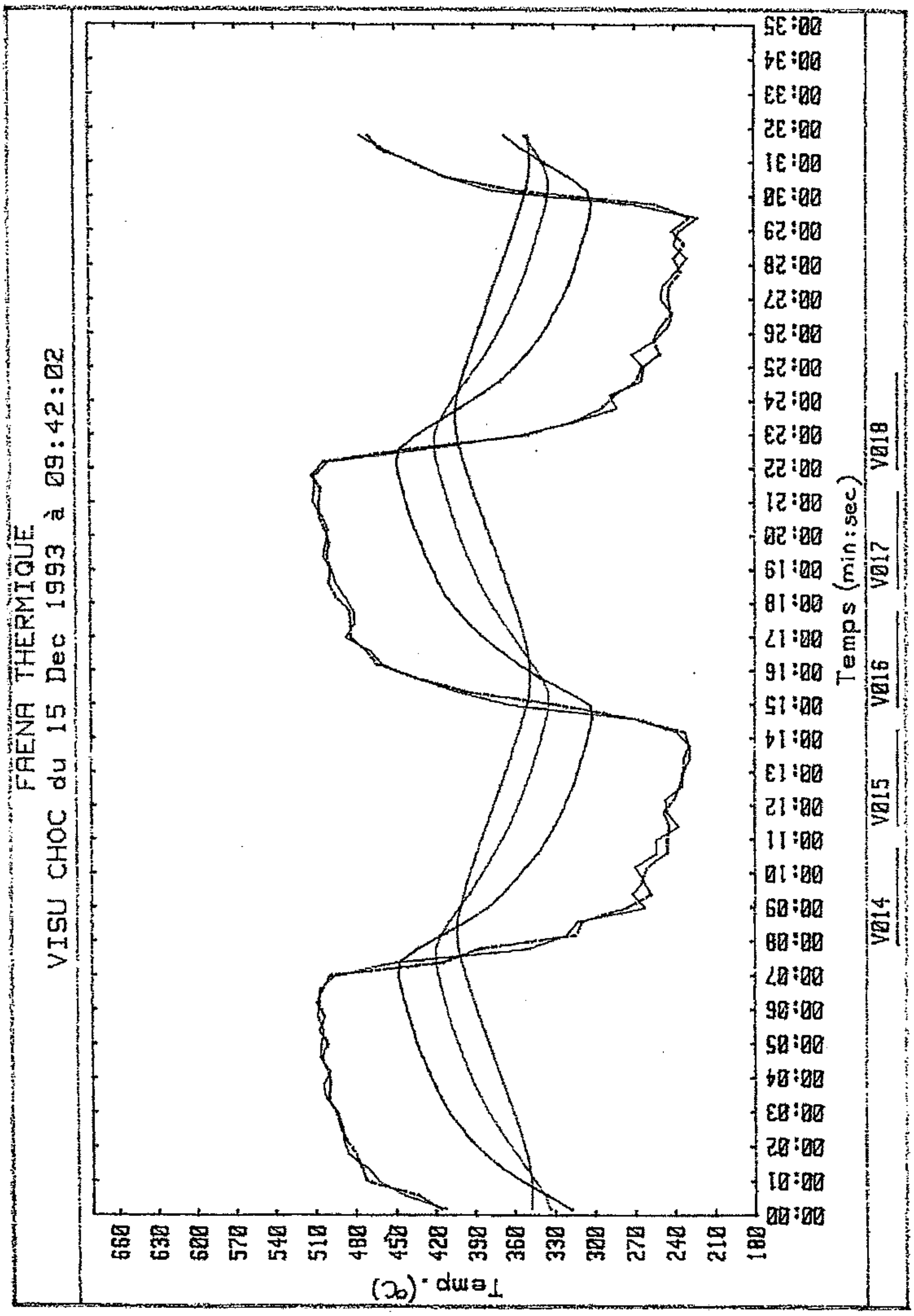


Fig 2.12 Cylindrical test piece made of 316L(N) steel, example of temperature measurements in section 3

Fig.2.13 Cylindrical test piece made of 316L(N) steel, example of cracks observed after test at frequency 0.3Hz

3. TIFFSS EXPERIMENT

3.1. TIFFSS SODIUM EXPERIMENTAL FACILITY

The TIFFSS test facility has a hot sodium line with an electric heater and a cold sodium line with an air-cooler (Fig.3.1). Sodium is driven by an electromagnetic pump and its flow rate can be regulated with control valves and electromagnetic flow meters. Cold trap loop is for purification of sodium. Fig.3.2 is a detail of the test section. Photographs of inner devices and an external appearance are shown in Fig.3.3 and Fig.3.4.

Hot and cold sodium is alternatively fed into a single nozzle with 6 mm of inner diameter and is projected to a specimen as a vertical jet in a sodium pool. Valves that change flow pass of hot and cold sodium control frequencies of temperature fluctuations.

This test section has such special devices as bypass lines and small chambers in the mixing tee to keep flow rate and peak temperature of sodium in the single nozzle. Frequency controller and temperature regulators are shown in Fig.3.5.

In order to change heat transfer coefficient from outlet sodium to a specimen, distance between outlet of the nozzle and upper surface of specimen is controllable.

During experiments, 13 channels of temperature are measured by thermocouples and analog units detect switch signals of valves. These data are digitized and recorded by data equation system (Fig.3.6).

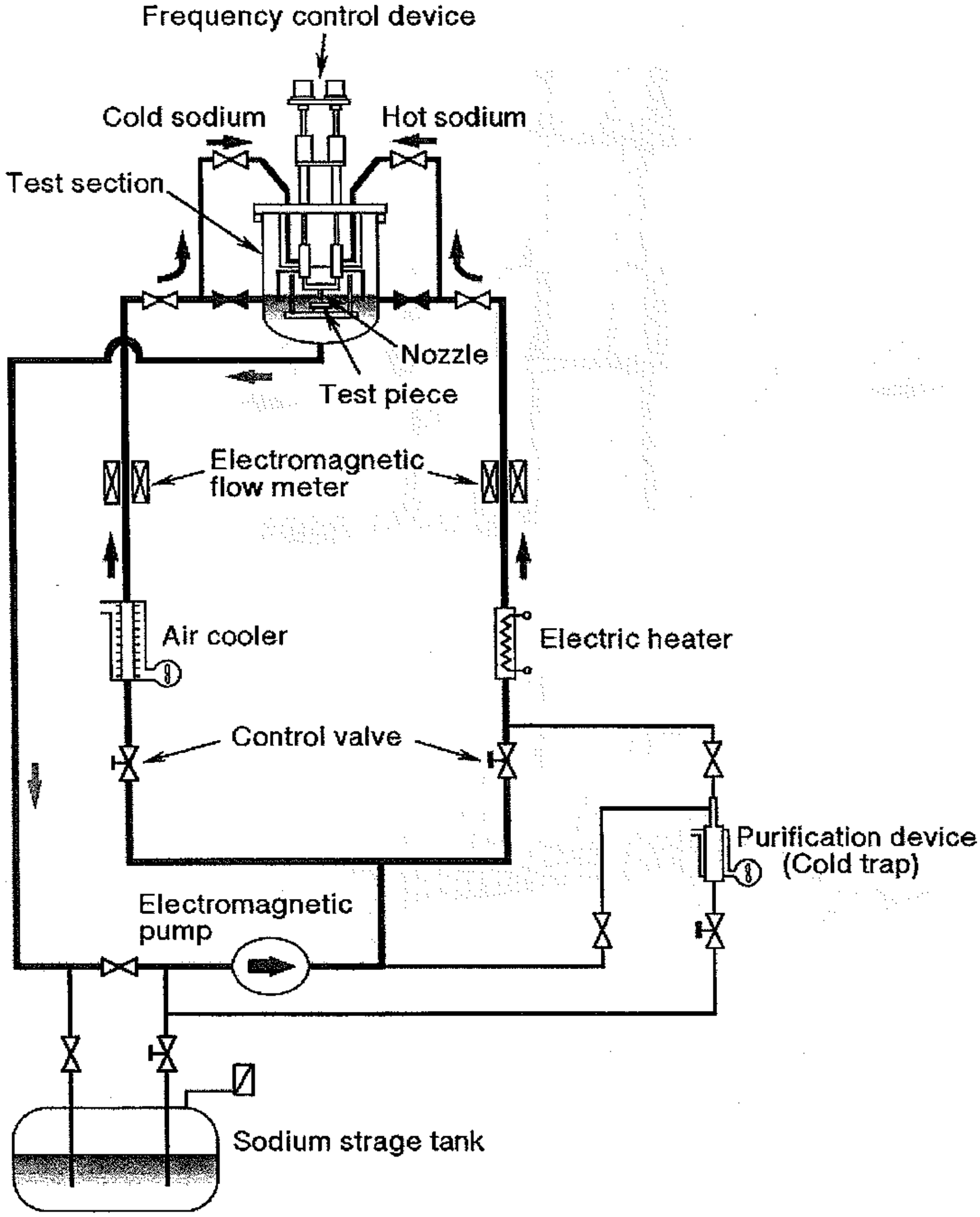


Fig.3.1 Schematic diagram of a TIFFSS sodium loop

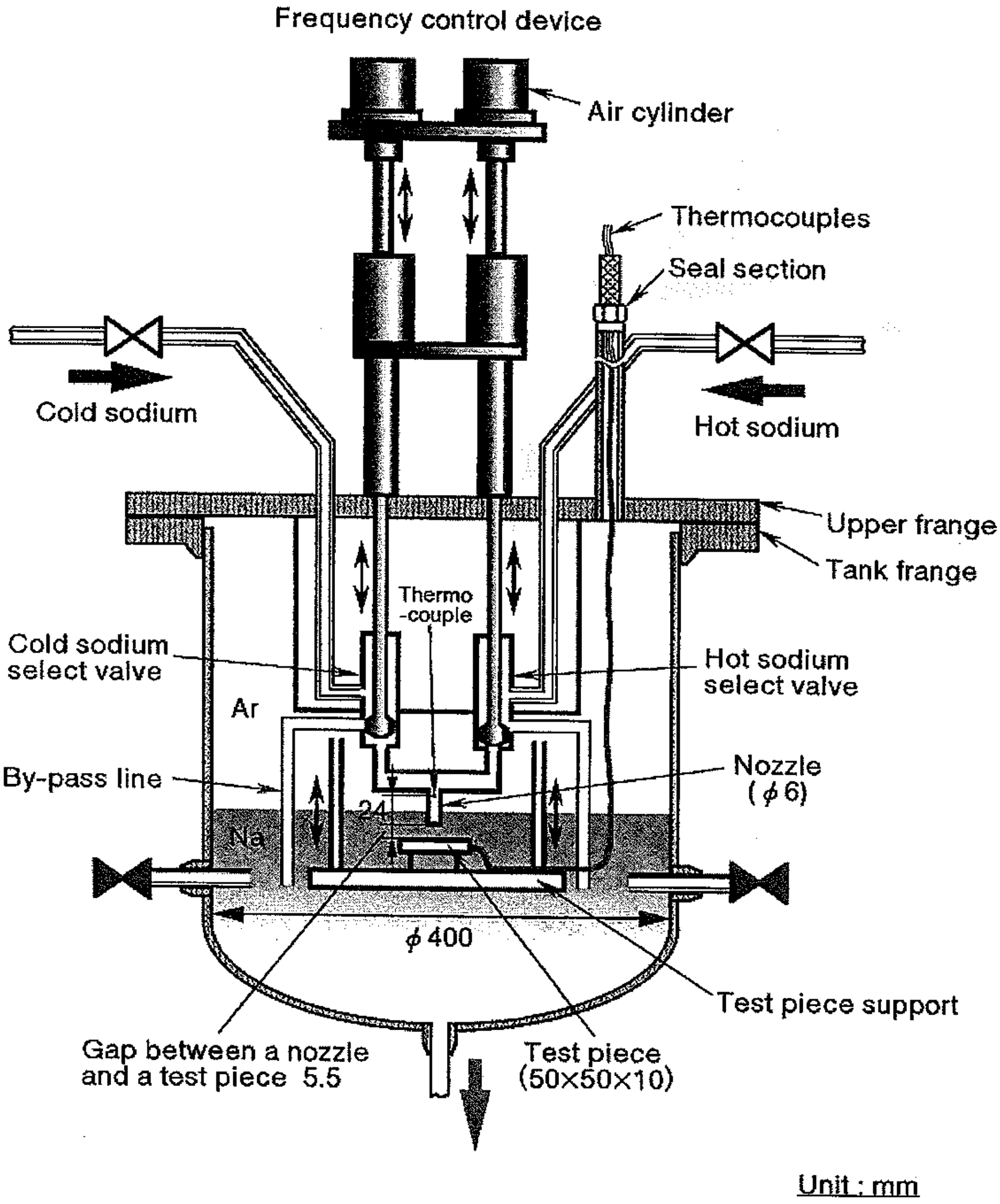


Fig.3.2 Details of TIFFSS test section

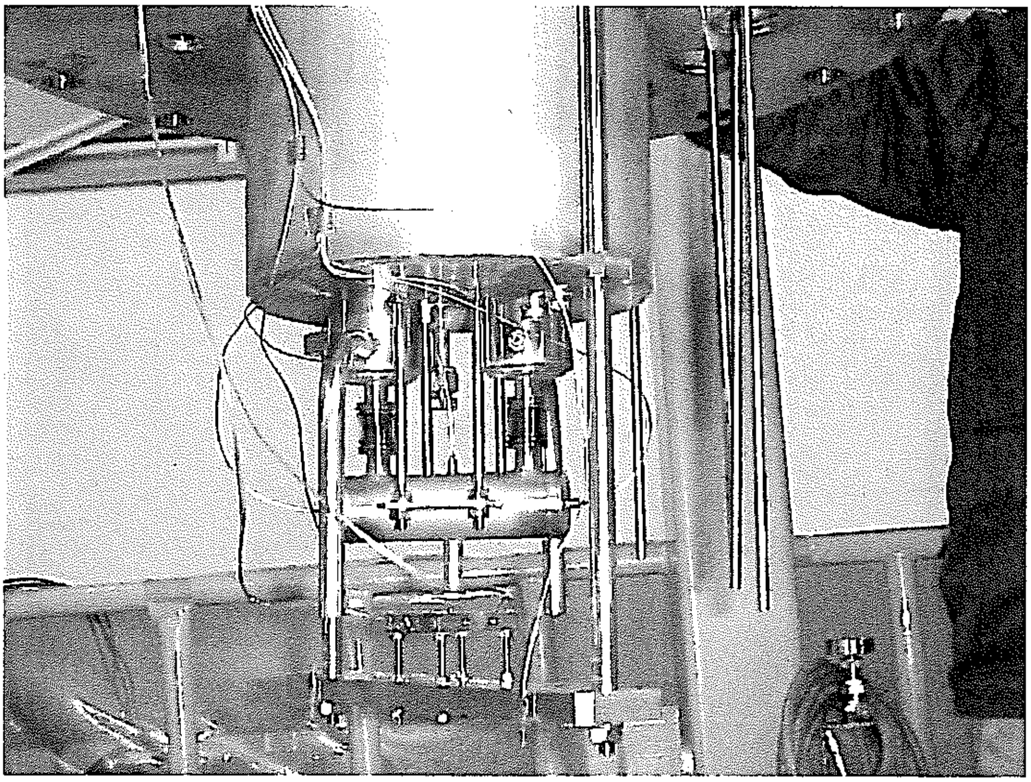


Fig.3.3 Photograph of inside of TIFFSS test section

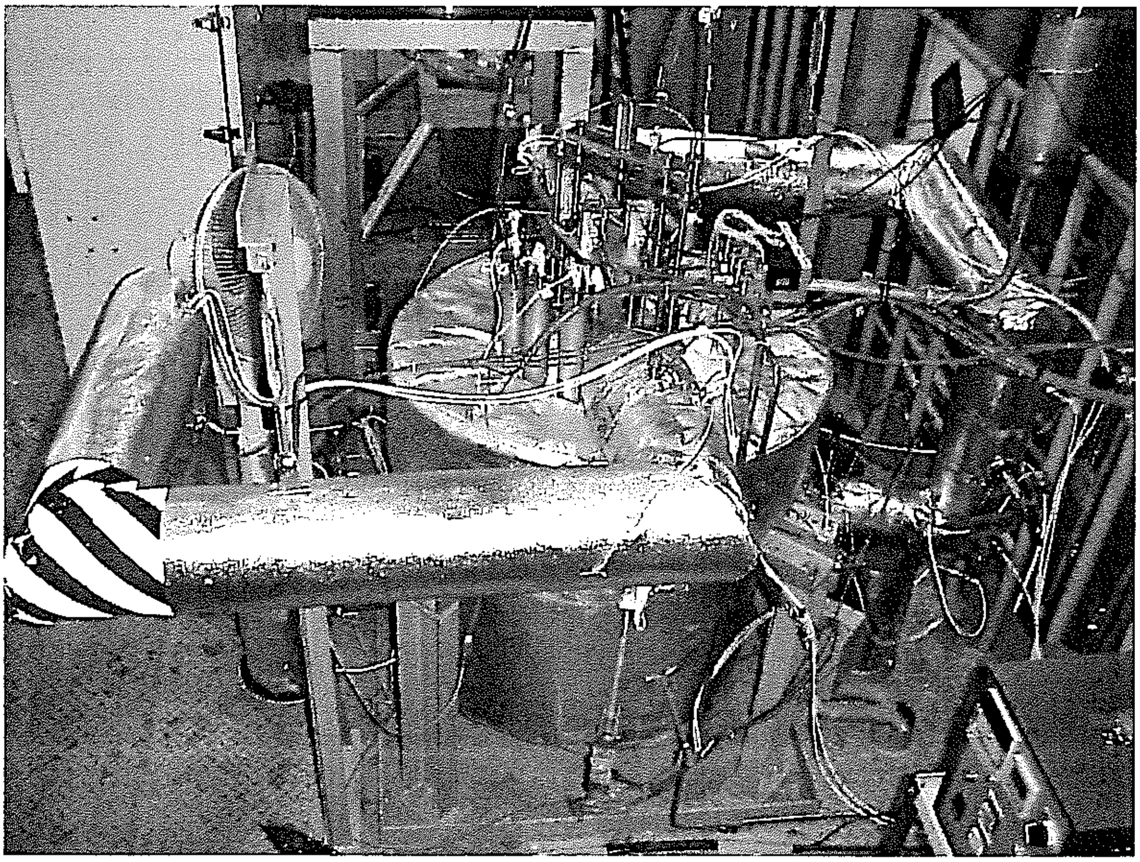


Fig.3.4 Photograph of outside of TIFFSS test section

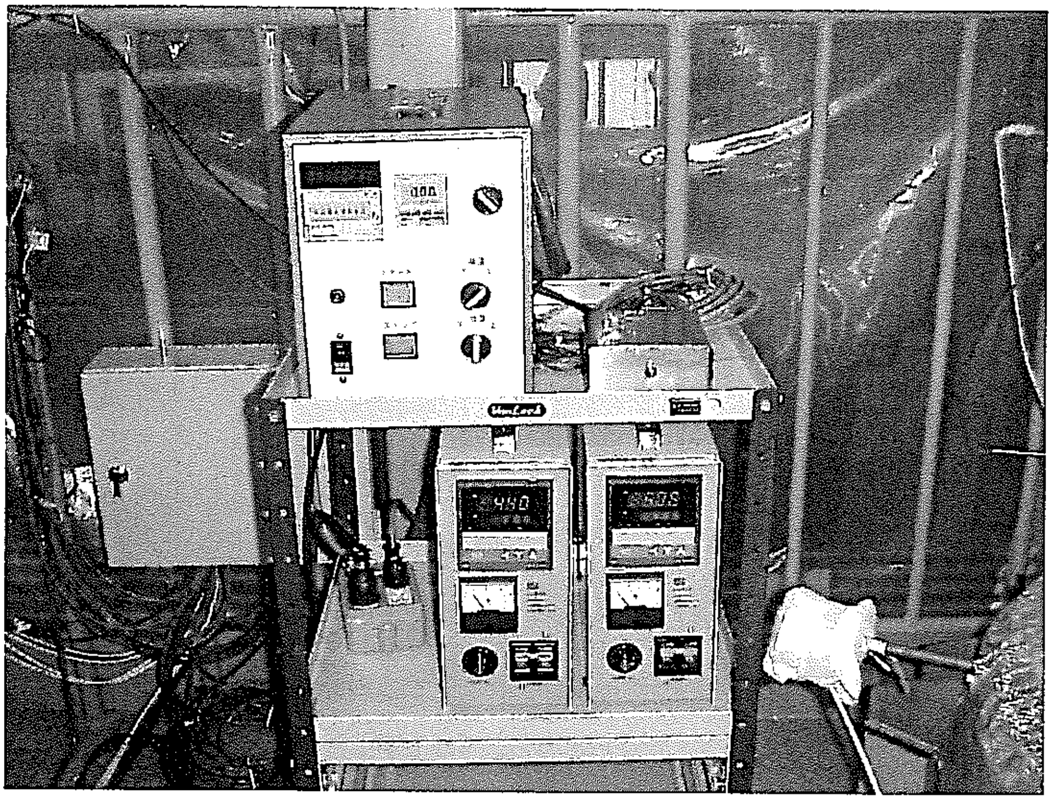


Fig.3.5 Frequency controller and temperature regulators

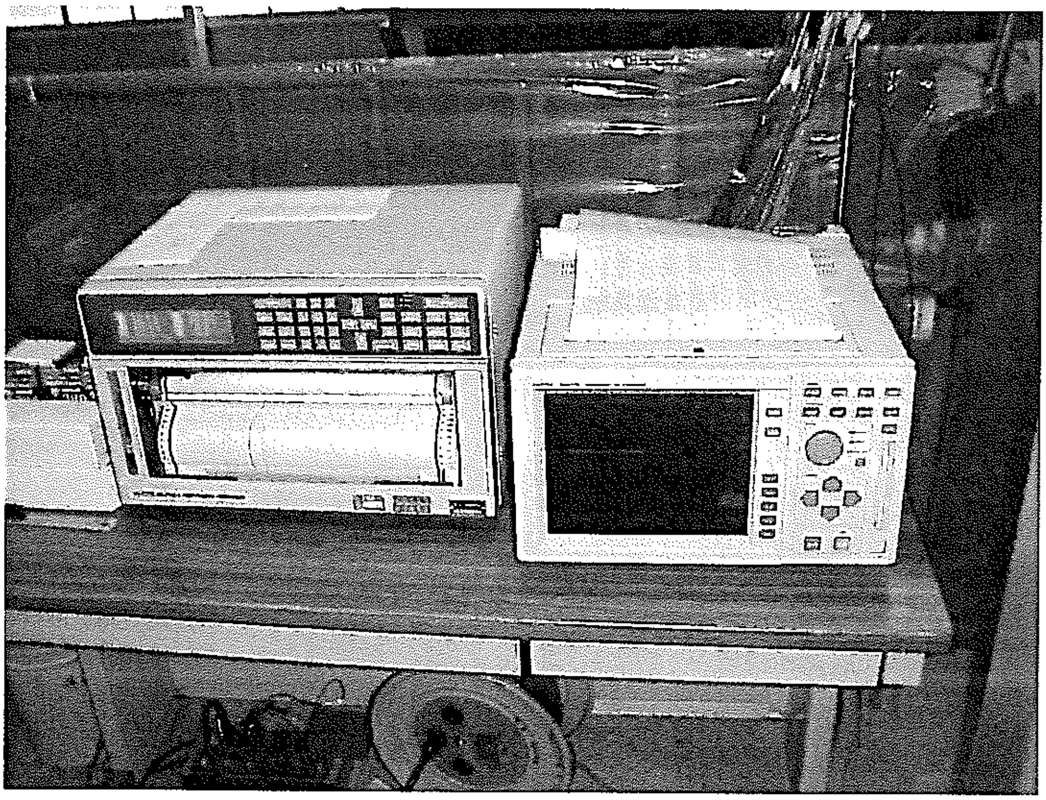


Fig.3.6 Data acquisition system

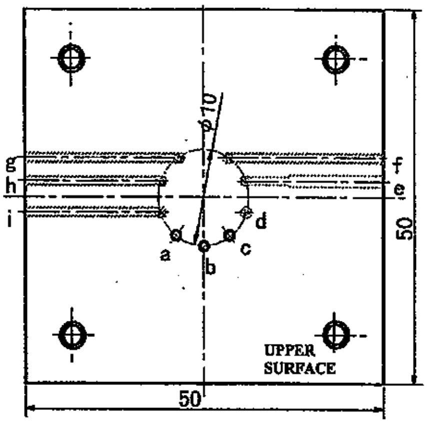
3.2 TIFFSS-3 TEMPERATURE TEST

3.2.1 TIFFSS-3 TEMPERATURE TEST

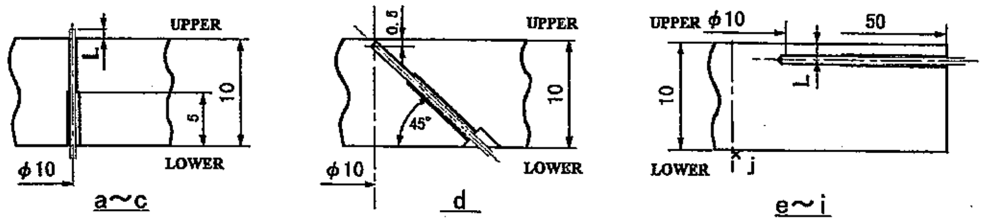
A specimen is a plate (50mm × 50mm × 10^t mm) made of 316FR (Fig.3.7, Fig.3.8). Material properties of 316FR are provided in ANNEXE.

Hot and cold sodium is alternatively projected to the center of a specimen through a single nozzle. Distance between bottom of the nozzle and surface of the specimen is 5.5 mm.

Thermocouples are attached at the position of 1.5mm and 0.1mm from the surface of specimen, and on the surface and the back surface. Furthermore, thermocouples are inserted into the wall at 0.5mm. 1.3mm, 2.3mm, 3.3mm, 5.3mm and 8.3mm from the upper surface (Fig.3.9). Distances of all thermocouples are 5 mm from the center of the specimen in plane. These thermocouples are K-type with 0.5mm diameter, 90% response time of which is 0.05sec. In order to avoid disturbance of vertical heat flow in structures, thermocouples are inserted from the side of specimen.



ch-No.	TC-No.	POSITION	REMARK
1	a	FLUID(1.5mm from upper surface)	
2	b	FLUID(0.1mm from upper surface)	
3	c	On the upper surface	
4	d	STRUCTURE(0.5mm from upper surface)	
~~5~~	~~e~~	~~STRUCTURE(1.3mm from upper surface)~~	failure
6	f	STRUCTURE(2.3mm from upper surface)	
7	g	STRUCTURE(3.3mm from upper surface)	
8	h	STRUCTURE(5.3mm from upper surface)	
9	i	STRUCTURE(8.3mm from upper surface)	
10	j	On the lower surface	
11	TC1	Hot SODIUM	
12	TC7	NOZZLE	
14	TC4	Cold SODIUM	
15	-	Valve signal	



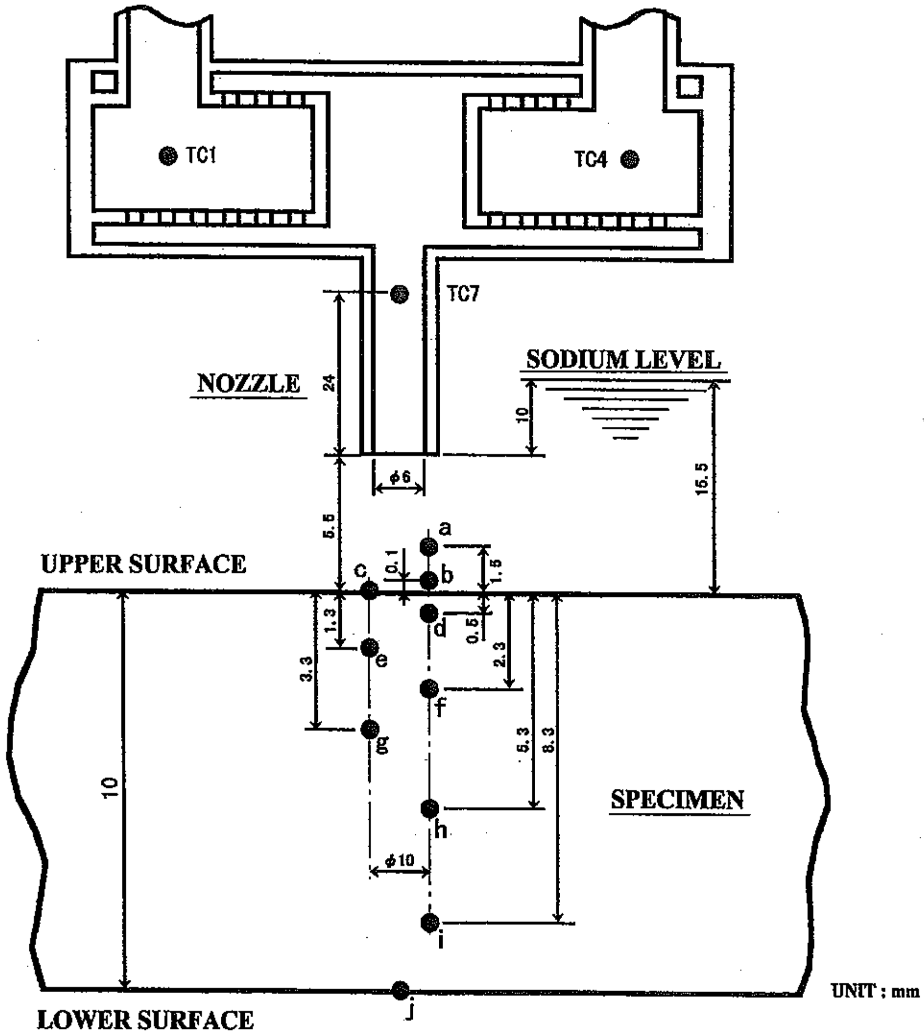


Fig.3.7 Configuration of TIFFSS-3 temperature test specimen with thermocouples

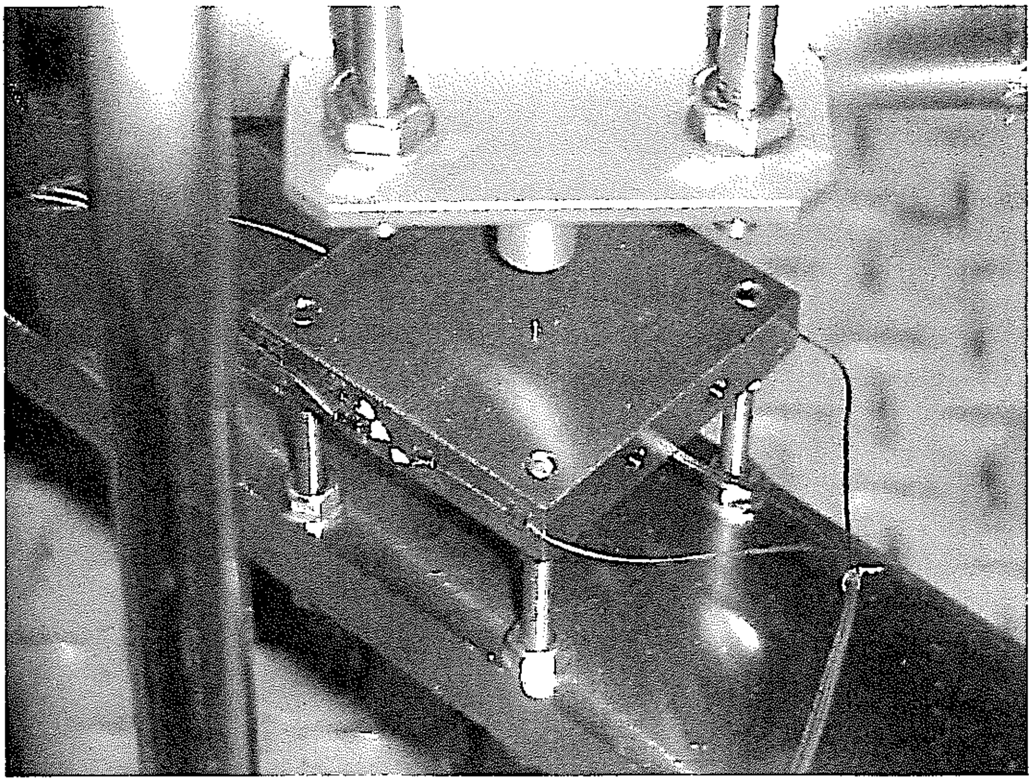


Fig.3.8 Photograph of TIFFSS-3 temperature test specimen

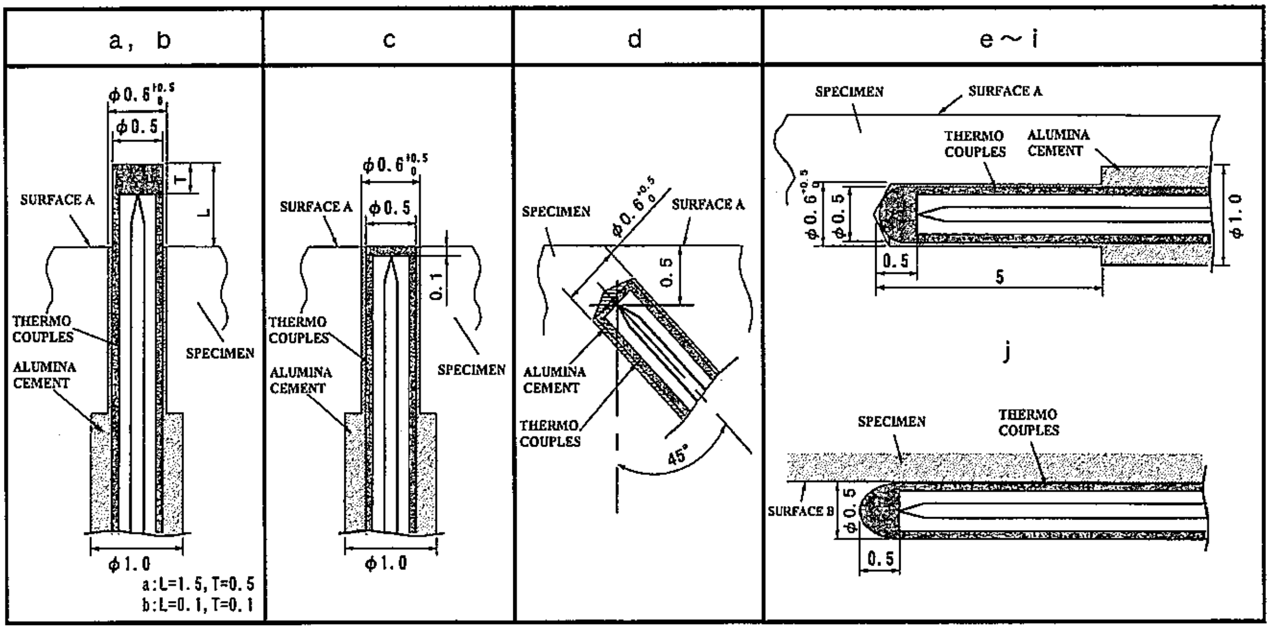


Fig.3.9 Details of thermocouples

3.2.2 THERMAL LOADING AND MEASURED TMEPERATURE

Flow rate at the exit nozzle is constant as 1.2 l/min (approximately 0.7m/s) in the nozzle). This value was adjusted to achieve the maximum temperature amplitude since flow rates are limited by capacity of a cooler and small flow rates are affected by heat capacity of the nozzle. Temperature amplitude at the nozzle keeps the constant value such as 240℃ (470℃ - 230℃). Frequencies of temperature fluctuation are 0.2Hz, 0.1Hz, 0.04Hz, 0.02Hz and 0.01Hz. Sodium is purificated oxygen ratio of which is within 1.0 ppm. Measured temperature histories of sodium at the exit nozzle (TC7) are described in Figs. 3.10(a)-3.10(e).

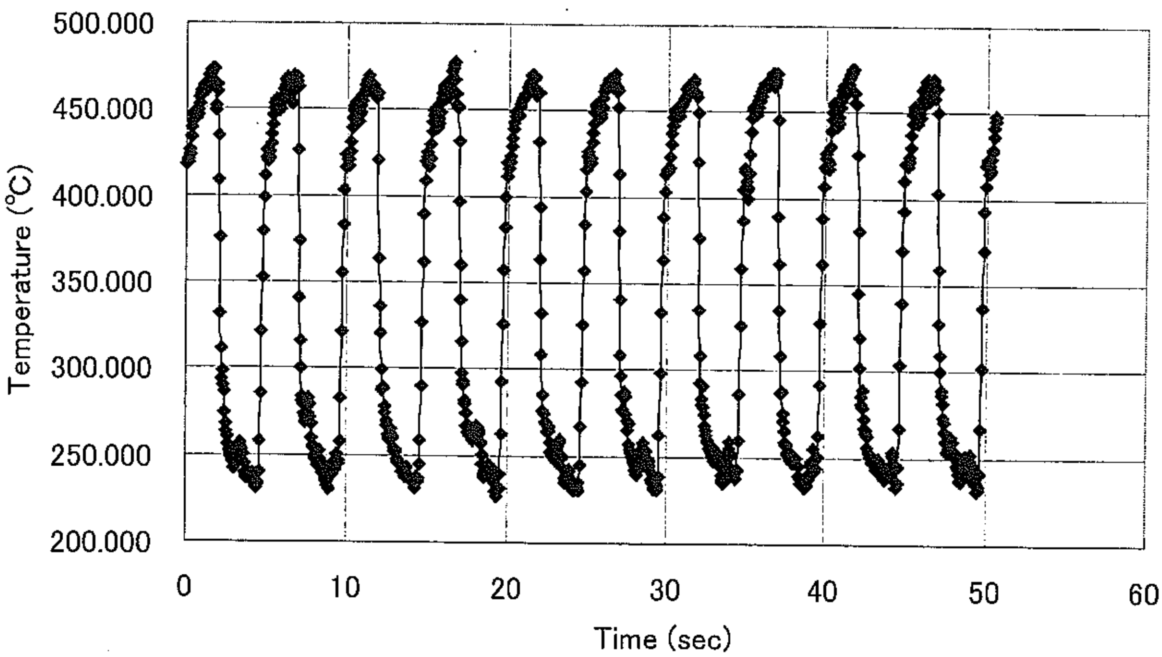


Fig.3.10 (a) Temperature history of sodium at the exit of nozzle (0.2Hz)

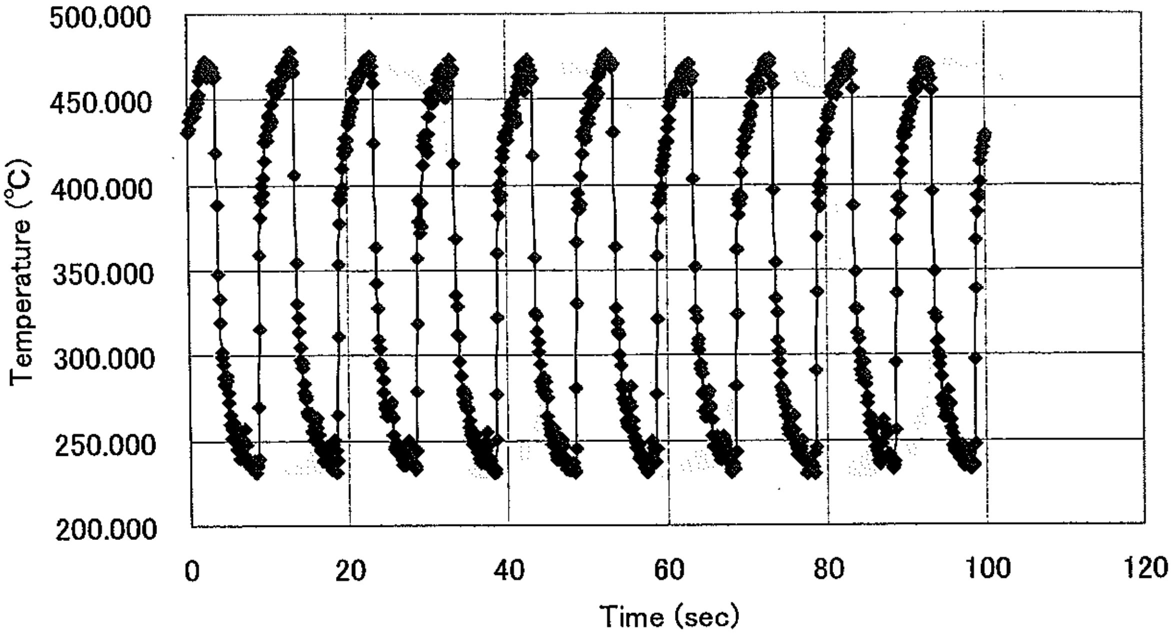


Fig.3.10 (b) Temperature history of sodium at the exit of nozzle (0.1Hz)

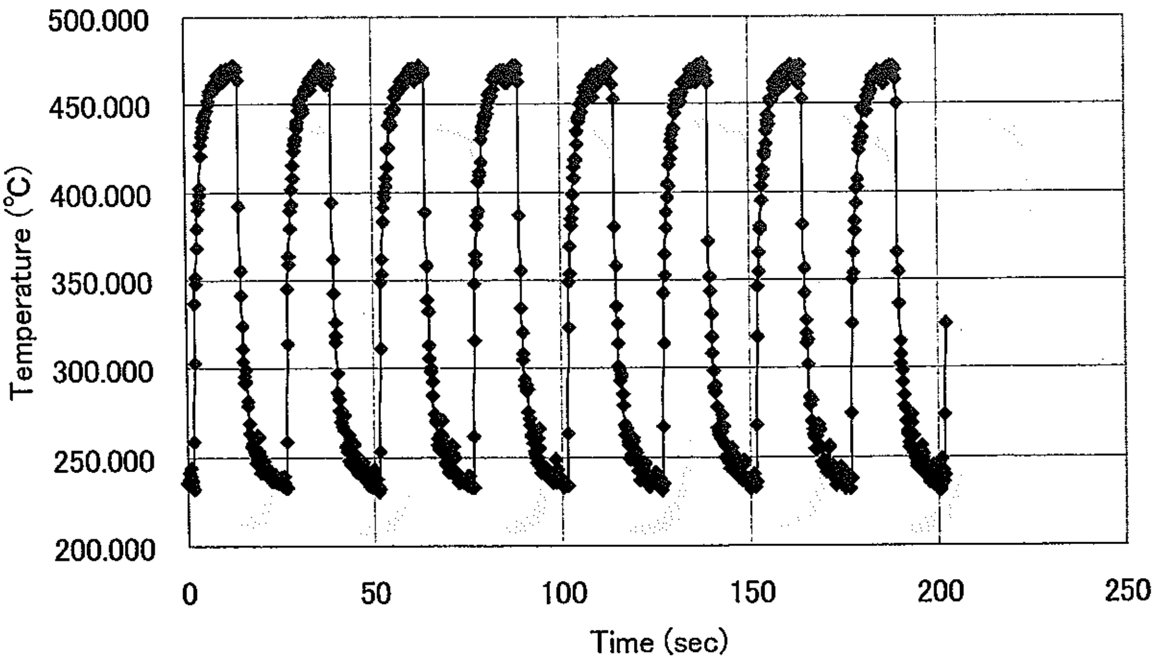


Fig.3.10 (c) Temperature history of sodium at the exit of nozzle (0.04Hz)

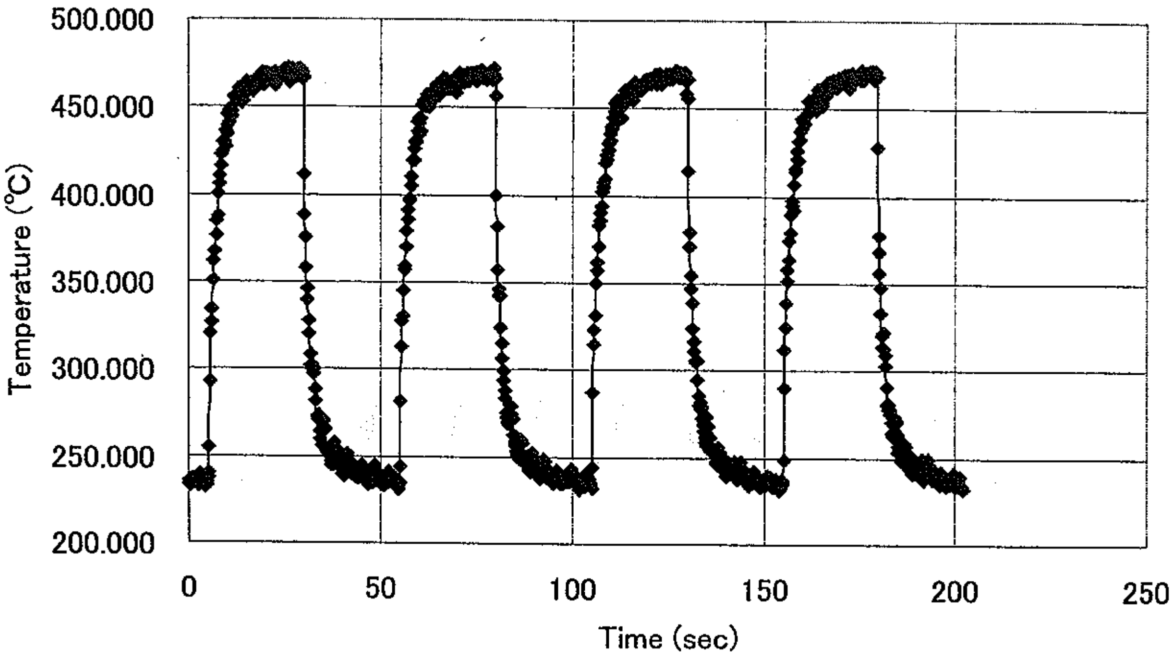


Fig.3.10 (d) Temperature history of sodium at the exit of nozzle (0.02Hz)

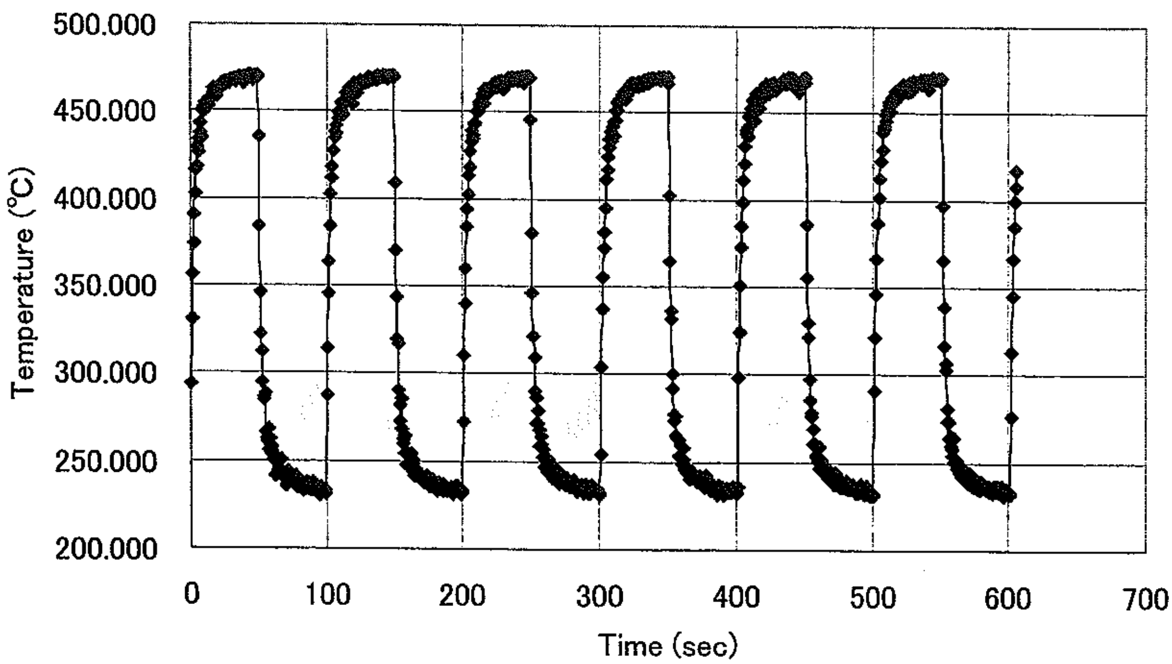


Fig.3.10 (e) Temperature history of sodium at the exit of nozzle (0.01Hz)

Measured temperature amplitudes of all thermocouples at each frequency are summarized in Table 3.1. Fig.3.11 shows measured temperature profiles across wall thickness at the time when temperature on the inner surface is the maximum and the minimum.

Table 3.1 Summary of TIFFSS-3 temperature test results

Frequency	ch-No.(TC-No.)	ch1(a)	ch2(b)	ch3(c)	ch4(d)	ch6(f)	ch7(g)	ch8(h)	ch9(i)	ch10(j)	ch11(TC1)	ch12(TC7)	ch14(TC4)
(Hz)	Position(mm)	high 1.5	high 0.5	surface0	depth 0.5	depth 2.3	depth 3.3	depth 5.3	depth 8.3	depth 10	Hot Na	Nozzle	Cold Na
0.2	Max. Temp.(Ave.)	424.82	425.39	421.70	386.68	376.39	363.58	352.01	348.11	348.91	497.75	471.87	203.67
	Min. Temp.(Ave.)	260.61	262.94	266.94	298.26	306.29	317.29	332.30	342.62	345.39	493.39	231.50	201.19
	Difference(ΔT)	164.21	162.45	154.76	88.42	70.10	46.29	19.71	5.49	3.52	4.36	240.37	2.49
0.1	Max. Temp.(Ave.)	434.48	435.66	433.12	405.04	394.71	380.88	364.34	353.35	351.34	494.51	473.65	207.43
	Min. Temp.(Ave.)	252.20	253.99	257.85	285.16	293.21	304.41	321.96	336.50	340.54	487.68	231.80	202.48
	Difference(ΔT)	182.28	181.67	175.27	119.88	101.50	76.47	42.38	16.85	10.80	6.83	241.85	4.95
0.04	Max. Temp.(Ave.)	446.51	447.78	446.37	427.23	419.22	407.73	390.78	371.25	364.58	482.47	472.15	222.50
	Min. Temp.(Ave.)	247.41	248.82	251.68	271.76	278.03	286.63	303.10	323.07	330.91	469.30	232.20	214.18
	Difference(ΔT)	199.10	198.95	194.69	155.47	141.19	121.09	87.68	48.17	33.66	13.16	239.95	8.32
0.02	Max. Temp.(Ave.)	451.28	452.69	451.42	434.76	427.56	417.17	401.03	378.54	369.85	478.49	471.65	243.13
	Min. Temp.(Ave.)	246.88	247.55	250.68	269.44	276.06	283.48	298.11	319.36	330.05	448.69	231.35	218.31
	Difference(ΔT)	204.40	205.13	200.74	165.33	151.50	133.69	102.92	59.18	39.80	29.80	240.30	24.82
0.01	Max. Temp.(Ave.)	453.70	455.60	454.43	438.51	431.60	421.35	404.95	382.03	372.96	475.80	470.80	274.70
	Min. Temp.(Ave.)	245.74	246.56	249.56	268.64	275.44	282.75	298.09	320.37	331.36	405.15	231.12	222.37
	Difference(ΔT)	207.97	209.05	204.87	169.87	156.16	138.60	106.86	61.66	41.60	70.64	239.68	52.32

high: distance from the upper surface (in fluid) , depth: depth from the upper surface (in structure)

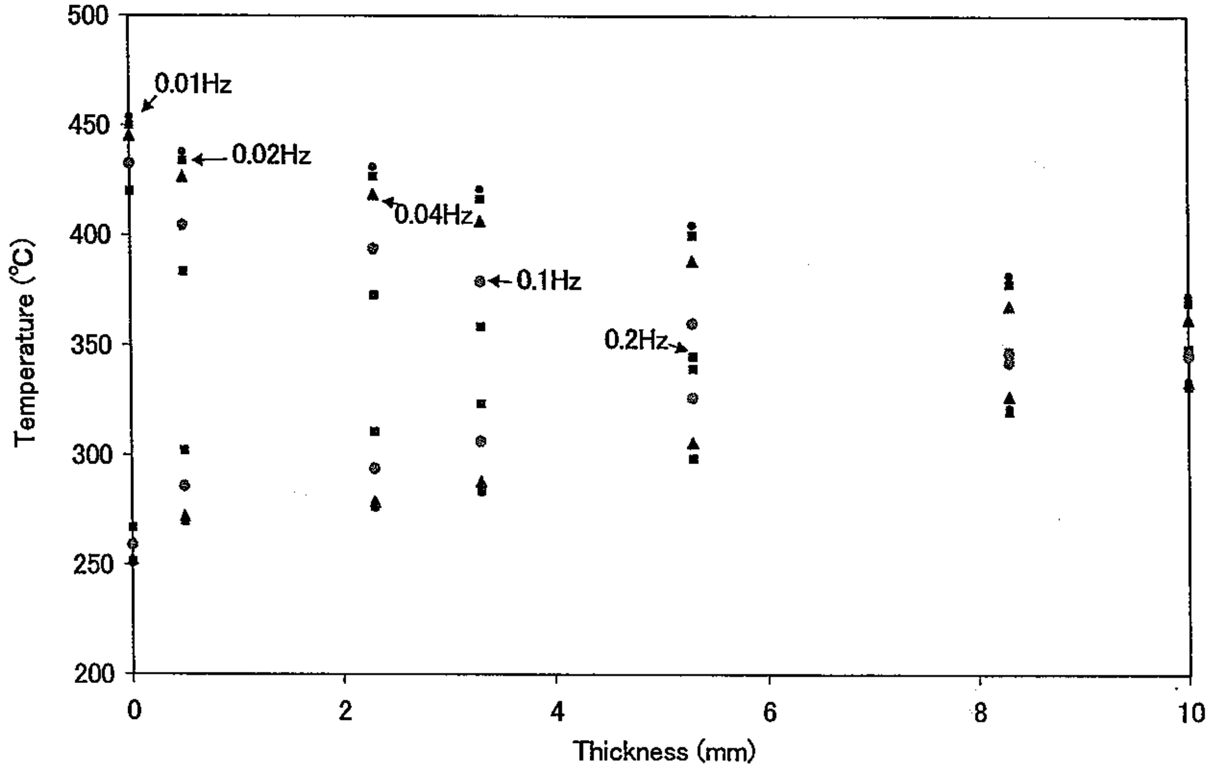


Fig.3.11 Measured temperature profiles at the time when temperature on the inner surface is the maximum and the minimum

3.3 TIFFSS-4 THERMAL FATIGUE TEST

3.3.1 FLEXIBLE PLATE TEST

A specimen is a plane plate (50mm * 50mm * 10t mm) made of 316FR. This specimen was attached to the TIFFSS facility without constraint as in Fig.3.12.

Thermal loads are temperature fluctuation with fixed frequency and amplitude. Such loading conditions as fluid temperature amplitude at the outlet of the nozzle, a flow rate and a distance between a specimen and a nozzle are the same as TIFFSS-3. Temperature fluctuation frequencies were planned as 0.04Hz, 0.1Hz and 0.2Hz.

After 90000cycles of temperature fluctuations with 0.1Hz, the surface of the specimen was inspected. No crack was observed as in Fig.3.13. Considering this result, test cases of 0.04Hz and 0.2Hz were suspended.

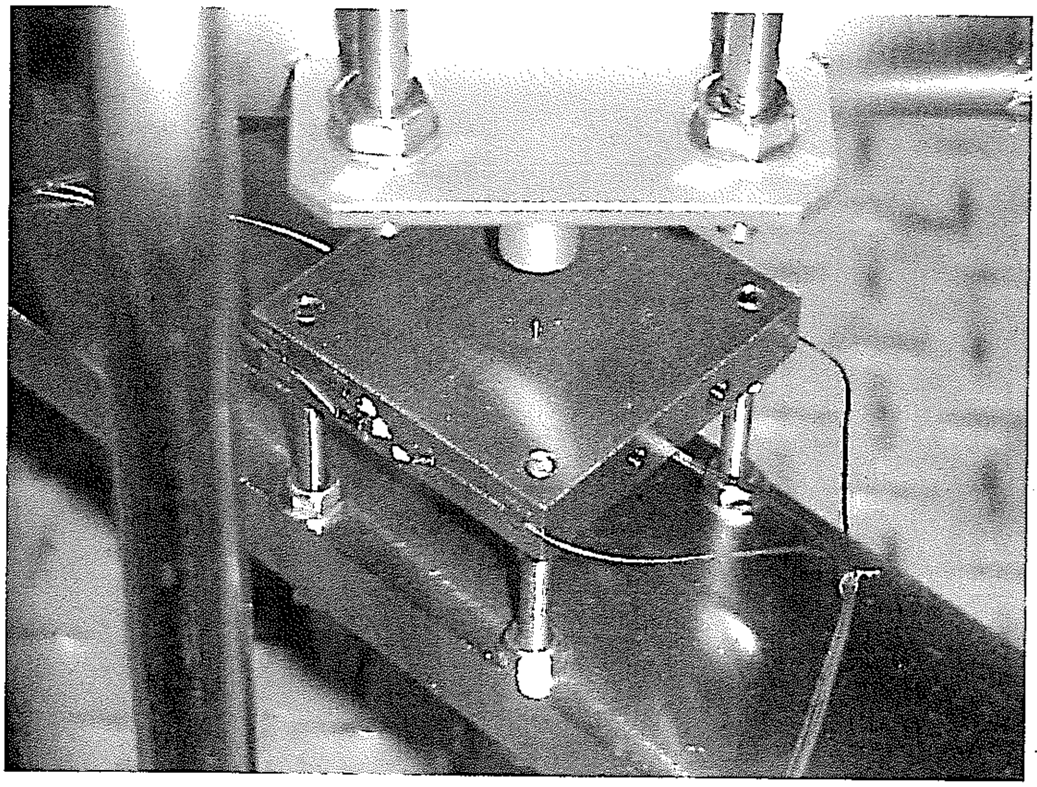


Fig.3.12 Flexible plate specimen for TIFFSS-4 fatigue test

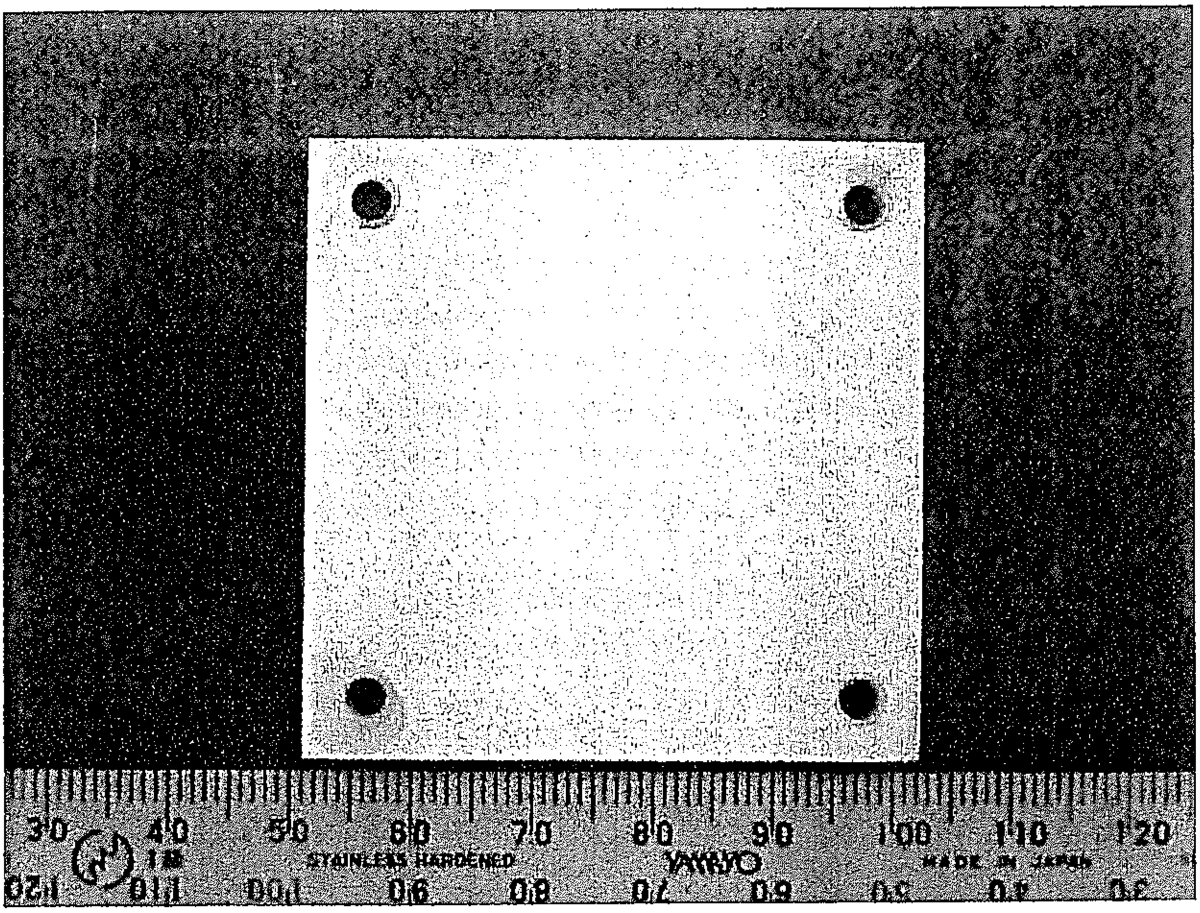


Fig.3.13 Photograph of Flexible plate specimen after thermal loading

3.3.2 CONSTRAINT PLATE TEST

A specimen is a plate (50mm * 50mm * 10t mm) made of 316FR with a thermal insulator. Its insulator is a ceramic plate made of Si_3N_4 with a 15mm diameter hole. A specimen is submitted to temperature fluctuations inside this hole and a surrounded portion keeps almost constant temperature. Configuration of specimen with a thermal insulator is shown as in Fig.3.14.

Fig.3.15 is a photograph of the specimen with thermocouples. A cover plate attached the thermal insulator to the specimen (See Fig.3.16). The constructed specimen was installed to the facility without mechanical constraint as in Fig.3.17.

In order to evaluate thermal boundary conditions, a temperature test was made with a specimen where eighteen thermocouples were attached. Fig.3.14 and Table 3.2 explain positions of thermocouples. Thermocouples for fluid temperature were attached at the location of 1.5mm and 0.1mm from the surface of specimen. Nine thermocouples locate on the surface, distances of which from the center are 0mm, 2.5mm. 5mm, 7.5mm 8.5mm, 10mm, 12.5mm, 15mm and 20mm. Furthermore, seven thermocouples measured temperature distribution in wall thickness with measurement points at 0.5mm, 1.3mm, 2.3mm, 3.3mm, 5.3mm and 8.3mm in depth and the back surface. Distances of all thermocouples in the specimen are 5 mm from the center of the specimen. These thermocouples are K-type with 0.5mm diameter, 90% response time of which is 0.05sec. In order to avoid disturbance of vertical heat flow in structures, thermocouples are inserted from the side of the specimen.

Thermal loads are temperature fluctuation with fixed frequency and amplitude. Such loading conditions as fluid temperature amplitude at the outlet of the nozzle, a flow rate and a distance between a specimen and a nozzle are the same as TIFFSS-3.

Temperature tests were made under frequency conditions of 0Hz, 0.04Hz, 0.1Hz and 0.2Hz. An objective of 0Hz test is evaluation of a heat transfer coefficient and temperatures were measured under a steady condition after sufficient time for stabilization. Both results of high and low temperature injections are summarized in Table 3.3.

Measured temperature under other frequencies will be provided separately. Thermal fatigue strength tests were planned for 5000cycles/0.04Hz, 10000cycles/0.1Hz and 20000cycles/0.2Hz.

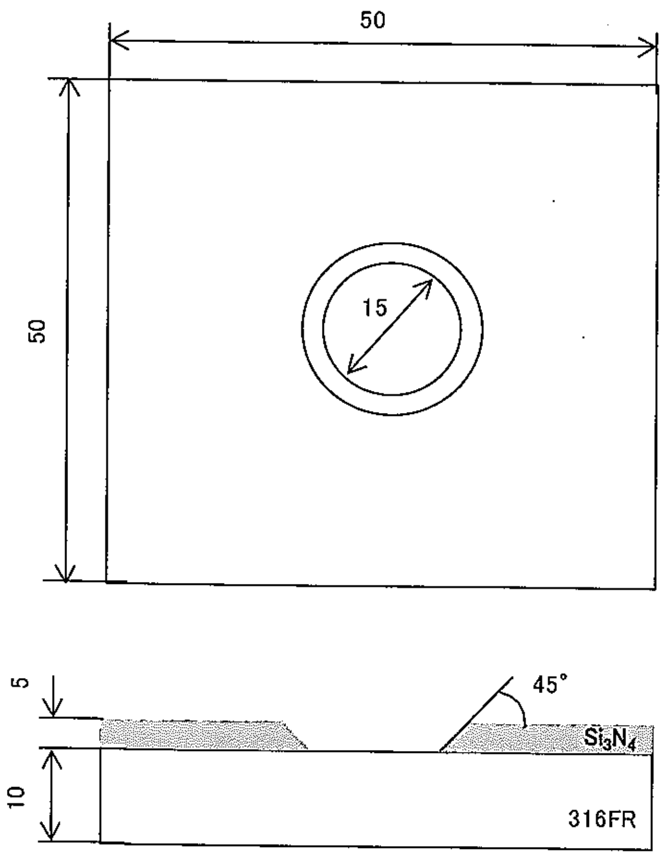


Fig.3.14 Configuration of a constraint plate specimen with thermal insulator for TIFFSS-4 fatigue test

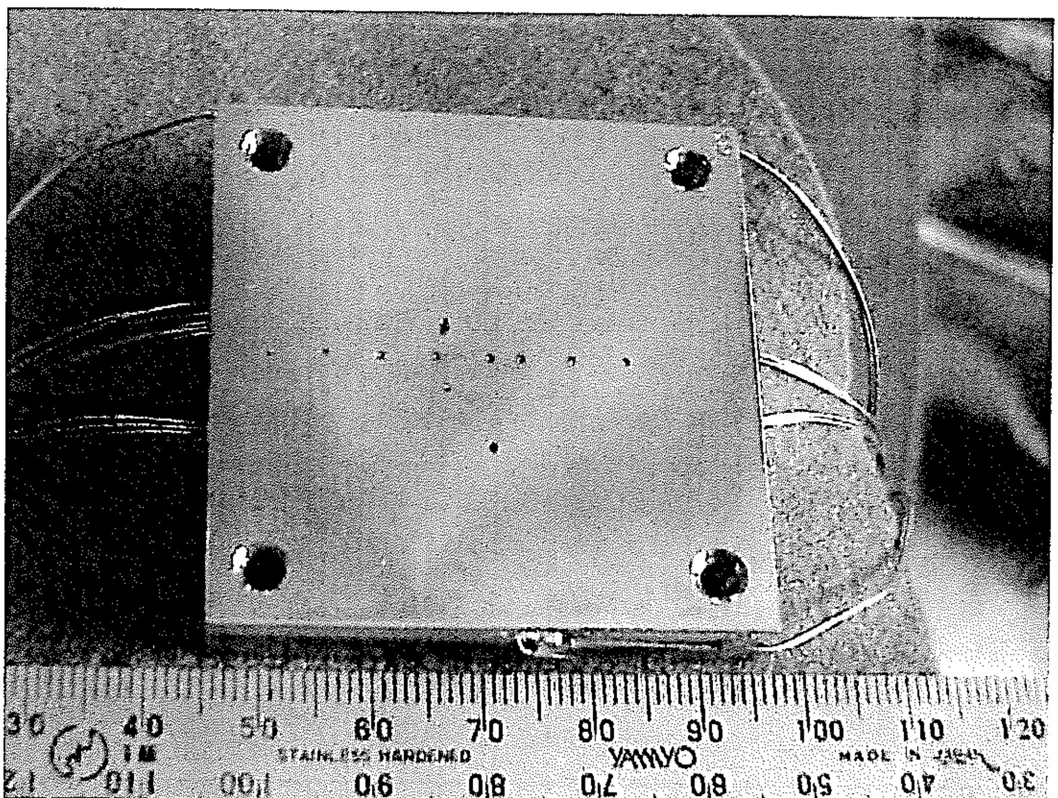


Fig.3.15 Photograph of a constraint plate specimen with thermocouples

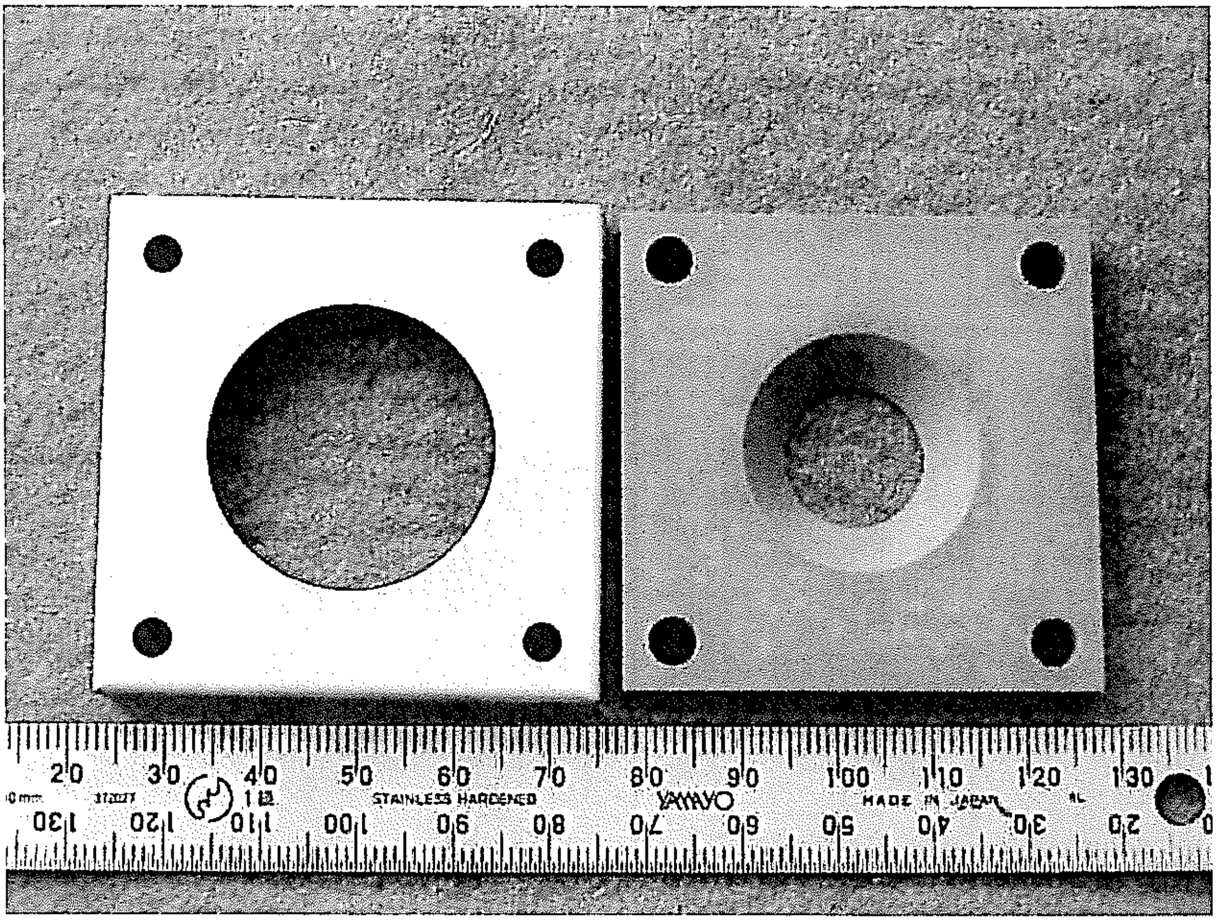


Fig.3.16 Thermal insulator made of Si_3N_4 and support cover

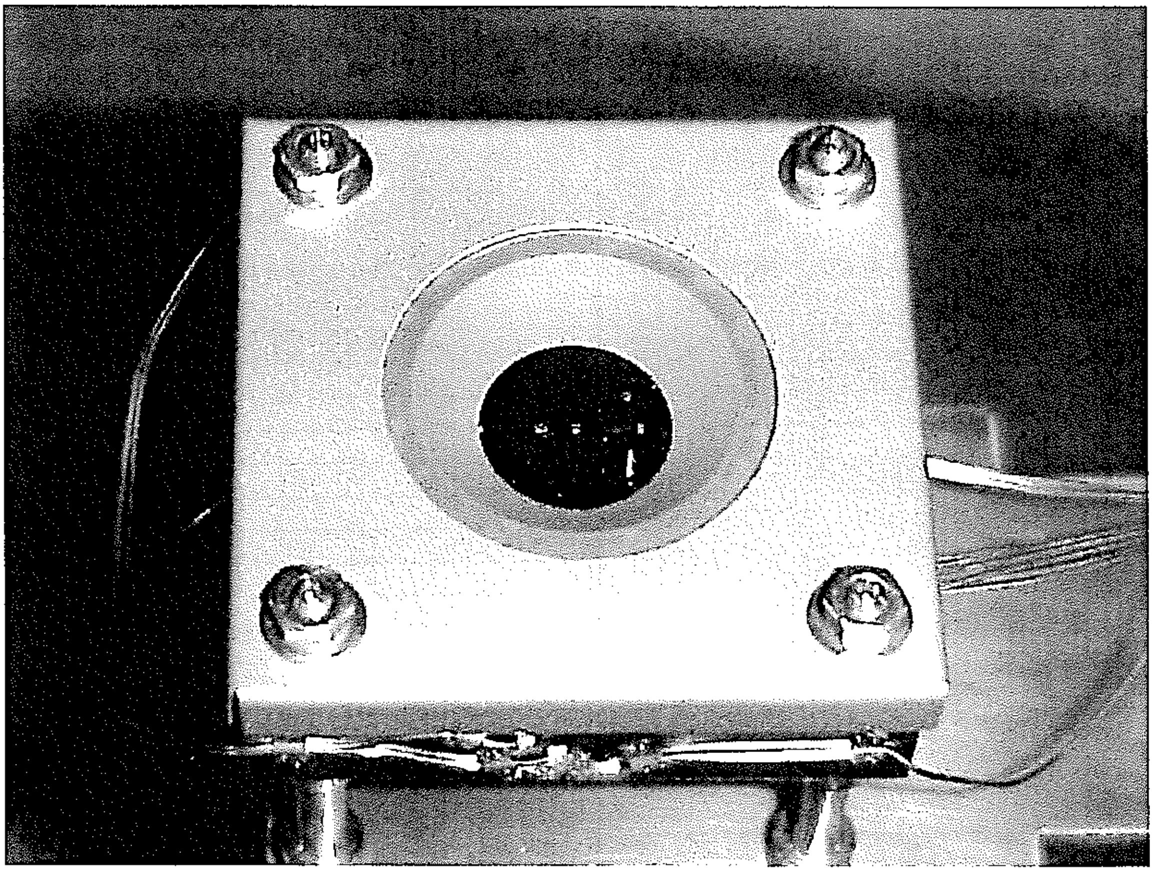


Fig.3.17 Specimen with thermal insulator mounted on TIFFSS facility

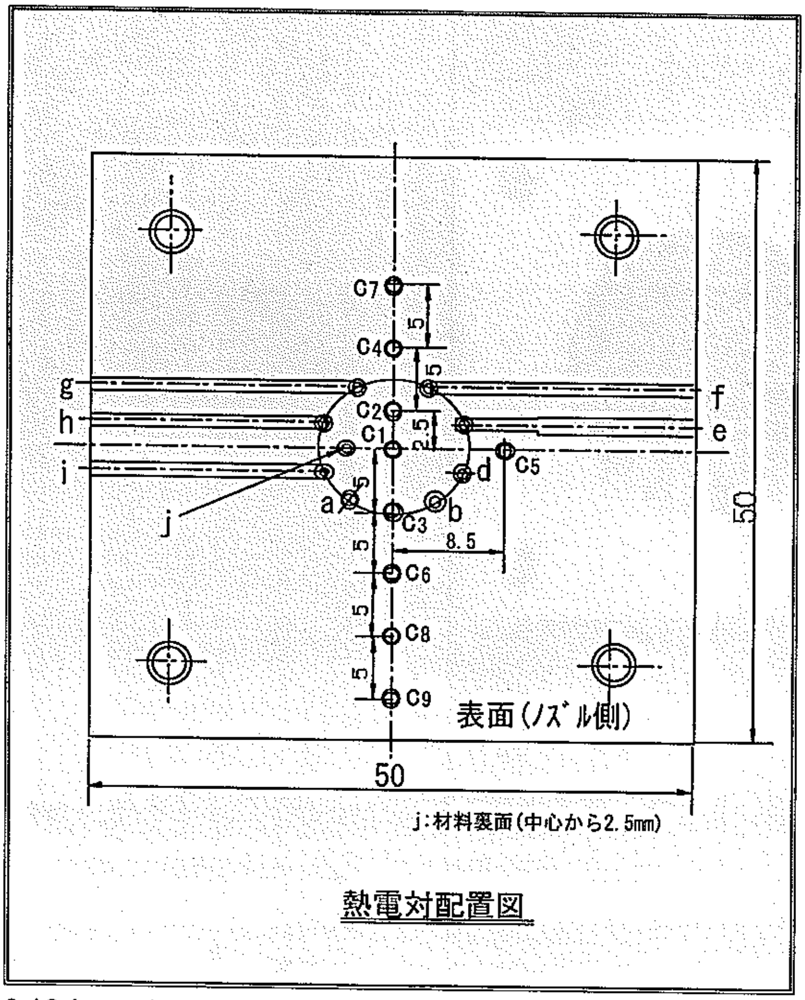


Fig.3.18 Location of thermocouples in the constraint plate specimen

Table 3.2 (a) Thermocouples in fluid and in the specimen

TC No.	Vertical distance from the surface of the specimen
TC7	-5.5mm(Nozzle)
a	-1.5mm (In fluid)
b	-0.5mm (In fluid)
c(See Table (b))	0mm (On the surface specimen)
d	0.5mm (In specimen)
e	1.3mm (In specimen)
f	2.3mm (In specimen)
g	3.3mm (In specimen)
h	5.3mm (In specimen)
I	8.3mm (In specimen)
j	10mm (On the back surface of specimen)

Table 3.2 (b) Thermocouples on the surface of the specimen

TC No.	Horizontal distance from the center of the specimen
c1	0mm (Center)
c2	2.5mm
c3	5mm
c4	7.5mm
c5	8.5mm
c6	10mm
c7	12.5mm
c8	15mm
c9	20mm

Table 3.3 Measured temperature of 0 Hz test

TC	d(mm)	High temperature injection Temp(℃)	Low temperature injection Temp(℃)
TC7(Nozzle)	-5.5	479.27	208.3
a	-1.5	473.56	211.95
b	-0.5	468.05	215.8
c3	0	467.3	218.5
d	0.5	439.74	252.64
e	1.3	448.97	243.31
f	2.3	438.77	253.53
g	3.3	428.74	273.32
h	5.3	407.39	296.4
I	8.3	385.02	318.88
j	10	368.66	329.21

3.4. DEFINITION OF BENCHMARK ON TIFFSS EXPERIMENT

The benchmark problem consists in the evaluation of temperature distribution in the specimen and induced thermal stresses on the surface.

Both European and Japanese participants are expected to make a report with following items for Tiffss sodium experiment.

1. Evaluation procedures of temperature, stress and fatigue damage
2. Temperature attenuation from fluids to structures defined by gains of temperature amplitude from fluids to structural surfaces for each frequency of the TIFFSS-3 experiment
3. Predicted thermal stresses on the surface of the TIFFSS-4 specimen
4. Fatigue damages and number of cycles for crack initiation of the TIFFSS-4 specimen

Test cases of Tiffss experiments are summarized as following tables.

Table 3.4 Case of TIFFSS−3 temperature tests

Specimen	Material	Frequency (Hz)	Fluid temperature range at nozzle (°C)	Flow rate (L/h)
Plane plate	316FR	0.01	240	72
Plane plate	316FR	0.02	240	72
Plane plate	316FR	0.04	240	72
Plane plate	316FR	0.1	240	72
Plane plate	316FR	0.2	240	72

Table 3.5 Case of TIFFSS−4 fatigue tests

Specimen	Material	Frequency (Hz)	Fluid temperature range at nozzle (°C)	Flow rate (L/h)	Cycle numbers N
Plane plate	316FR	0.04	240	72	
Plane plate	316FR	0.1	240	72	9×10^4
Plane plate	316FR	0.2	240	72	
Plate with insulator	316FR	0.04	240	72	5×10^3
Plate with insulator	316FR	0.1	240	72	1×10^4
Plate with insulator	316FR	0.2	240	72	2×10^4

Following material properties of Japanese 316FR are provided in ANNEXE.

- Heat conductivity
- Heat capacity
- Density
- Fatigue Curve
- Monotonic Stress-strain Curve
- Stress Range-Strain Range Relationship

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ANNEXE : Material properties of 316FR

Table A1 Thermal properties of 316FR

Temperature (℃)	Heat conductivity (kcal/mm·sec·℃)	Heat capacity (kcal/kg·℃)	Density (kg/mm^3)
20	3.48×10^{-6}	0.108	7.97×10^{-6}
50	3.53	0.112	7.96
100	3.73	0.118	7.94
150	3.89	0.122	7.92
200	4.05	0.125	7.89
250	4.21	0.128	7.87
300	4.37	0.129	7.85
350	4.53	0.131	7.83
400	4.70	0.132	7.80
450	4.86	0.133	7.78
500	5.02	0.134	7.76
550	5.18	0.136	7.74
600	5.34	0.138	7.72
650	5.51	0.140	7.69
700	5.67	0.142	7.67
750	5.83	0.145	7.65
800	5.98	0.147	7.63

Table A2 Average fatigue strength of 316FR

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

Unit

T : *Temperature* (℃)

$\dot{\varepsilon}$: *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 $R = \log_{10}\dot{\varepsilon}$

Table A3 Stress range – strain range relationship of 316FR

• $\Delta\sigma/2 > \sigma_p$

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

• $\Delta\sigma/2 \leq \sigma_p$

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

Unit

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

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

E : *Elastic Modulus* (kg/mm²)

σ_p : Pr*oportiol Limt*(*kg* / *mm*²)

$\Delta\sigma$: *Stress Range* (kg/mm²)

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	$26.8073 - 5.04547 \times 10^{-2} \times T + 8.03901 \times 10^{-5} \times T^2 - 5.11282 \times 10^{-8} \times T^3$ $-(40.0909 - 9.69990 \times 10^{-3} \times T) \times (0.002)^{0.326245 + 6.13276 \times 10^{-5} \times T}$

Table A4 Monotonic stress – strain relationship of 316FR

(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 (℃)	$315 \le T \le 650$
$E(kg/mm^2)$	$315 \le T < 400$ $E = 2.040\times10^4 - 8.000T$ $400 \le T \le 650$ $E = 2.126\times10^4 - 10.125T$
$\sigma_p(kg/mm^2)$	$\sigma_y - K(0.002)^m$
$\sigma_y(kg/mm^2)$	$26.8073 - 5.04547\times10^{-2}T + 8.03901\times10^{-5}T^2 - 5.11282\times10^{-8}T^3$
$K(kg/mm^2)$	$40.0909 - 9.69990 \times 10^{-3}T$
m	$0.326245 + 6.13276\times10^{-5}T$