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Thermal Cycle Test of Elemental Mockups of ITER Breeding Blanket

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Thermal cycle tests for mockups of breeder pebble beds of ITER breeding blanket have been carried out to investigate their thermo-mechanical behavior with the interaction between a pebble bed and a breeder rod containing the breeder pebbles.

The mockups have been designed to demonstrate a part of the "Breeder Inside Tube (BIT)" structure of ITER breeding blanket. Candidate material pebbles of Li_2TiO_3 was applied as breeder specimen, and Al pebbles were applied for simulating the neutron multiplier of Be pebbles. These pebbles have been packed in test tubes by using a vibration machine. Tested configurations were single layer mockups with Li_2TiO_3 single diameter packing and binary packing beds, and double layer mockups with Li_2TiO_3 / Al single diameter packing and binary packing beds. In order to clarify the deformation performance of breeder tube, two different thickness of the breeder rod were also tested: one for nominal condition and another for acceleration test. Pebble bed of Li_2TiO_3 is heated with an electric heater, which is equipped at the center of the breeder rod, simulating the temperature profile by volumetric heating of breeder pebbles. The outside of a breeder rod in a single layer mockup and the outside of the outer tube in case of double layer mockup is cooled by water. Temperature of the breeder beds has been controlled by a power input of the heater. After the thermal cycle tests, the internal dimensions and local packing fraction of mockups have been examined by using an X-ray CT device.

As the result, no significant change of packing fraction was observed after five thermal cycles with maximum heater temperature of 600 °C. Any bulging of the breeder rod or any cracking of the pebble has not been observed. A soundness of the typical structure and breeder pebble bed of ITER breeding blanket against thermal cycles was confirmed.

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Keywords: ITER Breeding Blanket, Pebble Bed, Li_2TiO_3, Thermo-mechanical Interaction, Thermal Cycles, X-ray CT Device, Packing Fraction

ＩＴＥＲ増殖ブランケットの要素モックアップの熱サイクル試験

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ＩＴＥＲ増殖ブランケットにおいて熱サイクルで誘起されるペブル充填層と増殖管との熱機械的相互作用を評価するため、模擬試験体を製作し熱サイクル試験を実施した。

ペブル充填層の熱挙動は、ペブル間ですべりを生じる等の粒子充填層での複雑な機械挙動により、解析で予測するのは困難である。そのため、実機 ITER の BIT(Breeder Inside Tube)設計を模擬した試験体を設計し、熱サイクルによる構造健全性を実証した。増殖材として Li_2TiO_3 ペブルを増殖管に充填し、中性子増倍材である Be の模擬材として Al ペブルを用いた。これらのペブルを試験体に充填する際は、加振機で振動しつつ充填した。シングルとバイナリの Li_2TiO_3 ペブルを用いた増殖管のみの単層試験とシングルとバイナリの Li_2TiO_3/Al ペブルを用いた二層試験を実施した。増殖管の肉厚としては、2 種類用いた。ひとつは実機の寸法を模擬したもので、他方は肉厚が薄く、変形の効果を顕著に観測するための加速試験用である。加熱試験では、増殖管の中心に配したヒータにて、増殖材 Li_2TiO_3 を加熱した。単層試験では増殖管の外側を、二層試験では外管の外側を水で冷却した。増殖材の温度はヒータの出力で制御した。昇温、降温を繰り返す熱サイクル試験の後、X 線-CT 装置を用いて試験体の断層寸法を観察した。

試験の結果、ヒータの最高温度 600℃で 5 回の熱サイクル試験後においても充填率の顕著な変化は観察されなかった。また、管の膨れやペブルの割れも観察されなかった。以上の結果から、増殖管と増殖ペブル充填層の熱サイクルに対する機械的健全性を確認した。

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1. Introduction

Thermal cycle tests for mockups of ITER breeding blanket have been carried out to demonstrate the soundness of packing of breeder and multiplier pebbles from the aspect of thermo-mechanical behavior with the interaction between a pebble bed and the breeder rod containing the breeder pebbles. ITER breeding blanket design is based on the concept of "Breeder Inside Tube (BIT)" blanket, as shown in Fig.1-1 [1]. Since the operation of ITER is pulse operation, the breeder and multiplier pebble beds are to be heated repeatedly. The difference of thermal expansion rate of pebbles and container material may cause the stress or space between pebbles and container. If pebbles are fully packed close to theoretical packing fraction of 74% in a perfect tetrahedral geometry of single size pebble and are assumed to be induced about 0.1% thermal strain in a rigid rod, the thermal stress in the pebble bed would be greater than the rupture strength of pebble material itself. In an actual pebble bed with packing fraction of around 60 to 65%, pebbles have compliance or ability to move to accommodate volume changes to some extent. However, it is difficult to predict the behavior of pebble bed by analyses, especially a local behavior of pebbles, because of lack of database and analysis model development of thermo-mechanical behavior of pebble bed in a container. From such view points, mockups were manufactured in order to demonstrate a part of the ITER BIT blanket, and subjected to thermal cycle tests.

Breeding material of Li_2TiO_3 was packed as a pebble bed in a breeder rod, and Al pebbles are used to simulate neutron multiplier Be. Pebbles are packed in the mockups by using a vibration machine. The tested mockups are single layer mockups with Li_2TiO_3 single and binary packing beds, and double layer mockups with Li_2TiO_3 / Al single and binary packing beds. Two different thickness of the breeder rod wall have been tested: one for nominal condition and another for enhancement test to identify the effect of the thermal expansion stress of pebbles to the wall. Li_2TiO_3 pebble bed was heated with an electric heater, which is equipped at the center of the breeder rod. In case of single layer mockup, outer surface of the breeder rod was cooled by ambient temperature water. In case of double layer mockup, outer surface of the outer tube was cooled by ambient temperature water. The temperature of the breeder is controlled by the thermocouple at the middle point of the heater to 600 °C by the power of the heater. The set condition of the breeder temperature (600 °C) was derived to induce the thermal strain of about 0.3%. After the thermal cycle tests, the test mockups were observed by X-ray CT (Computerized Tomography) scanning technique to clarify the following critical issues of the pebble bed:

1) Change or localization of the packing fraction or a fragmentation of the pebble bed
2) Failure (bulging or a buckling) of the breeder rod or outer tube
3) Thermal ratcheting effect in the pebble bed and progressive incremental inelastic deformation of the breeder rod.

2. Test Mockups

In order to investigate the region around one breeder in the ITER BIT blanket, two types of test mockups have been prepared. One is single layer mockups, which have simple geometry of the breeder rod and aims at the demonstration of the mechanical interaction between the breeder pebble bed and the breeder rod, by elimination of the outer pebble bed which simulates the neutron multiplier bed. The other mockup is a double layer mockup, which includes the outer pebble bed of Al in the outside of the breeder rod. This test was performed to investigate the effect of the outer pebble bed on the deformation of the breeder rod. The photographs of appearance of the test mockup with vibration machine are shown in Fig. 2-1.

2.1 Test Mockup for Single Layer Test

A layout of the mockup for single layer test is schematically shown in Fig. 2-2. The single layer test was planned to demonstrate thermo-mechanical interaction between the breeder pebbles and the breeder rod. Li_2TiO_3 pebbles were packed in the breeder rod by using a vibration machine. Li_2TiO_3 pebble bed was heated with the electric heater, which is equipped at the center of the breeder rod. The outer surface of the breeder rod was cooled by ambient temperature water. The temperature of the heater was controlled by a thermo-couple equipped on the sheath of the heater at the center of the breeder rod. Strain gages were attached on the outer surface of the breeder rod in order to measure strains of the breeder rod. For the enhancement of thermal stress effect by pebble bed such as bulging of the breeder rod, a rod with thickness of 0.2 mm was tested as well as the nominal rod with thickness of 1.0 mm.

Test parameters are shown in Table 2-1. The single layer test was carried out to investigate the soundness of Li_2TiO_3 pebble bed and the breeder rod, on which cyclic thermal strains were loaded. Two kinds of thickness of the breeder rods made of SS316L was selected. The breeder rod with thickness of 1.0 mm is for nominal case and the other has the reduced thickness of 0.2 mm for an enhancement test, which clarify the effect of expanding force caused by the thermal expansion of Li_2TiO_3 pebble bed. The temperature of heater was controlled at 400 °C for the nominal case and at 600 °C as the accelerating test condition. The temperature of 400 °C for the nominal case was selected in order to simulate the same thermal strain of the pebble bed as ITER condition shown in section 4.3. X-ray CT images of the mockups were recorded before and after thermal cycle test in order to evaluate dimension of the breeder rod and packing density distribution in the breeder pebble bed, which represents effects of the thermo-mechanical interaction on the pebble bed and the breeder rod. The effect of vibration on the change of the packing fraction was also tested. The mockups were vibrated at a frequency of 30 Hz and amplitude of 1 mm for 5 minutes during each cooling period. The characteristics of the utilized vibration machine are known in elsewhere [2]. Single layer mockups packed with Li_2TiO_3 single size pebble (2mmϕ) and binary packing bed of 2mmϕ and 0.3mmϕ were tested.

2.2 Test Mockup for Double Layer Test

The schematic structure of the test mockup for double layer test is shown in Fig. 2-3. The test mockup for double layer test consists of two pebble bed layers, which are a breeding material layer and a neutron multiplier one. Li_2TiO_3 pebbles were packed in the breeder rod as the breeding material, and Al pebbles are used for simulating the neutron multiplier Be. Li_2TiO_3 pebble bed was heated with an electric heater, which is equipped at the center of breeder rod. The outer surface of the outer tube, which was filled with Al pebble, was cooled by ambient temperature water. The temperature of the heater was controlled by a thermo-couple equipped on the sheath of the heater at the center of the breeder rod. Strain gages were attached on the outer surface of the breeder rod in order to measure strains of the breeder rod.

Test parameters are shown in Table 2-1. The objective of the double layer test is to observe the effect of the neutron multiplier pebbles packed around the breeder rod. The breeder rod (1.0 mm thickness) was made of SS316L. The thickness of the outer tube was 3 mm. The temperature of heater is controlled at 500 °C to simulate the same thermal strain of the pebble bed as ITER condition shown in section 4.4. X-ray CT images of the mockups were recorded before and after thermal cycle test to evaluate the effects of the thermo-mechanical interaction on the pebble bed and the breeder rod.

2.3 Pebble Specification

Specifications of pebbles used for the thermal cycle tests are shown in Table 2-2. Photographs of the appearance of Li_2TiO_3 of 2mm and 0.3mm diameter are shown in Fig. 2-4 (a) and (b), respectively.

3 Test Procedure

The test procedure is shown in Fig. 3-1. Pebbles were packed in the breeder rod by using a vibration machine. A method applied to pack binary pebble in the rod is as follows: first, pebbles of 2 mm were packed by using the vibration machine and constrained with a plug with smal holes at the top. Then the second size pebbles of 0.3mm sphere were packed gradually with small amount of butches through holes prepared in the plug. The diameter of the holes is designed to be 1 mm so that the smaller pebbles can go through but the larger ones are constrained. As the first pebbles were constrained in the breeder rod with a spring force on the plug, they cannot move even when they were vibrated. Vibration conditions are summarized in Table 3-1. Net packing fractions were measured by weight of packed pebbles. Also the packing fraction distribution was measured by the permeation rate of X-ray by the treatment of the X-ray CT image data.

The temperature of the pebble bed was regulated by a power of heater controlled by temperature of the heater at the center of the breeder rod. Figure 3-2 shows achievable maximum heater temperature as a function of heater power. The heater power about 500 W/m is needed to reach the maximum temperature of 600 °C. After the thermal cycle test, the X-ray CT device was used to observe the change of the rod shape and the packing fraction distribution in the pebble bed. As the final check, the mockup was disassembled for observations of the pebbles fragments.

4. Analyses of Thermal Strain

4.1 Thermal Strain of Breeder with Uniform Volumetric Heating Source

If a volumetric heating source in the breeder rod is assumed to be uniform, a temperature distribution in the breeder rod is estimated by the following equation,

$$T(r)=T_{max}-q'''r^2/(4\lambda) \quad \text{------ (4.1)}$$

If the radial elongation of the rod induced by the thermo-mechanical interaction between the pebbles and the rod is negligible, a thermal strain of the breeder pebble bed is calculated as follows;

$$\Delta L/L=\{(\alpha_{BR}(T_m-T_O)-\alpha_{SS}(T_w-T_O)) \quad \text{------ (4.2)}$$

,where T_m is a mean temperature of the breeder given by:

$$T_m=(T_{max}+T_w)/2 \quad \text{------ (4.3)}$$

The temperature of the breeder rod varies, depending on the position of the breeder rod in the ITER breeding blanket structure [3]. In order to make a rough estimation for the thermal strain in the ITER condition, the temperature of the breeder rod was assumed to be constant at 350 °C. A calculation result of thermal strain of the breeder pebble bed is shown in Fig. 4-2 as a function of the maximum temperature of the breeder. The thermal strain of the breeder in the ITER condition is estimated to be about 0.18 % when the maximum temperature is 550 °C.

4.2 Thermal Strains of Breeder and Neutron Multiplier with Uniform Volumetric Heating Source

If the volumetric heating rate in the breeder rod is assumed to be uniform and that in the neutron multiplier to be negligible, temperature distributions in the breeder pebble bed and the neutron multiplier pebble bed in a cylindrical geometry are estimated by the following equations.

For the breeder,

$$T(r)=T_{max}-q'''(r^2/4)\,\lambda_1 \quad \text{------ (4.4)}$$

$$\Delta T_1=q'''(R_1^2/4)\lambda_1 \quad \text{------ (4.5)}$$

For the neutron multiplier,

$$T(r)=T_{w1}-(q'/2\pi)\,\lambda_1 \ln(r/R_1) \quad \text{------ (4.6)}$$

$$q'=\pi R_1^2 q''' \quad \text{------ (4.7)}$$

$$\Delta T_2=(q'/2\pi)\,\lambda_2 \ln(R_2/R_1) \quad \text{------ (4.8)}$$

If the radial elongation of the rod induced by the thermo-mechanical interaction between the pebbles and the rod is negligible, the thermal strains of the breeder and the neutron multiplier are given by the next equations.

For the breeder,

$$\varepsilon_{BP}=\alpha_{BR}(T_{m1}-T_O)-\alpha_{ss}(T_{w1}-T_O) \quad \text{------ (4.9)}$$

For the neutron multiplier,

$$\varepsilon_{NM}=\alpha_{NM}(T_{m2}-T_O)+\alpha_{ss}(T_{w1}-T_O)\cdot R_1/(R_2-R_1)-\alpha_{ss2}(T_{w2}-T_O)\cdot R_2/(R_2-R_1) \quad \text{------ (4.10)}$$

, where T_{m1} and T_{m2} are the mean temperature of breeder and the mean temperature of neutron multiplier, respectively. Each value is defined by the following equation.

$$T_{m1}=(T_{max}+T_{w1})/2 \quad \text{------ (4.11)}$$

$$T_{m2}=T_{w1}-(T_{w1}-T_{w2})/\ln(R_2/R_1)\,(R_2^2/(R_2^2-R_1^2)\ln(R_2/R_1)-1/2) \qquad (4.12)$$

Calculation results of thermal strains of the breeder and neutron multiplier are shown in Fig. 4-3 as a function of the maximum temperature of the breeder, as the wall temperature is assumed to be constant at 350 °C as described in section 4.1. The thermal strain of the breeder in the ITER condition is estimated to be about 0.18 % when the maximum temperature is 550 °C.

4.3 Thermal Strain of Breeder in Test Condition of Single Layer

When a breeder pebble bed is heated at the center with a constant linear heating rate, a temperature distribution in the breeder is calculated by the following equation.

$$T(r)=T_{w1}-q'/2\pi\lambda\,\ln(r/R_1) \qquad (4.13)$$

If the radial elongation of the rod induced by the thermo-mechanical interaction between the pebbles and the rod is negligible, a thermal strain of the breeder is calculated as described as follows.

$$\Delta L/L=\alpha_{BR}\Delta T_{BR}+\alpha_{SS1}\Delta T_{w1}R_1/(R_2-R_1)-\alpha_{SS2}\Delta T_{w2}R_2/(R_2-R_1) \qquad (4.14)$$

$$\Delta T_{BR}=T_{m3}-T_0 \qquad (4.15)$$

$$\Delta T_{w1}=T_{w1}-T_0 \qquad (4.16)$$

$$\Delta T_{w2}=T_{w2}-T_0 \qquad (4.17)$$

$$T_{m3}=\frac{\int_{R1}^{R2} rT(r)dr}{\int_{R1}^{R2} rdr} \qquad (4.18)$$

$$T_{m3}=T_{w1}-\frac{(T_{w1}-T_{w2})}{\ln(R_2/R_1)}\left\{\frac{R_2^{\,2}}{R_2^{\,2}-R_1^{\,2}}-\ln(R_2/R_1)-\frac{1}{2}\right\} \qquad (4.19)$$

The calculation result of a thermal strain of the breeder is shown in Fig. 4-4 as a function of the maximum temperature of the breeder, as the wall temperature is kept to be constant at 30 °C. At 400 °C, the thermal strain of the breeder becomes equal to that of the ITER condition, 0.18 % .

4.4 Thermal Strains of Breeder and Neutron Multiplier in Test Condition of Double Layers

When a breeder pebble bed is heated at a center with a constant linear heating rate, temperature distributions in the breeder and the neutron multiplier are calculated by the next equations.

For breeder layer,

$$T(r)=T_{w1}-q'/2\pi\lambda\,\ln(r/R_1) \qquad (4.20)$$

$$\Delta T_1=q'/2\pi\lambda\,\ln(R_2/R_1) \qquad (4.21)$$

For neutron multiplier,

$$T(r)=T_{w2}-q'/2\pi\lambda_3\,\ln(r/R_2) \qquad (4.22)$$

$$\Delta T_2=q'/2\pi\lambda_3\,\ln(R_3/R_2) \qquad (4.23)$$

If the radial elongation of the rod induced by the thermo-mechanical interaction between the pebbles and the rod is negligible, the thermal strains of the breeder and the neutron multiplier are given as follows.

Thermal strain of breeder:

$\varepsilon_{BR}=\alpha_{BR}(T_{m1}-T_0)+\alpha_{ss1}(T_{w1}-T_0)\,R_1/(R_2-R_1)-\,\alpha_{ss2}(T_{w2}-T_0)\,R_2/(R_2-R_1)$ ----------------------- (4.24)

Thermal strain of neutron multiplier:

$\varepsilon_{NM}=\alpha_{NM}(T_{m2}-T_0)+\,\alpha_{ss2}(T_{w2}-T_0)\,R_2/(R_3-R_2)-\,\alpha_{ss3}(T_{w3}-T_0)\,R_3/(R_3-R_2)$ ----------------------- (4.25)

, where, T_{m4} and T_{m5} are the mean temperature of breeder and the mean temperature of neutron multiplier, respectively. Each value is defined by the following equations.

$T_{m4}=T_{w1}-(T_{w1}-T_{w2})/\ln(R_2/R_1)(R_2^2/(R_2^2-R_1^2)\ln(R_2/R_1)-1/2)$ ---------------------------------(4.26)

$T_{m2}=T_{w2}-(T_{w2}-T_{w3})/\ln(R_3/R_2)(R_3^2/(R_3^2-R_2^2)\ln(R_3/R_2)-1/2)$ ---------------------------------(4.27)

where, α_{BR} is the thermal expansion coefficient of breeder Li_2TiO_3 [/K], α_{SS1} is the thermal expansion coefficient of heater sheath (Inconel 600) [1/K], α_{SS2} is the thermal expansion coefficient of breeder tube (SS316) [1/K], and α_{SS3} is the thermal expansion coefficient of cooling wall (SS316) [1/K], and T_0 is the room temperature [K].

Calculation results of thermal strains of the breeder are shown in Fig. 4-5 as a function of the maximum temperature of the breeder, as the outer wall temperature is kept to be constant at 30 °C. At 470 °C, the thermal strain of the breeder becomes equal to that of the ITER condition, 0.18 % .

5. Test Results

5.1 Initial Packing Fraction of Pebble Bed

The pebble bed was packed by using a vibration machine. The frequency of 30Hz and the amplitude of 1mmp-p were applied to all cases except for Al pebble of ϕ0.1mm. The charts of the weight of pebble, the gap between the plug and the edge of the rod and the packing fraction are plotted by vibration time in Fig. 5-1 through Fig. 5-4. Figure 5-1 shows the vibration time of Li_2TiO_3 of ϕ2mm. The packing fraction of 62% to 65% is obtained in vibration time of 30 min to 180min. The packing behavior of Li_2TiO_3 of ϕ0.3mm is shown in Fig. 5-2. The packing fraction of 18% to 20% have been obtained in about 1 hour. The packing behavior of Al pebble of ϕ1mm is shown in Fig. 5-3. The packing fraction of 64% was obtained in 5 min. Also, it was observed that the packing fraction gradually increased to 64.5% in 50 min. The packing behavior of Al of ϕ0.1mm is shown in Fig. 5-4. This case exhibits the most difficult packing behavior to take 700 min and to be finally required the higher frequency of 50 Hz. The summary of the packing fraction and the vibration time is shown in Table 5-1. In the case of the single size pebble bed, the packing fraction of 62% to 65% is obtained for both of Li_2TiO_3 and Al pebbles. In case of binary packing, the secondary pebble packing fractions of 18 to 20 % were added to those of single pebble beds.

The X-ray CT devise was used to measure packing fractions, and the results of initial states were shown in Table 5-2 and in Fig. 5-5. Cross-sectional X-ray CT images were taken at upper, middle and lower parts of the mockup as shown in Fig. 5-6 and Fig. 5-7. Packing fractions of pebble bed were evaluated with these images by comparing the average density in the breeder rod to the material density of pebble itself. The packing fraction of the bottom shows the slightly higher than that of the upper case. The packing fraction measured with the X-ray CT device shows lower than that of the weight method.

5.2 Change of Packing Fraction Caused by Thermal Cycle Test

The gap between the plug and the edge of rod was measured after each thermal cycle as shown in Fig. 5-8 in order to get information for a change of the packing state. The rapid sinking of the plug was observed in test No. 1, 2 and 3, after the first thermal cycle and the changing ratio became smaller in the following cycles. The sinking of the plug of 1 mm corresponds to the change of the packing fraction of 0.25%. Therefore, the change of the packing fraction calculated from the sinking of the plug becomes to be 0.1% for test No. 1 and 2. The sinking of the plug in the test No.3 was larger than that of others due to the vibration applied between the thermal cycles. The changes of the packing fraction measured by X-ray CT method are shown in Fig. 5-9 and summarized in Table 5-2. No significant change of the packing fraction was observed for every case.

5.3 Strain of Rod Induced by Thermal Cycle

The temperatures of the heater and the rod were measured with thermo-couples. The strains of the rods are measured with strain gages attached on outer surface of the rods. Typical data of the strains and the temperature in test No.1 and No.2 are shown in Fig. 5-10(a) and (b), respectively. The results of the measured temperatures and strains are listed in Tables 5-3, 5-4 and 5-5 and shown in Fig. 5-11 through 5-17. Figure 5-18 shows the comparison of the effects of rod thickness and the packed density (single or binary pebble bed) on the strain, where strains after the first thermal cycle are also shown. The strain of the breeder rod in test No.1 is about 60×10^{-6}, which corresponds to the temperature increase of 4 degree. The temperature of the breeder rod increased to about 10 degree as shown in Fig. 5-10(a) and table 5-4. Therefore, the strain of the breeder rod in test No.1 is induced mainly by temperature rise of the rod. The interaction between the pebbles and the breeder rod is considered to be negligible. On the other hand, the strain of the breeder rod in test No.2 showed 350×10^{-6} at the middle and 280×10^{-6} at the upper and the lower positions. The strain at the middle was higher than those at the upper and lower positions, because the temperature of pebbles at middle was higher than other positions, as can be seen from Fig. 5-12. The thermo-mechanical interaction between the tube and the pebble bed could expand the breeder rod in test No.2 because of the thinner rod thickness of 0.2 mm. The expansion of 0.035% of the middle is still within an elastic strain range. After the temperature cool down, the strain of the tube returns to the initial condition as shown in Fig.5-10 (b), which shows the second thermal cycle. The dependency of the strain of the breeder rod on the number of the thermal cycles was shown in Fig. 5-19. The increase of the strain was not observed in the course of the thermal cycle progress. This shows the expansion of the breeder rod induced by the thermo-mechanical interaction remained within the elastic range of the breeder rod, even though the accelerating test condition was applied on the breeder rod.

5.4 Evaluation of Induced Stress between Rod and Pebble

The stress induced by the thermo-mechnical interaction between the rod and pebble could be estimated by the following equations. The stress of the breeder rod σ_t keeps a balance against the stress of pebble bed σ_p.

$$\sigma_t=\sigma_p D/2t \quad \text{-----(5.1)}$$

, where, D is the diameter of the breeder rod and t is the thickness of the breeder rod. When a thermal strain ε_{th} is induced due to the temperature rise, it is separated into a strain of rod ε_t and a strain of pebble bed ε_p.

$$\varepsilon_{th}=\varepsilon_t+\varepsilon_p \quad \text{-----(5.2)}$$

Stresses are expressed asfollows.

$$\sigma_t=E_t\varepsilon_t \quad \text{-----(5.3)}$$

$$\sigma_p=E_p\varepsilon_p \quad \text{-----(5.4)}$$

, where, E_t and E_p are a Young's modulus of the breeder rod and the pebble bed, respectively.

The strain of the rod was about 400×10^{-6} in the test No. 2. This strain results in the stress to be 76 MPa of the rod and 1.1MPa of the pebble by using the equation (5.1), (5.3) and the Young's modulus of SS316L of 190 GPa. The Young's modulus of pebble bed was estimated to be 0.4GPa with an initial strain of the pebble bed of 0.1 % by an analytic method [4]. From this estimation, the stress of the breeder rod in the acceleration test condition is still low as compared with a yield strength 160 MPa of SS316 at 350 °C. Therefore, the soundness of the tube in the ITER condition was confirmed.

5.5 Appearance of Pebble after Thermal Cycle Test

Photographs of the pebbles before and after the test are shown in Fig. 5-20(a), (b) and (c). An appearance of the pebbles was not changed after thermal cycles test, and also a crack or a fragmentation was not observed. Therefore these results show that a soundness of the rod and the pebble would be kept during thermal cycle operation of ITER.

6. Conclusions

The thermal cycle test of the ITER breeding blanket mockup was carried out and the following conclusions were obtained.

(1) Pebbles were compressed by a thermal expansion of the pebbles under constraint with cooled breeder rod and outer tube. But no significant change of the packing fraction was observed with X-ray CT method.

(2) Any change of an appearance of the pebble was not observed.

(3) A strain of the breeder rod, which is caused by the thermo-mechanical interaction between the breeder rod and the pebble bed, was negligible even though in case of thinner tube.

(4) A soundness of the breeder rod and the pebbles under thermal cycles is confirmed in simulated ITER condition.

Acknowledgement

The authors wish to acknowledge Dr. Ohara for supporting guidance. They also would like to show their grateful to the members of Hitachi Ltd. and Hitachi Engineering Co., especially for observance with X-ray CT device.

Nomenclature

T_{max}	Maximum temperature of breeder
T_w	Wall temperature
T_o	Room temperature
T_m	Mean temperature of breeder
q'	Linear heating power of heater [W/m]
q'''	Volumetric heating rate [W/m^3]
α_{BR}	Thermal expansion coefficient of breeder, Li_2TiO_3 [/K] (shown in Fig. 4-1)
α_{SS}	Thermal expansion coefficient of tube, SS316L [/K] (shown in Fig. 4-1)
α_{SS1}	Thermal expansion coefficient of heater, Inconel 600 [1/K] (shown in Fig. 4-1)
λ	Effective thermal conductivity of breeder, Li_2TiO_3, pebble bed in the air; 0.3 [W/m K]
λ_1	Effective thermal conductivity of Li_2TiO_3 pebble bed in He(0.1MPa): 1.2 [W/m K]
λ_2	Effective thermal conductivity of Be pebble bed in He(0.1MPa): 12 [W/m K]
λ_3	Effective thermal conductivity of Al pebble bed in air, 1.0 [W/m K]

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[2] M. Enoeda, H. Yoshida, S. Hirata and K. Ishida, "Test Apparatus for ITER Blanket Pebble Packing Behavior", JAERI-M 92-104 (1992).

[3] Design Description Document, Tritium Breeding Blanket System, 1998 Technical Basis For The

ITER Final Design Report, Cost Review and Safety Analysis (FDR), ITER EDA Documentation Series, No. 7, (1996).
[4] K.Walton, J.Mech.Phys.Solid.Vol.35, No.2, pp.213-226, (1987).

Table 2-1 Test Parameters for Thermal Cycle Tests

single/ double	single/ binary	Test No.	breeder rod ID/ Thick [mm]	outer tube ID/ Thick [mm]	temperatures of heater surface / cooling wall [C]	number of thermal cycles	vibrations during cooling period
single layer Li2TiO3	single (ϕ2.0mm)	1	26/1.0	-	400/30	1, 5	no
		2	26/0.2	-	600/30	1, 5	no
		3	26/0.2	-	600/30	1, 5	applied
	binary (ϕ2.0/ϕ0.3mm)	4	26/1.0	-	400/30	1, 5	no
		5	26/0.2	-	600/30	5	no
Double layer (Li2TiO3/Al)	single (ϕ1.0mm)	6	26/1.0	60/3.0	500/30	1, 5	no
	binary (ϕ1/0.1mm)	7	26/1.0	60/3.0	500/30	1, 5	no

(*): Xray-CT images were taken after these cycles.

Table 2-2 Specifications of pebbles

	Li_2TiO_3 pebble		Al pebble	
	single	binary	single	binary
Diameter(mm)	2	2 0.3	1	1 0.1
Theoretical density(g/cm3)	3.44		2.70	
Density(%TD)	83		100	

Table 3-1 Vibration Conditions for Packing Li_2TiO_3 Pebbles.

	Pebble of 2mm sphere	Pebble of 0.3mm sphere
Frequency(Hz)	30	30
Amplitude(mm)	1	1
Vibration time (min.)	Longer than 12	Longer than 20

Table 5-1 Packing Fraction

Packing fraction of single layer mockup					
	Li_2TiO_3 pebble with ϕ2mm		Li_2TiO_3 pebble with ϕ0.3mm		Total
test No.	filling time [min]	packing fraction [%]	filling time [min]	packing fraction [%]	packing fraction [%]
1	28	64	-		64
2	14	64	-		64
3	102	62	-		62
4	50	65	92	18	83
5	180	63	105	20	83
Packing fraction of double layer mockup					
	inner layer				
	Li_2TiO_3 pebble with ϕ2mm		Li_2TiO_3 pebble with ϕ0.3mm		Total
test No.	filling time [min]	packing fraction [%]	filling time [min]	packing fraction [%]	packing fraction [%]
6	40	64	-		64
7	105	63	120	19	82
	outer layer				
	Al pebble with ϕ1mm		Al pebble with ϕ0.1mm		Total
test No.	filling time [min]	packing fraction [%]	filling time [min]	packing fraction [%]	packing fraction [%]
6	50	65	-		65
7	40	64	710	16	80

Table 5-2 Initial Packing Fraction and Dependency of Change of Packing Fraction on Thermal Cycle

Test No.	Pebble Material	Packing Fraction by Weight* [%]	Packing Fraction by X-CT method [%]								
			Initial			after 1st cycle			after 5th cycle		
			Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower
1	Li_2TiO_3	64	56	62	63	56	62	63	56	63	64
2	Li_2TiO_3	64	55	63	64	56	63	64	55	63	64
3	Li_2TiO_3	62	52	61	60	53	62	61	53	62	60
4	Li_2TiO_3	83(65)	72	80	78	72	80	80	71	80	80
5	Li_2TiO_3	82(63)	71	78	78	-	-	-	71	78	79
6	Li_2TiO_3	64	53	62	63	54	62	62	52	62	64
	Al	65	60	63	63	60	62	61	62	64	63
7	Li_2TiO_3	82(63)	69	73	76	71	75	76	70	75	76
	Al	80(64)	68	77	78	69	78	79	69	78	79

* Packing fraction of test No.4, 5 and 7 shows total packing fraction of binary pebble and packing fraction of large size pebble in parentheses.

Table 5-3 Temperature of Heater Measured at each measurement position in this study

Test No.	No. of cycles	1	2	3	4	5
No.1	Upper	175	171	167	167	167
	Middle	400	400	400	400	400
	Lower	290	276	277	279	282
No.2	Upper	260	244	256	253	256
	Middle	600	600	600	600	600
	Lower	295	298	301	295	302
No.3	Upper	253	247	243	247	242
	Middle	600	600	600	600	600
	Lower	421	433	436	437	441
No.4	Upper	155	157	157	158	157
	Middle	400	400	400	400	400
	Lower	262	268	274	273	278
No.5	Upper	216	218	216	216	216
	Middle	600	600	600	600	600
	Lower	400	417	407	421	422
No.6	Upper	208	210	212	212	211
	Middle	500	500	500	500	500
	Lower	351	360	357	357	353
No.7	Upper	190	190	190	190	189
	Middle	500	500	500	500	500
	Lower	336	347	342	344	350

Table 5-4 Temperature of Breeder Rod Measured at each measurement position

Test No.	No. of cycles	1	2	3	4	5
No.1	Upper	28	29	28	29	29
	Middle	30	31	31	31	32
	Lower	23	24	24	24	24
No.2	Upper	44	25	30	30	30
	Middle	44	28	30	35	34
	Lower	29	21	22	25	24
No.3	Upper	27	30	29	26	26
	Middle	30	29	28	28	29
	Lower	26	26	28	28	27
No.4	Upper	24	24	25	24	23
	Middle	28	26	28	26	26
	Lower	22	22	23	23	23
No.5	Upper	26	25	26	26	26
	Middle	33	32	32	31	31
	Lower	20	20	20	20	20
No.6	Upper	58	52	54	55	55
		18	23	23	23	23
	Middle	76	75	77	77	77
		20	25	25	25	25
	Lower	50	55	54	55	55
		17	19	19	19	19
No.7	Upper	42	42	42	42	43
		24	23	21	22	22
	Middle	65	60	61	62	62
		26	26	26	26	24
	Lower	42	42	42	42	42
		19	18	18	18	18

(Note)

In test No.6 and 7 the upper row shows the temperature of the breeder rod, and the lower row shows the temperatureb of the outer tube.

Table 5-5 Strain of Breeder Rod Measured at each measurement position ($\times 10^{-6}$)

Test No.	No. of cycles	1	2	3	4	5
Test No.1	Upper	17	25	20	23	21
	Middle	62	-	-	44	41
	Lower	20	34	32	33	31
Test No.2	Upper	286	260	188	212	205
	Middle	345	471	335	308	232
	Lower	274	254	244	396	205
Test No.3	Upper	93	73	-	164	152
	Middle	410	465	380	367	308
	Lower	226	318	165	285	260
Test No.4	Upper	50	54	45	49	42
	Middle	113	128	115	110	107
	Lower	80	100	77	72	71
Test No.5	Upper	295	245	210	190	161
	Middle	400	480	470	475	475
	Lower	370	320	290	280	242
Test No.6	Upper	15	15	14	12	5
	Middle	7	0	18	20	15
	Lower	35	46	46	44	30
Test No.7	Upper	28	105	102	100	100
	Middle	75	22	30	27	28
	Lower	57	65	62	58	58

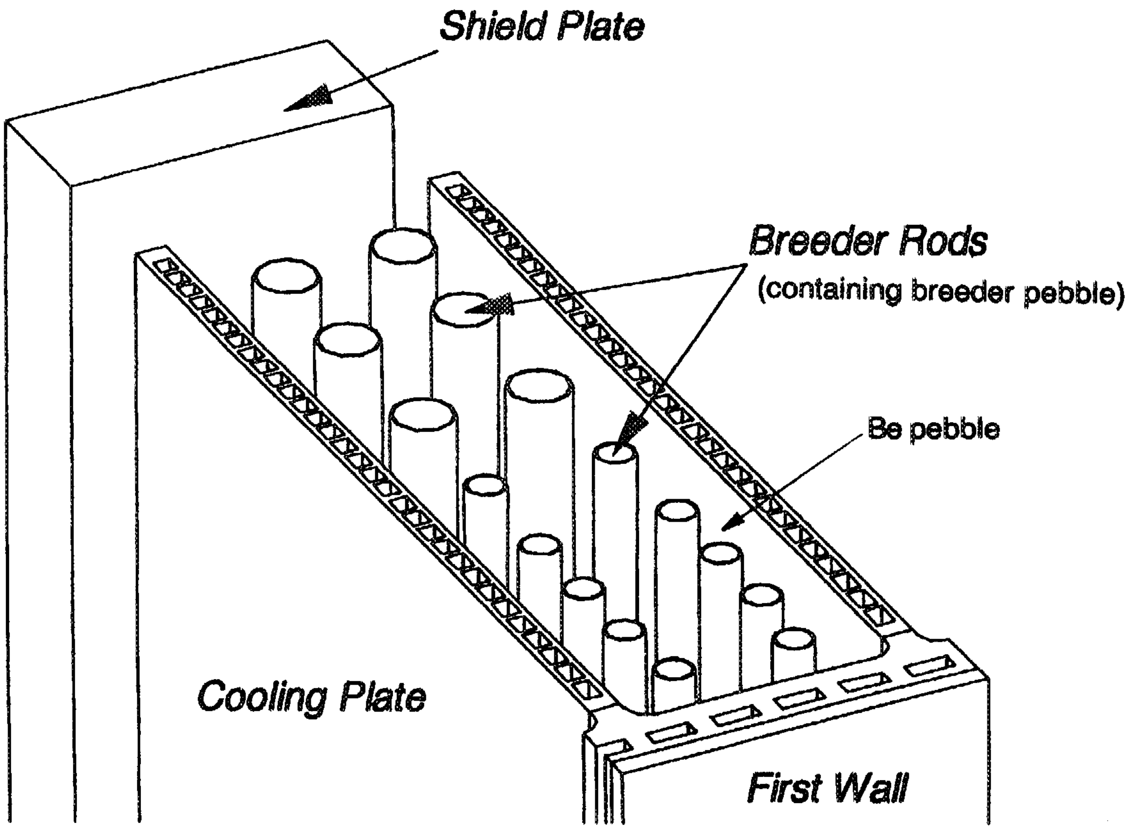
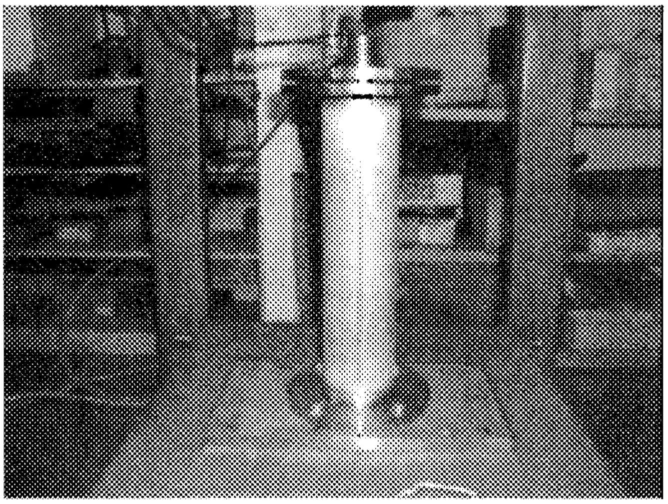
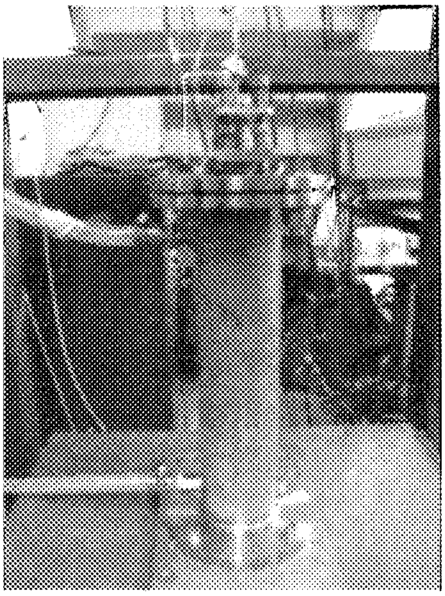


Fig. 1-1 ITER Breeding Blanket [1]



Photograph of the mockup installed on the vibration machine for packing pebbles



Photograph of the mockup prepared for thermal cycle tests

Fig. 2-1 Appearance of the test mockup

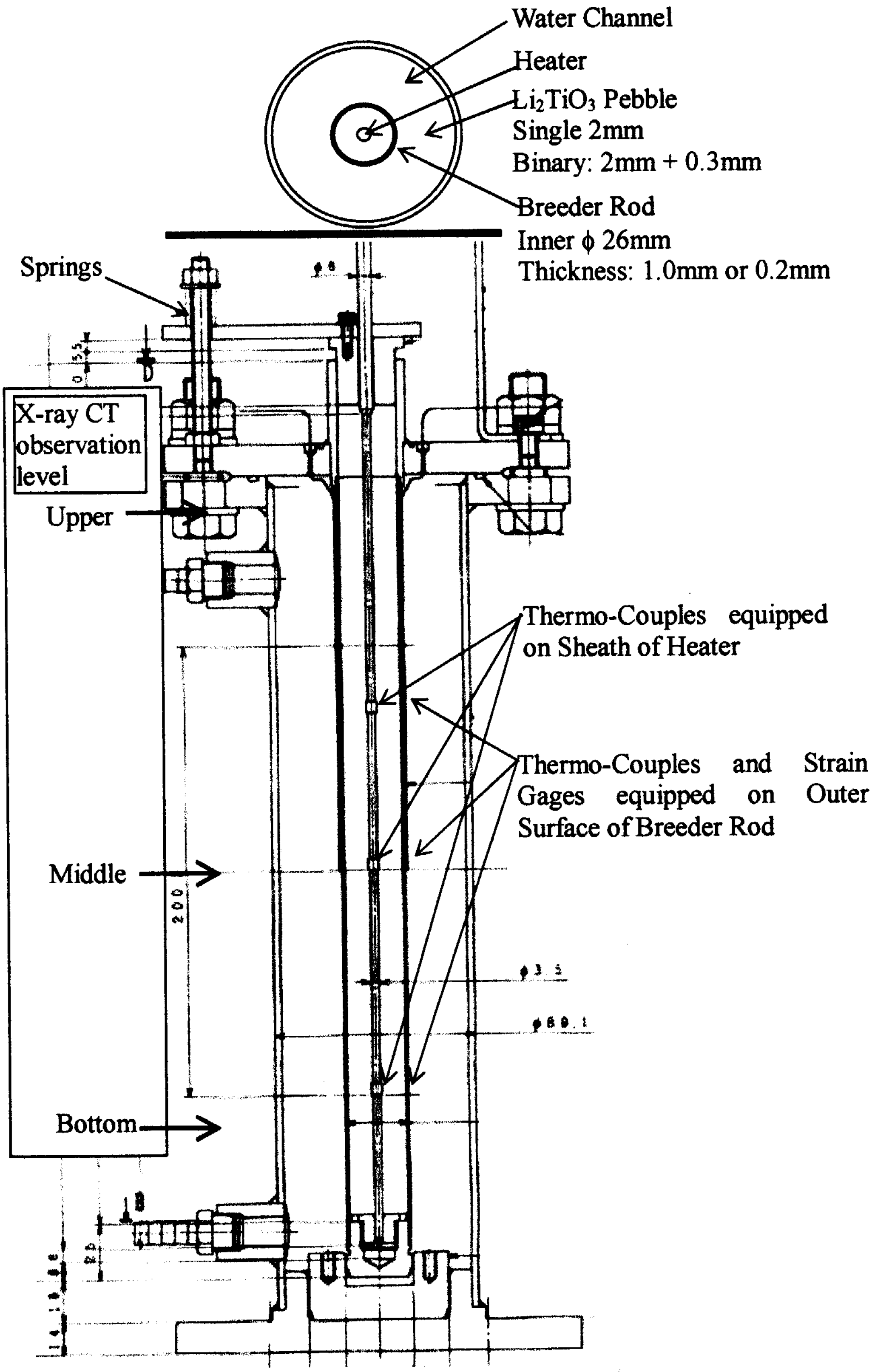


Fig. 2-2 Test mockup for single layer tests

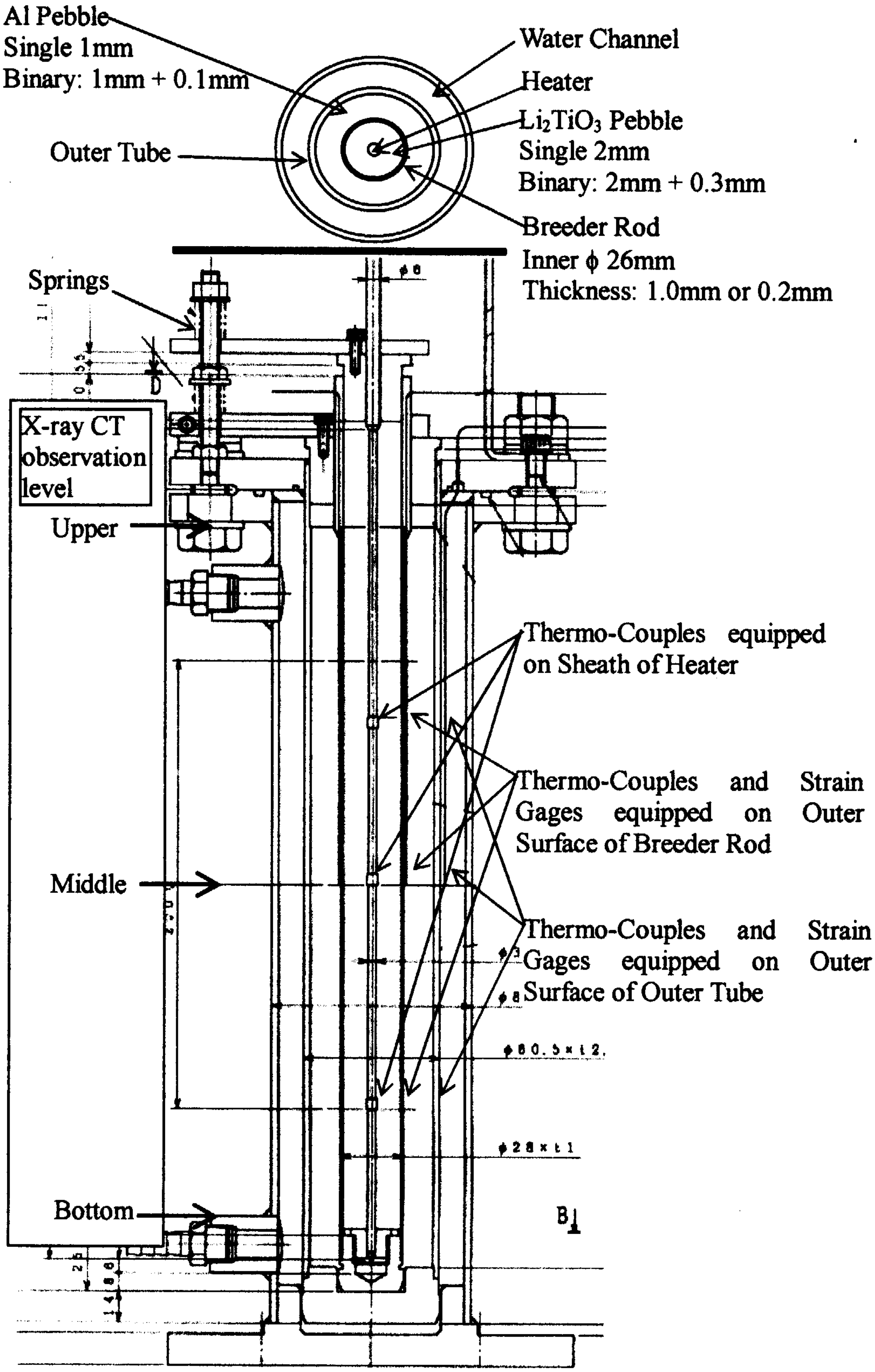


Fig. 2-3 Test mockup for double layer tests

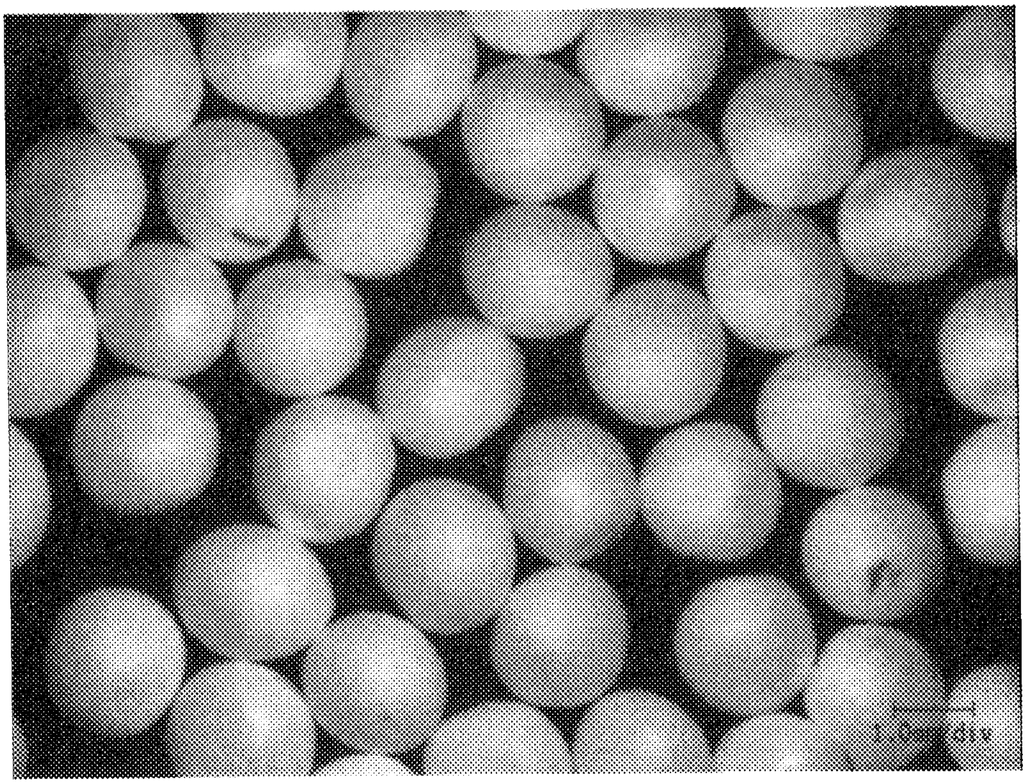


Fig. 2-4(a) Photograph of Li_2TiO_3 of 2 mm dia

Fig. 2-4(b) Photograph of Li_2TiO_3 of 0.3 mm dia.

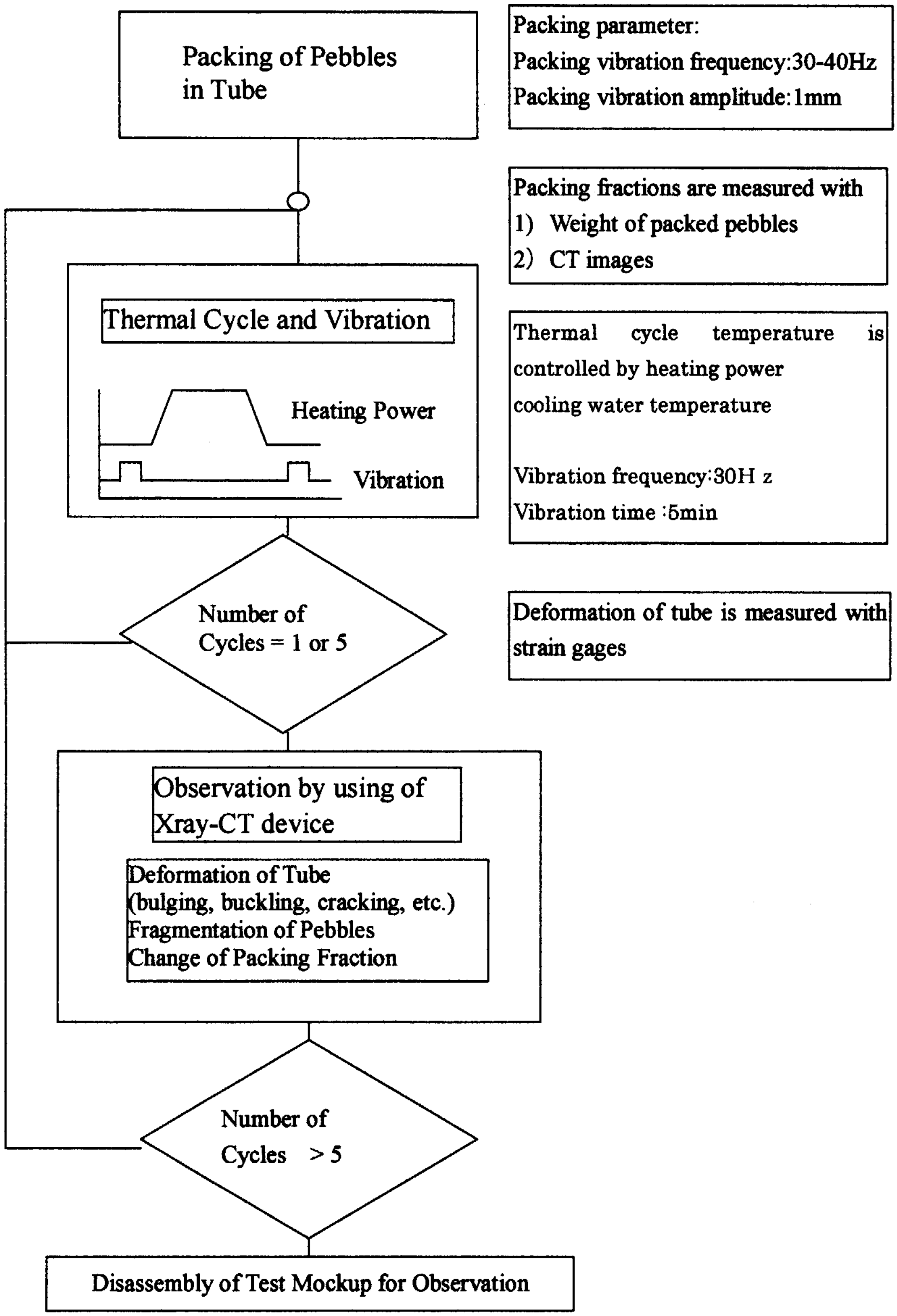


Fig. 3-1 Test procedure

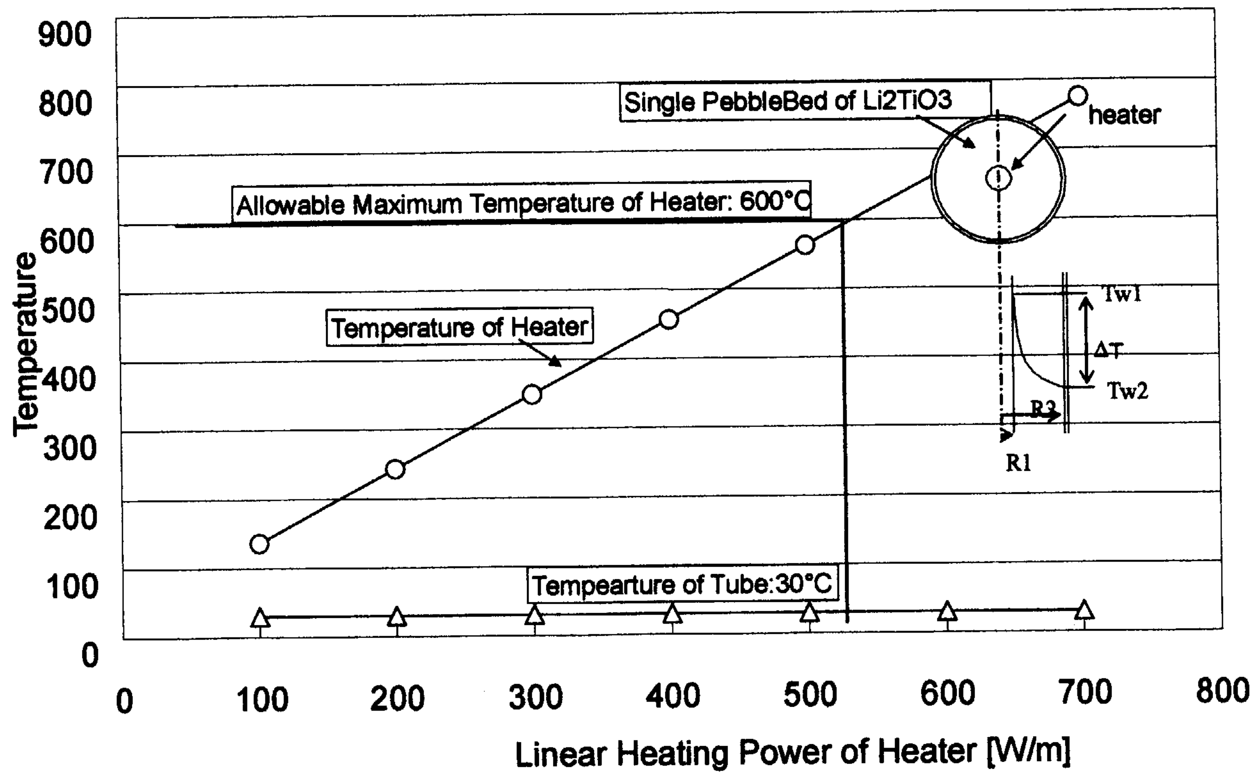


Fig.3-2 Required linear heating power of heater

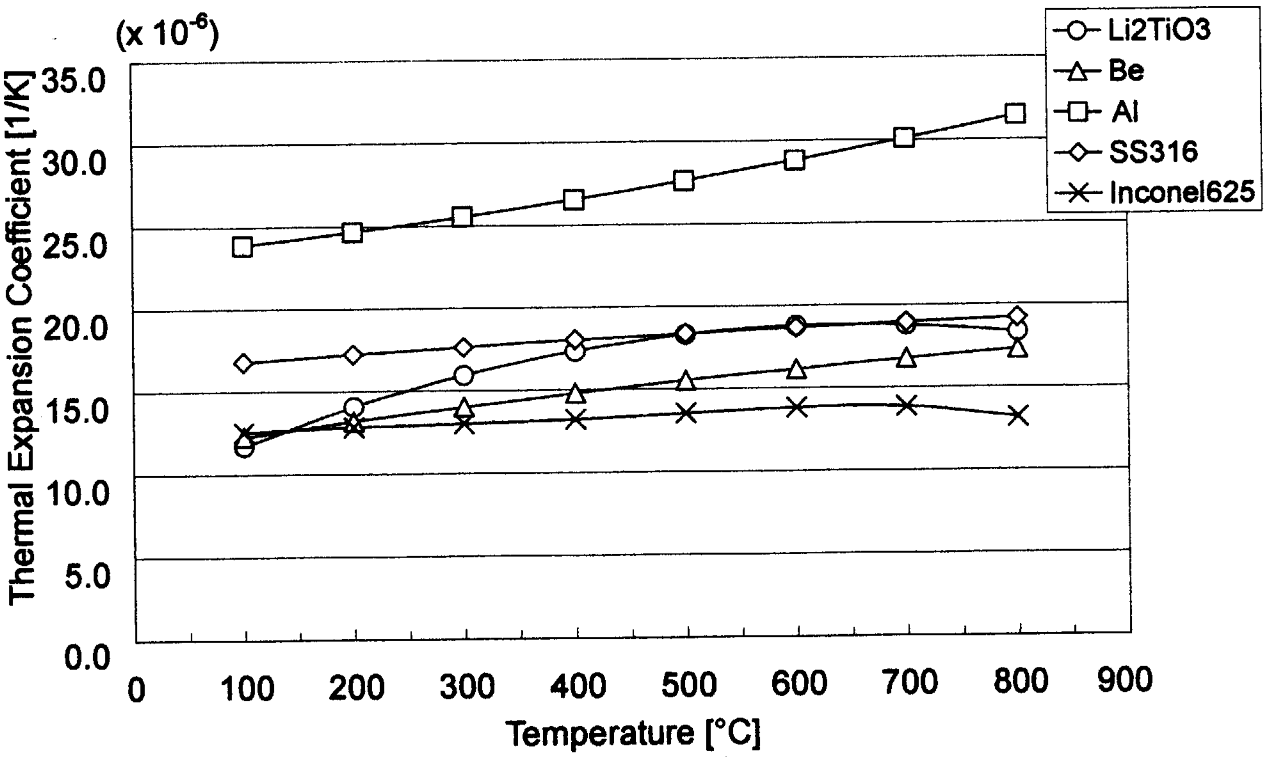


Fig. 4-1 Thermal expansion coefficients of the applied materials in this tests

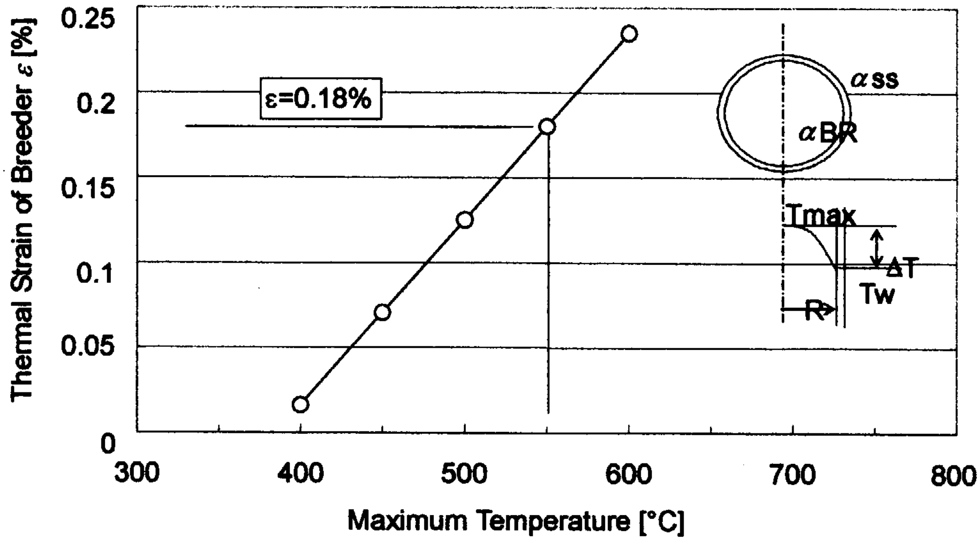


Fig. 4-2 Thermal strain of breeder with uniform volumetric heating source

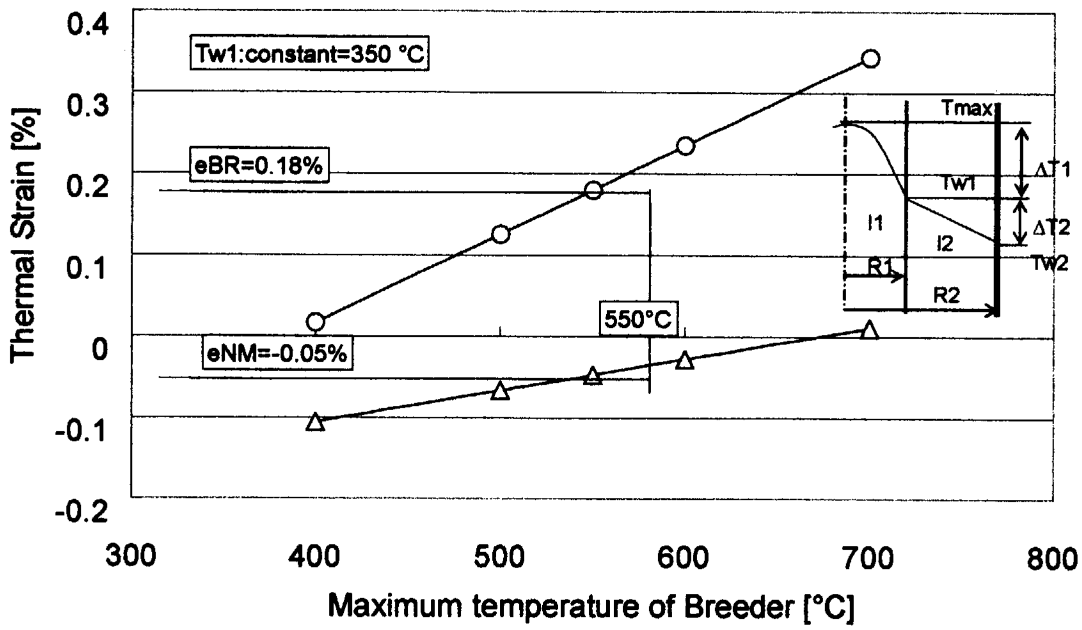


Fig. 4-3 Thermal strains of breeder and neutron multiplier with uniform volumetric heating source

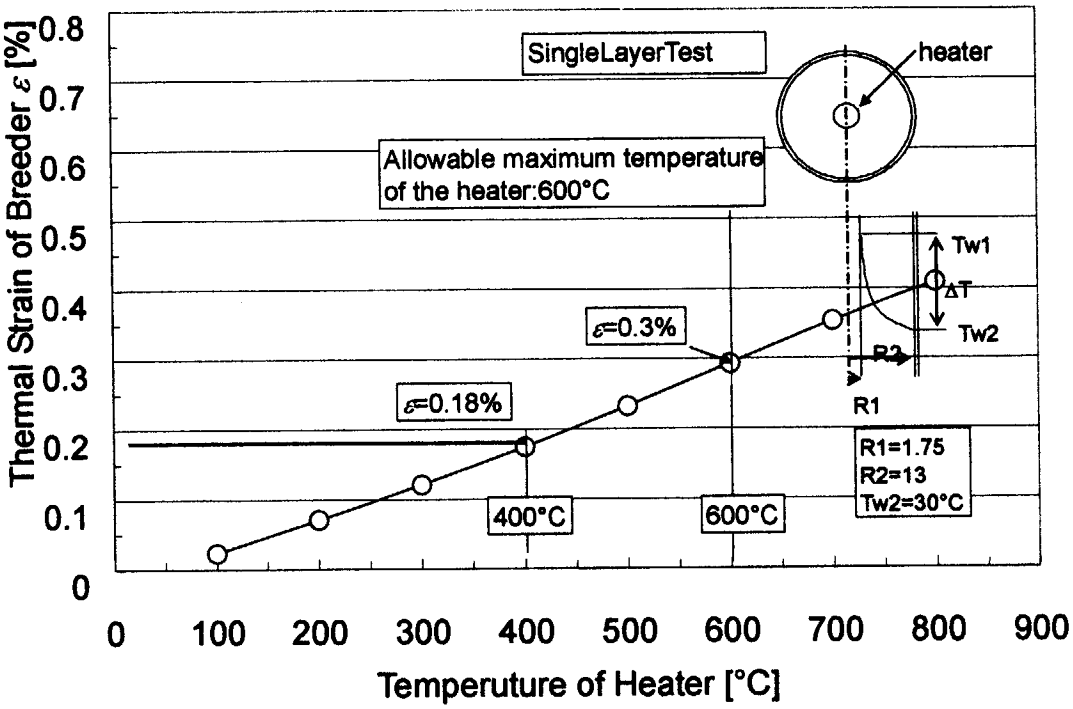


Fig. 4-4 Thermal strain of breeder in test condition of single layer

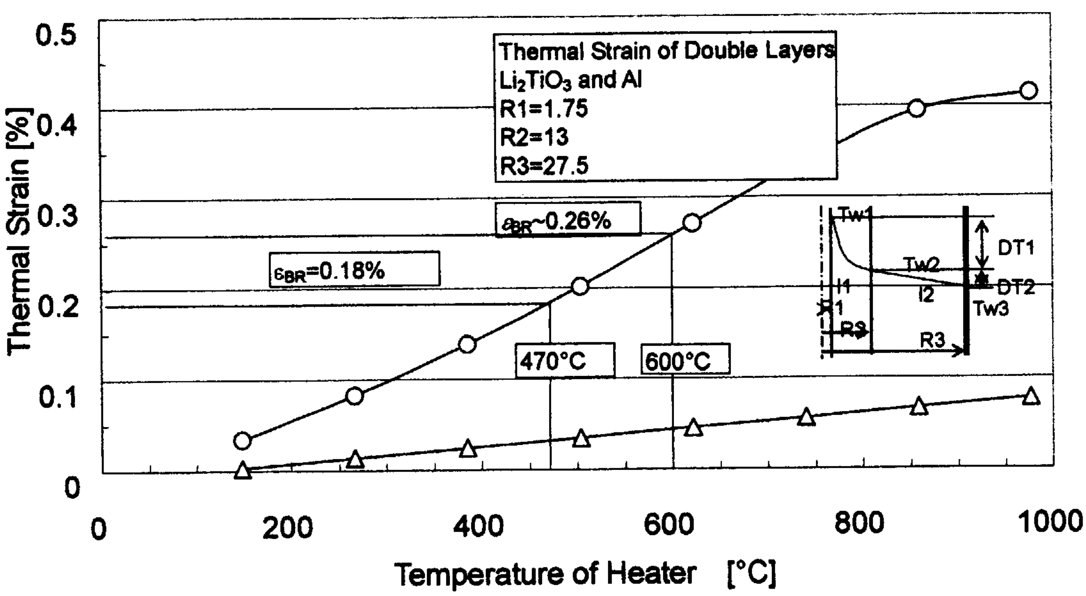
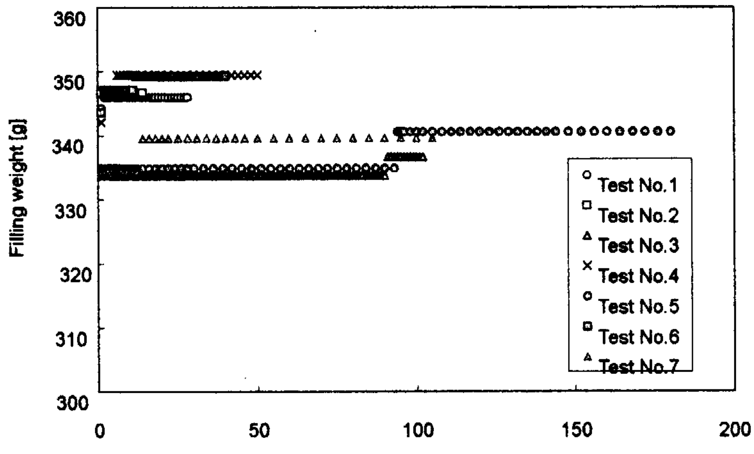
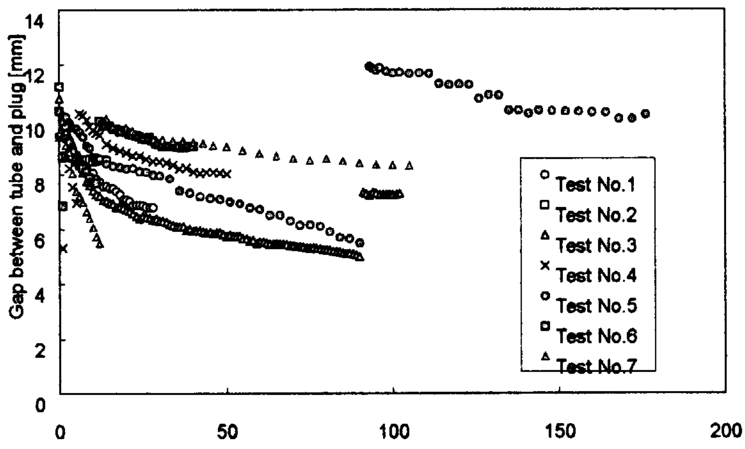


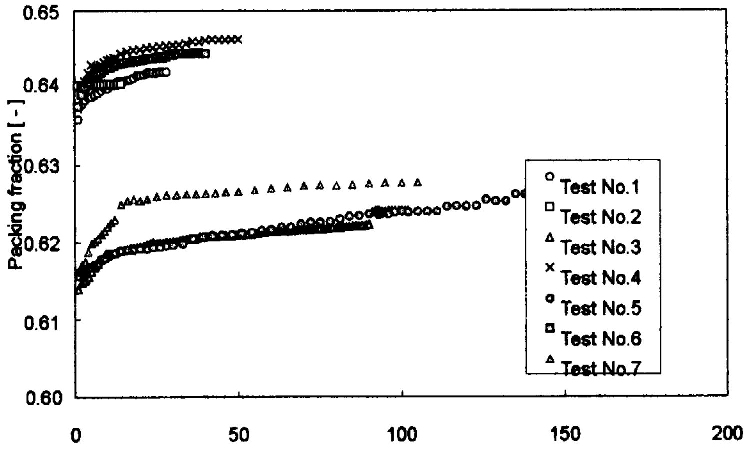
Fig. 4-5 Thermal strains of breeder and neutron multiplier in test condition of double layers



(a) Evolution of filling weight of pebbles

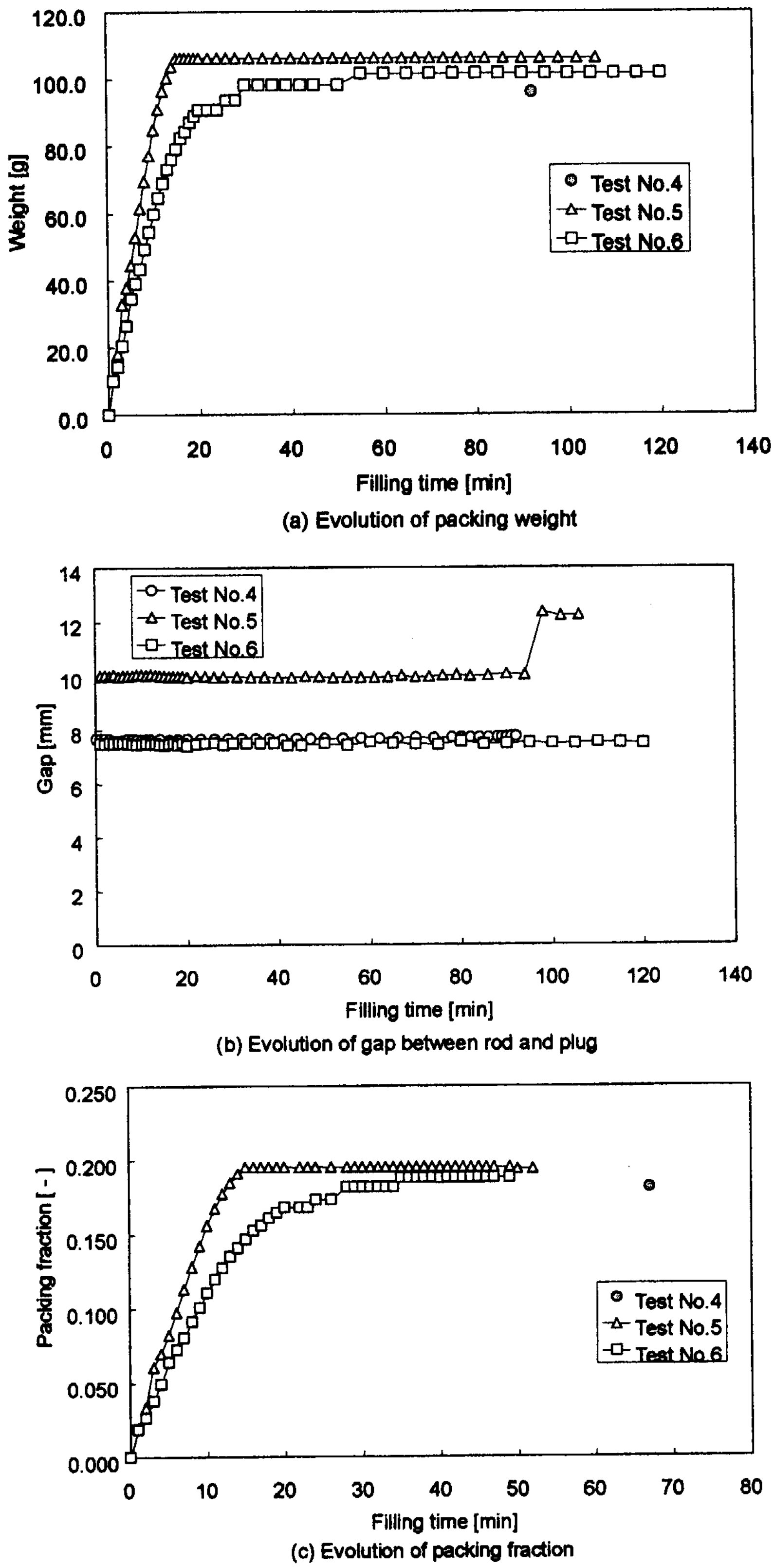


(b) Evolution of gap between tube and plug



(c) Evolution of packing fraction

Fig. 5-1 Filling Behavior of Li_2TiO_3 Pebble of 2mm Sphere against Vibration Time

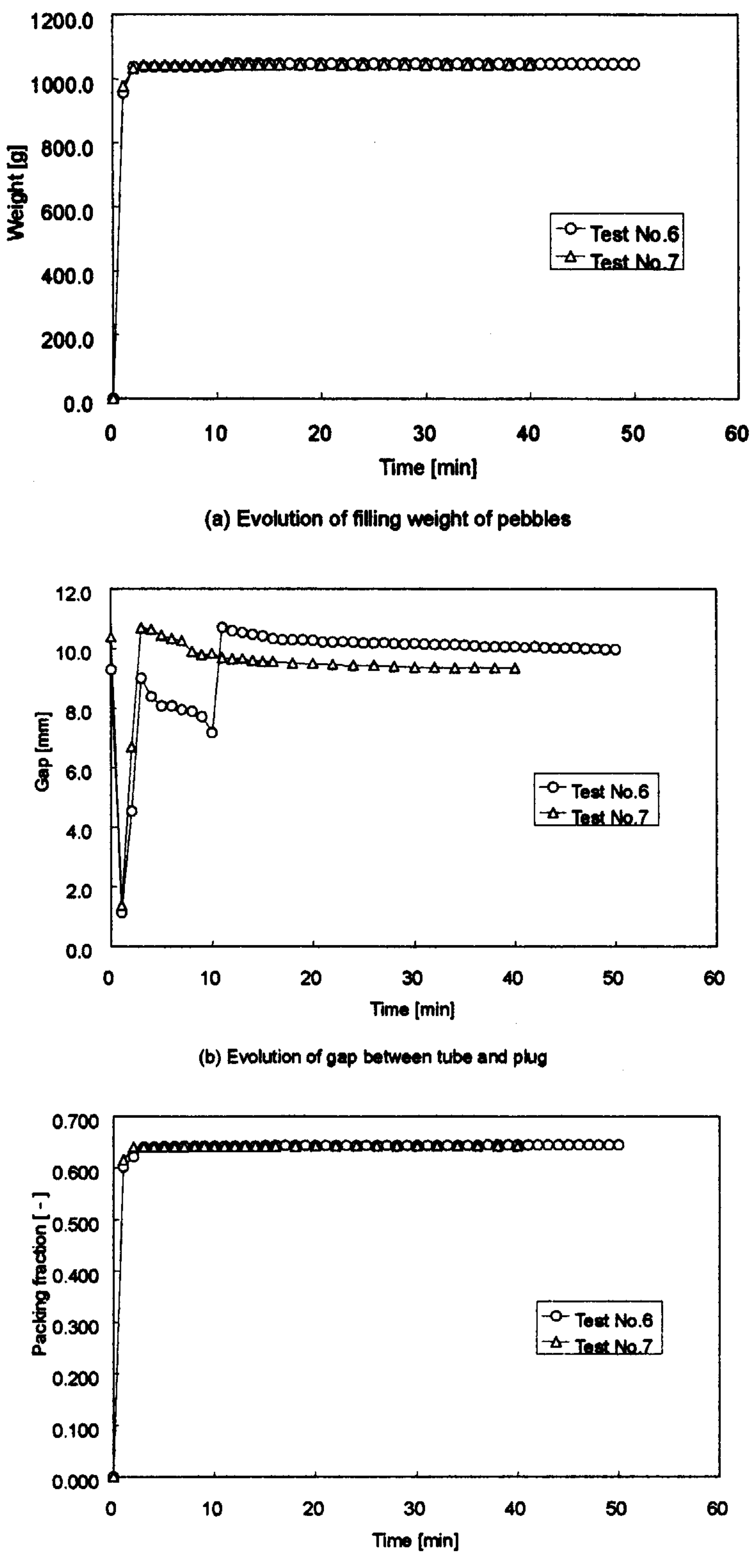


(a) Evolution of packing weight

(b) Evolution of gap between rod and plug

(c) Evolution of packing fraction

Fig. 5-2 Filling Behavior of Li2TiO3 Pebble of 0.3mm Sphere against Vibration Time



(a) Evolution of filling weight of pebbles

(b) Evolution of gap between tube and plug

(c) Evolution of packing fraction

Fig. 5-3 Filling Behavior of Al Pebble of 1.0mm Sphere against Vibration Time

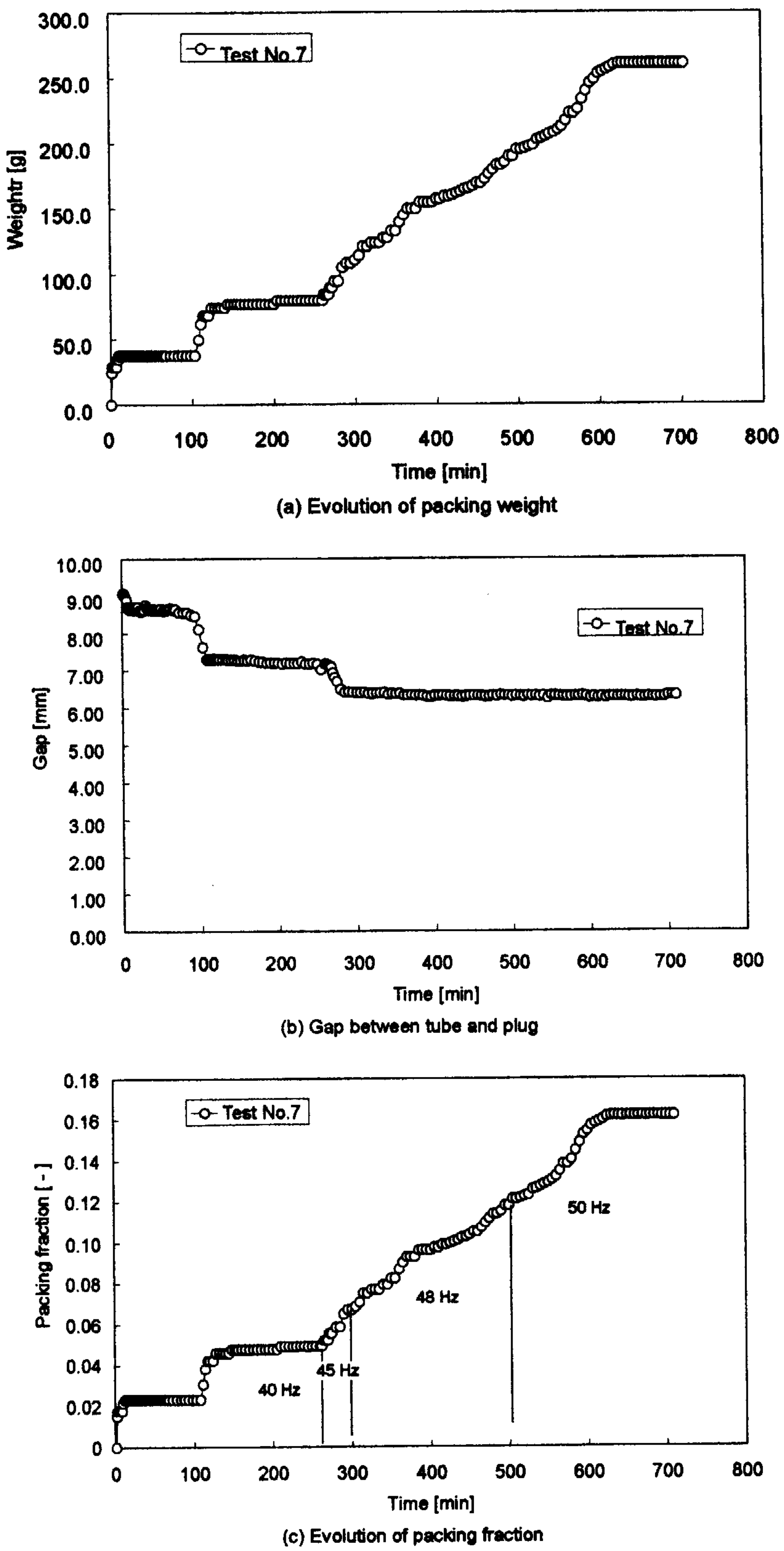


Fig. 5-4 Filling Behavior of Al Pebble of 0.1mm Sphere against Vibration Time

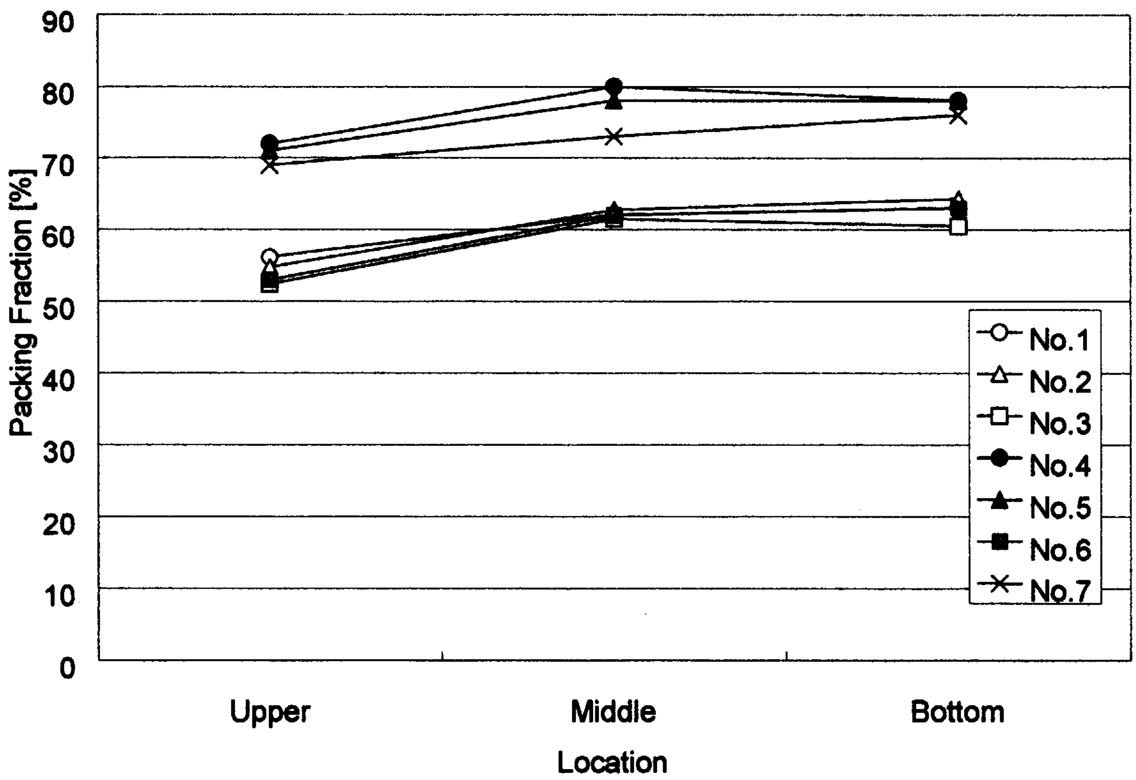
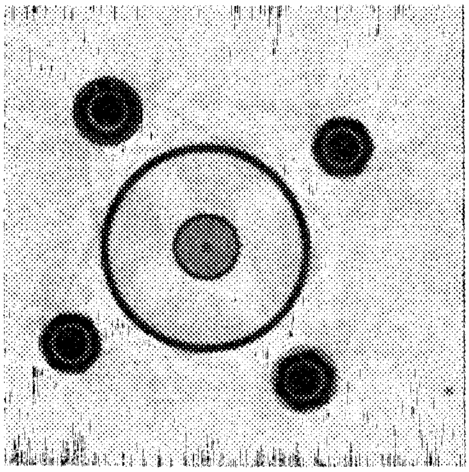
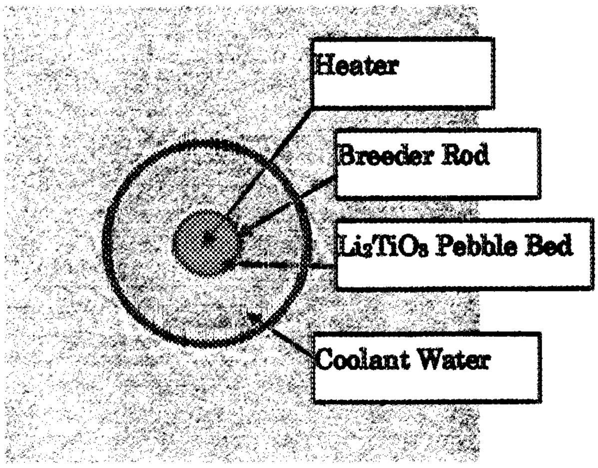


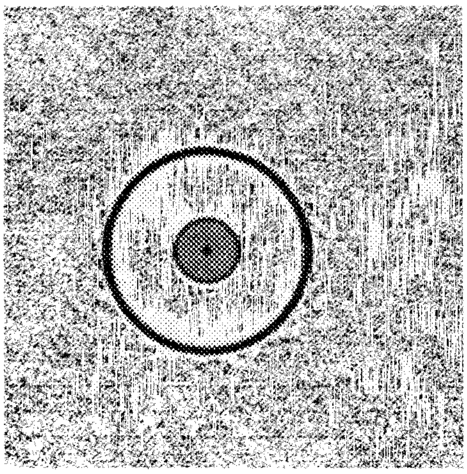
Fig. 5-5 Initial Packing Fraction of Pebble Bed Measured by X-ray CT Device



(a) Upper

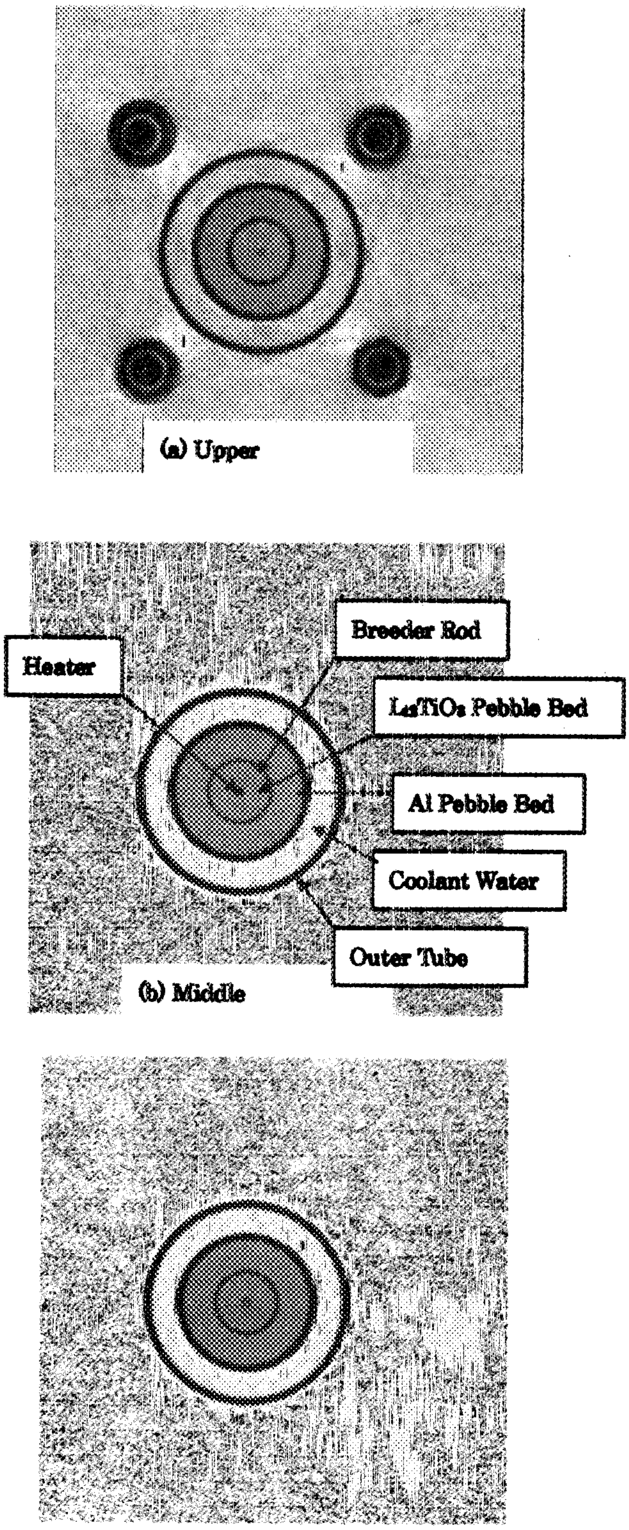


(b) Middle



(c)Bottom

Fig 5-6 X-ray CT Image of Mockup of No.1 Test



(a) Upper

(b) Middle

(c) Bottom

Fig 5-7 X-ray CT Image of Mockup of No.6 Test

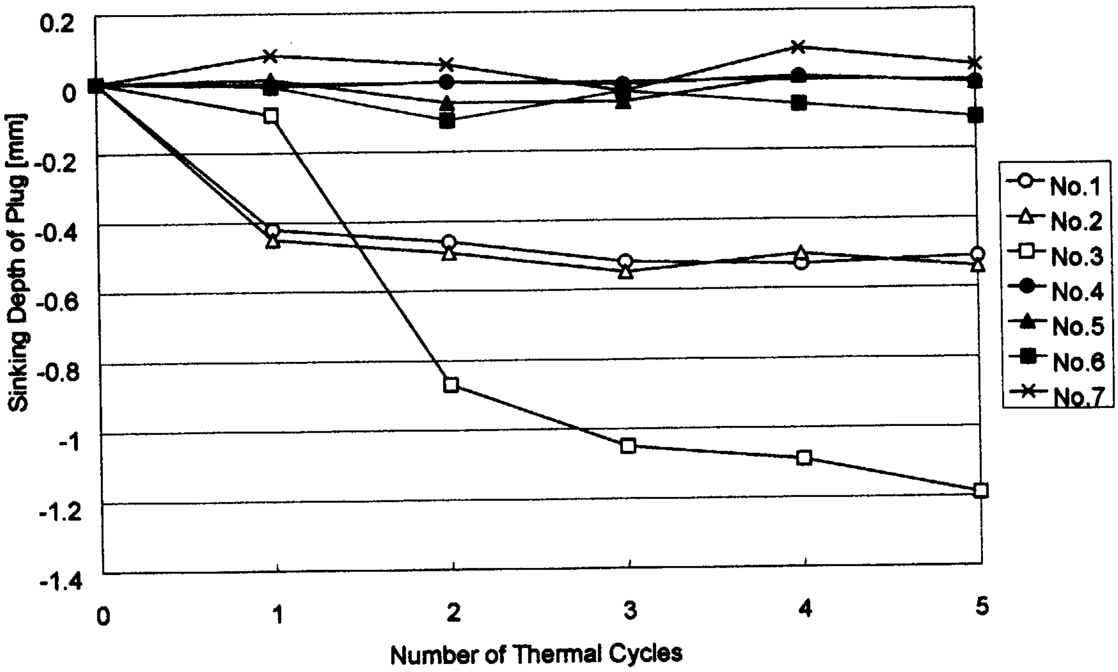
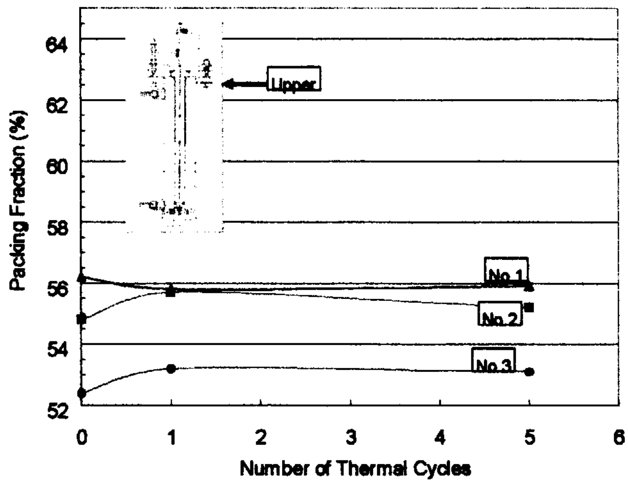
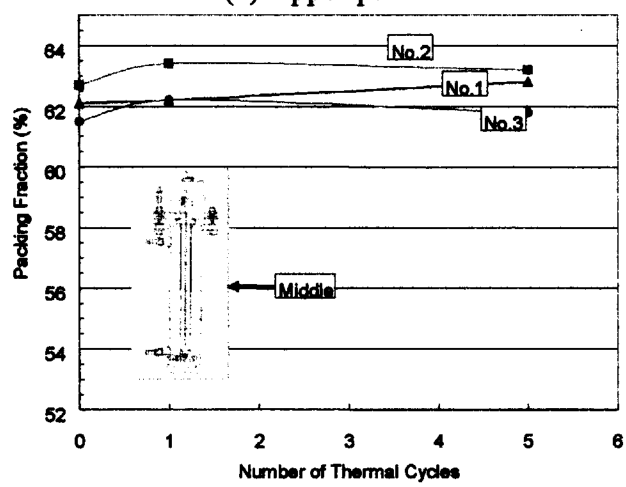


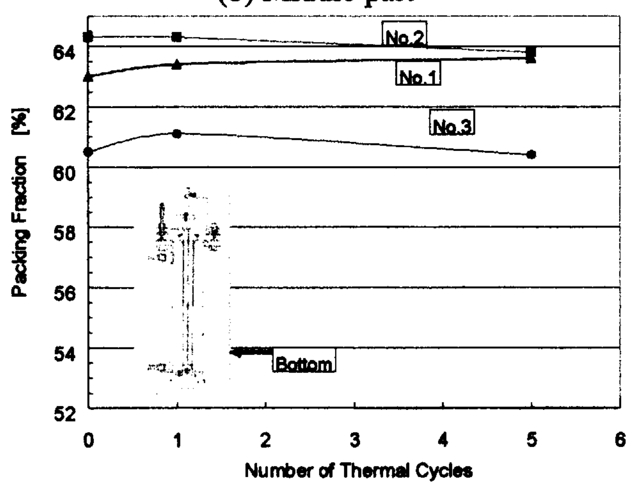
Fig.5-8 Sinking Depth of Plug



(a) Upper part

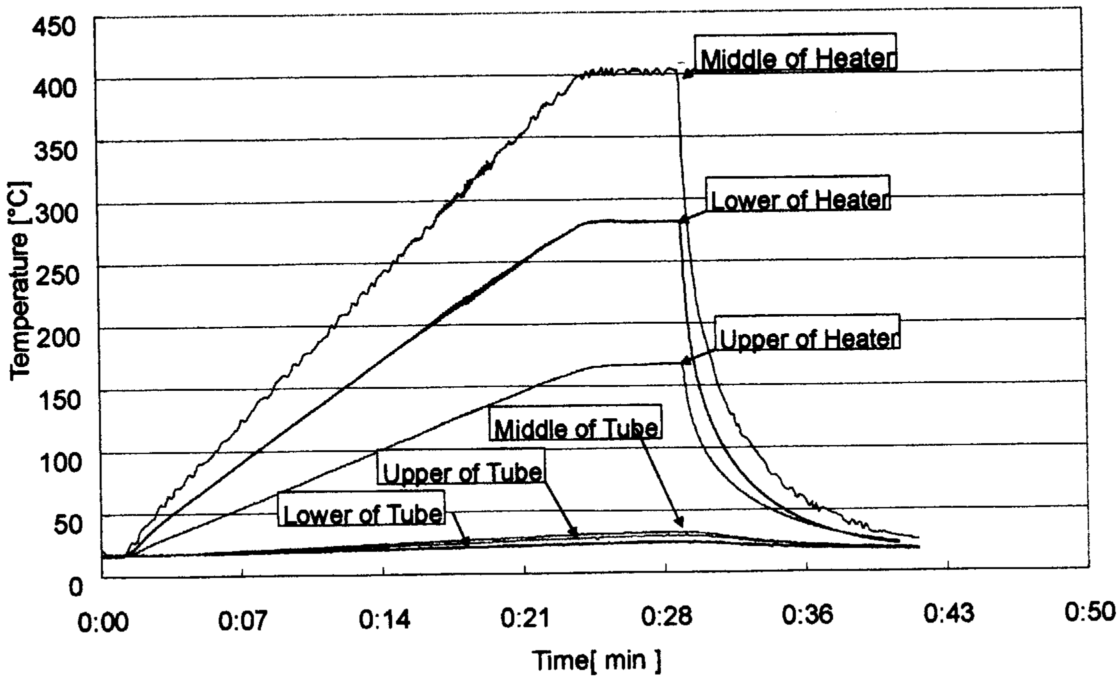


(b) Middle part



(c) Lower part

Fig. 5-9 Change of packing fraction after thermal cycles



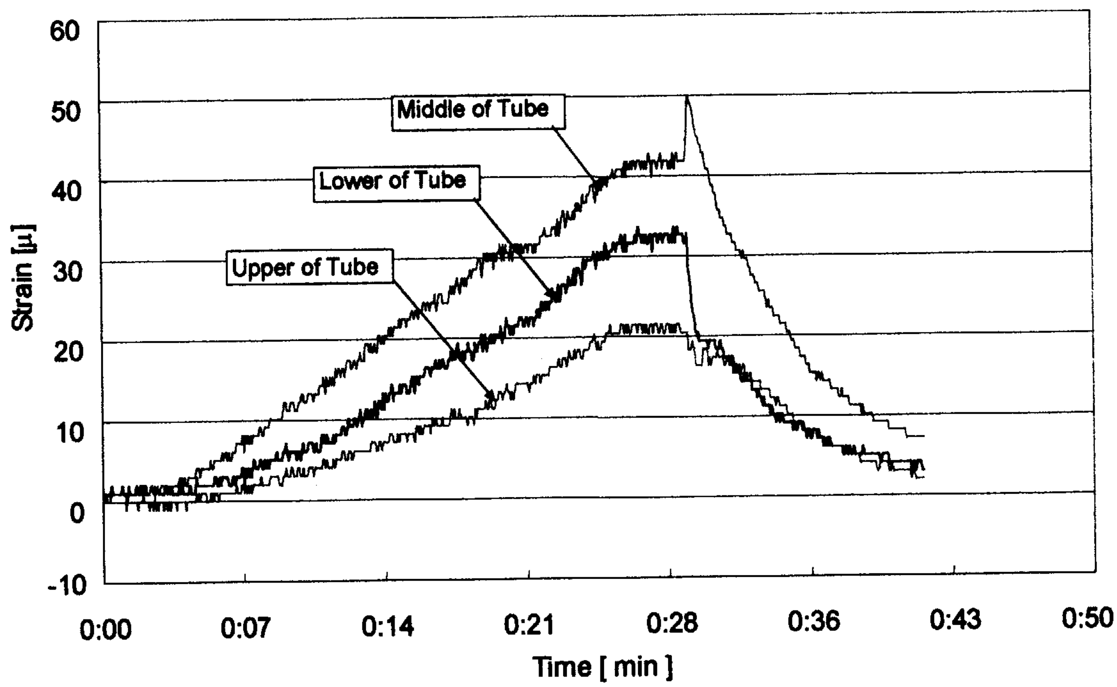
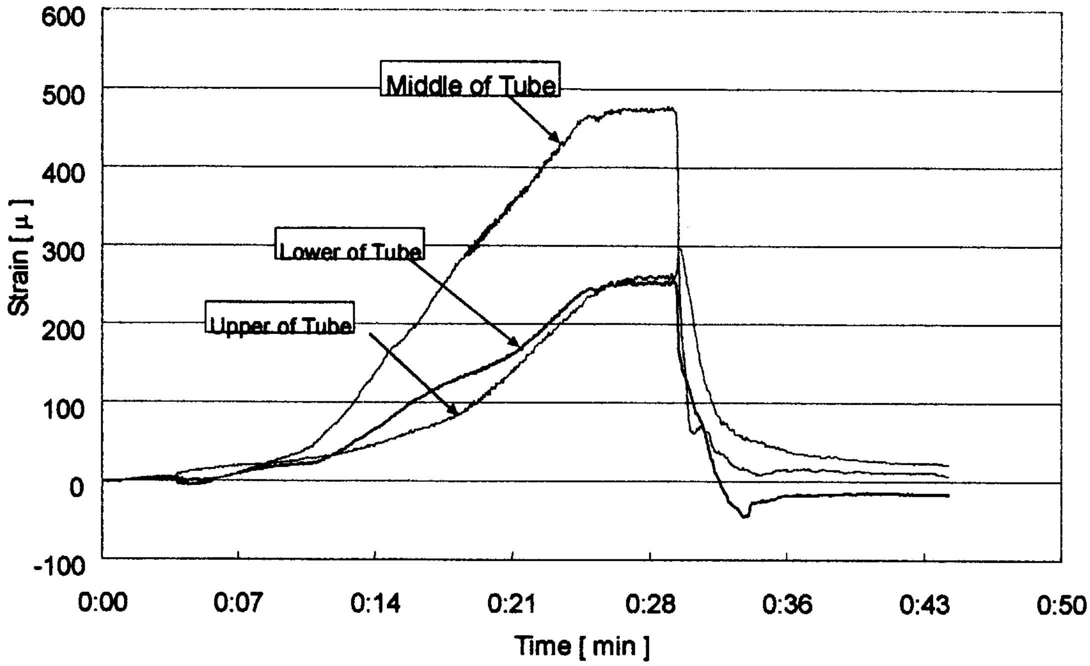


Fig. 5-10(a) Temperature and Strain of No.1 Test



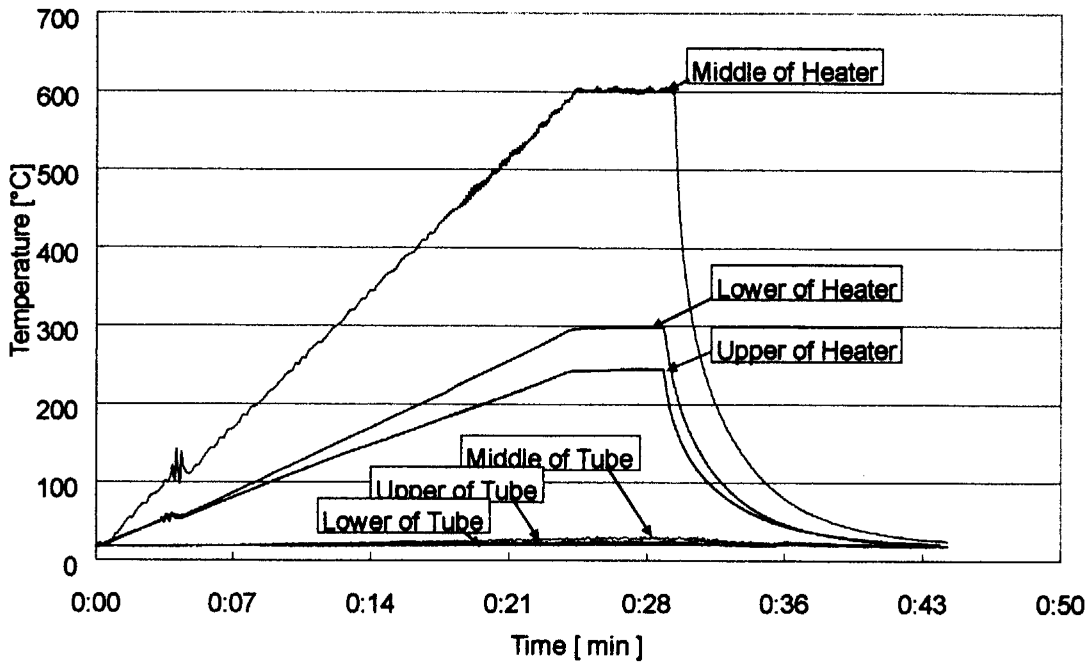
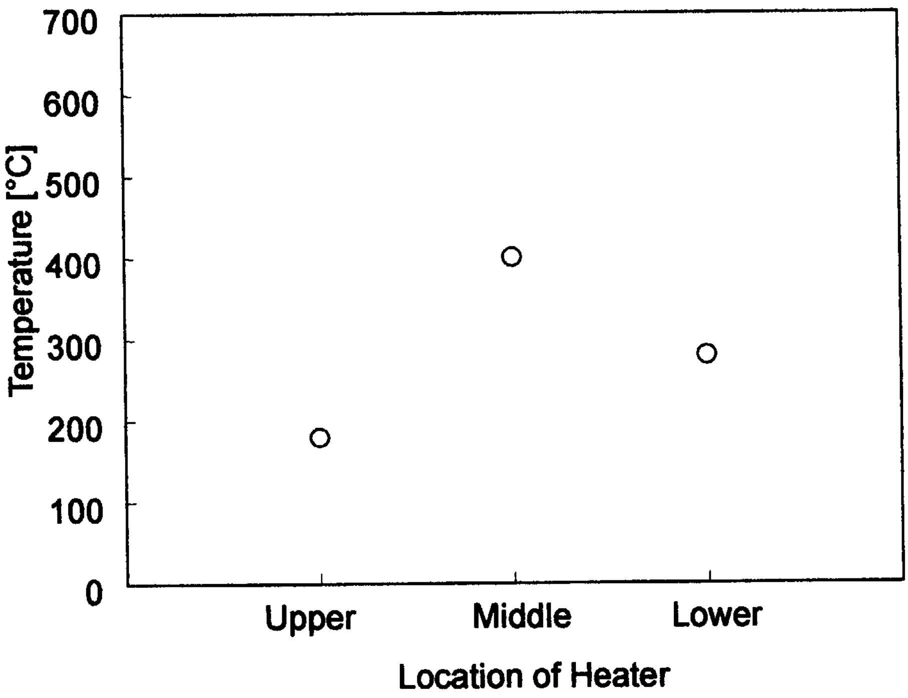
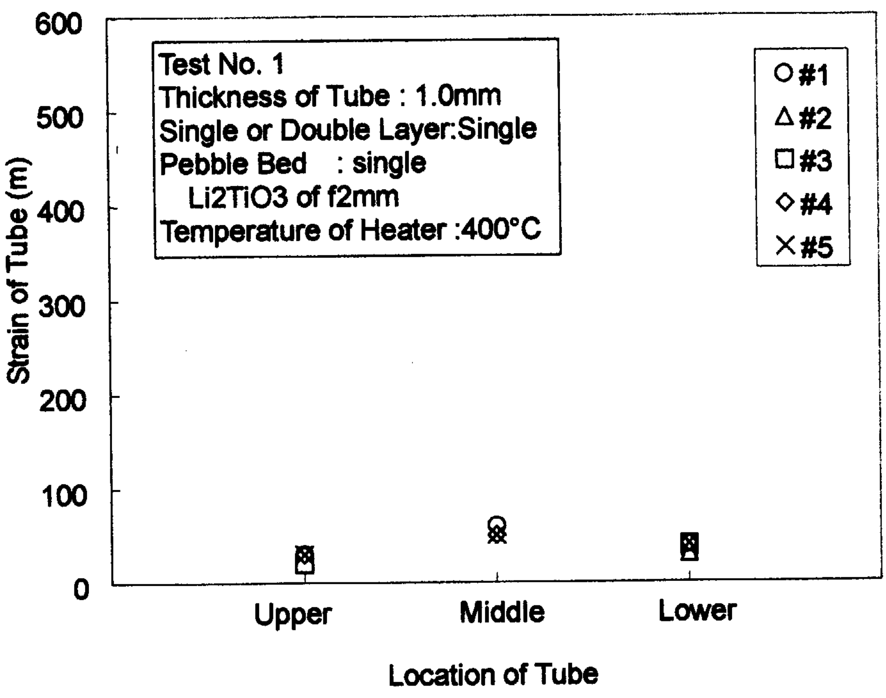


Fig. 5-10(b) Temperature and Strain of the 2nd cycle in No.2 Test

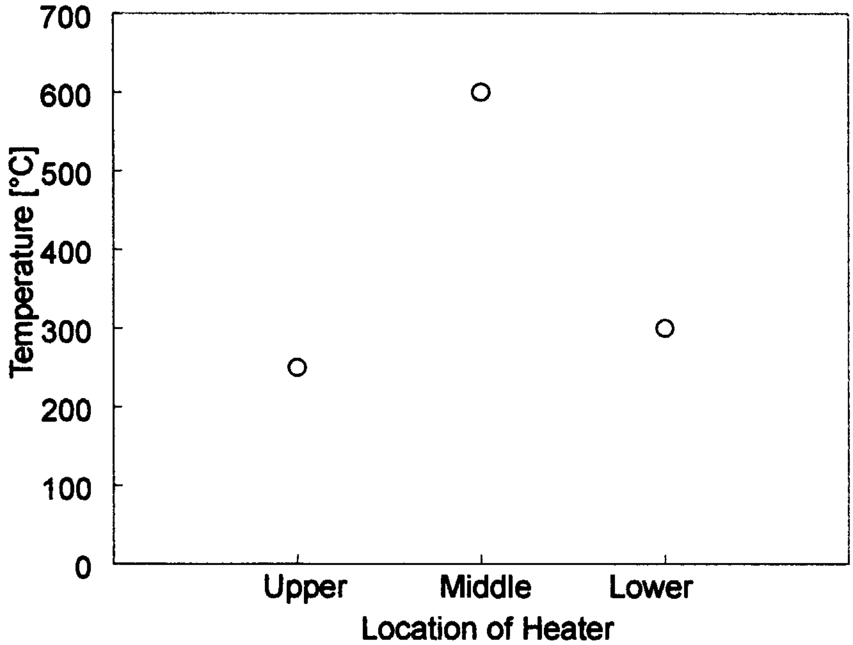


(a) Temperature of heater

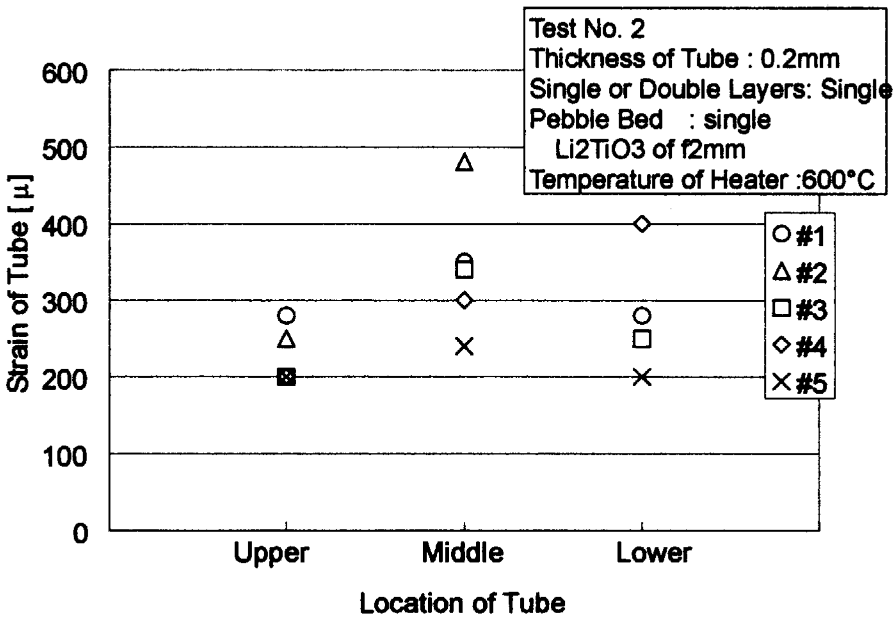


(b) Strain of tube

Fig. 5-11 Temperature of Heater and Strain of Breeder Rod Measured in No.1 Test

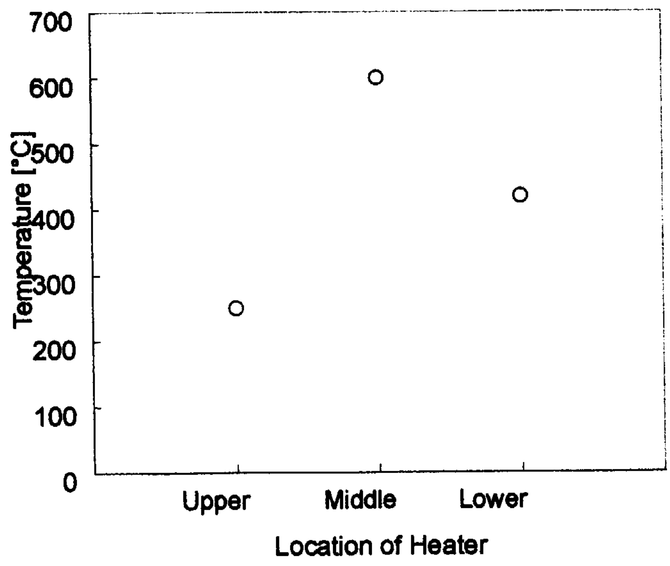


(a) Temperature of heater

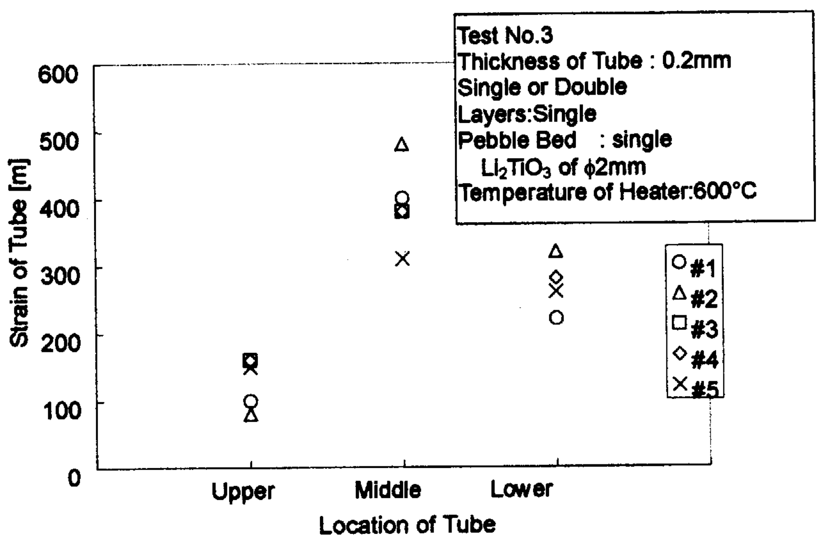


(b) Strain of tube

Fig. 5-12 Temperature of Heater and Strain of Breeder Rod Measured in Test No.2

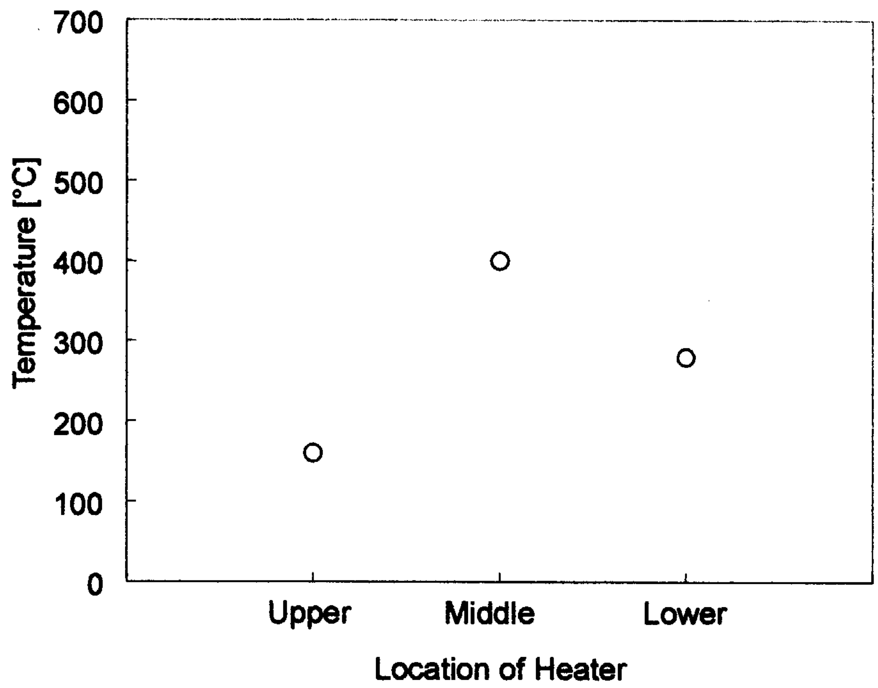


(a) Temperature of heater

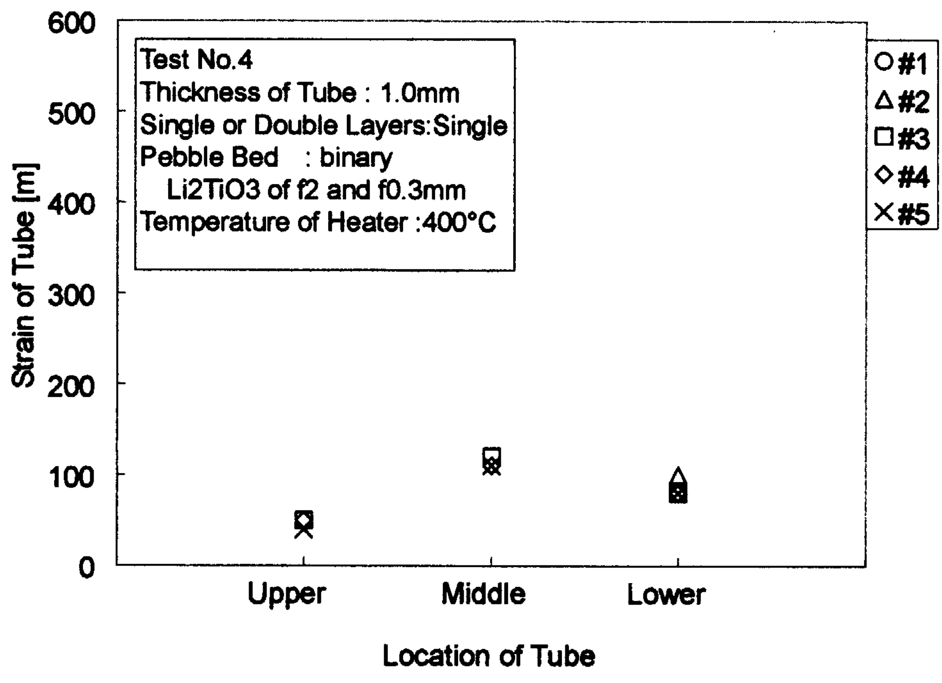


(b) Strain of tube

Fig. 5-13 Temperature of Heater and Strain of Breeder Rod Measured in No.3 Test

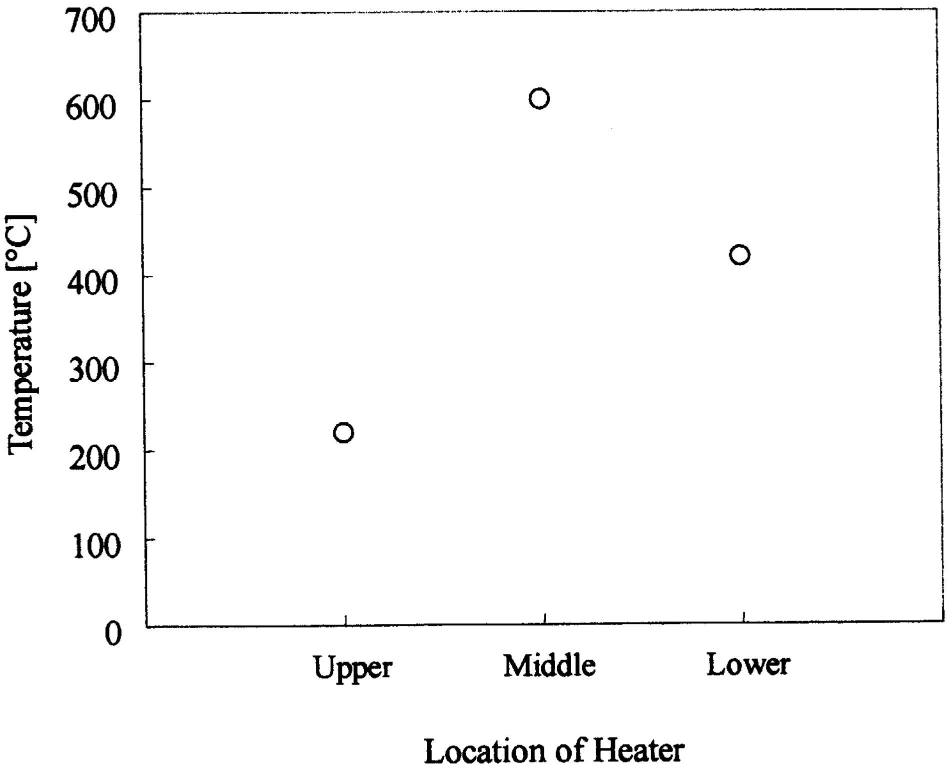


(a) Temperature of heater



(b) Strain of tube

Fig. 5-14 Temperature of Heater and Strain of Breeder Rod Measured in No.4 Test



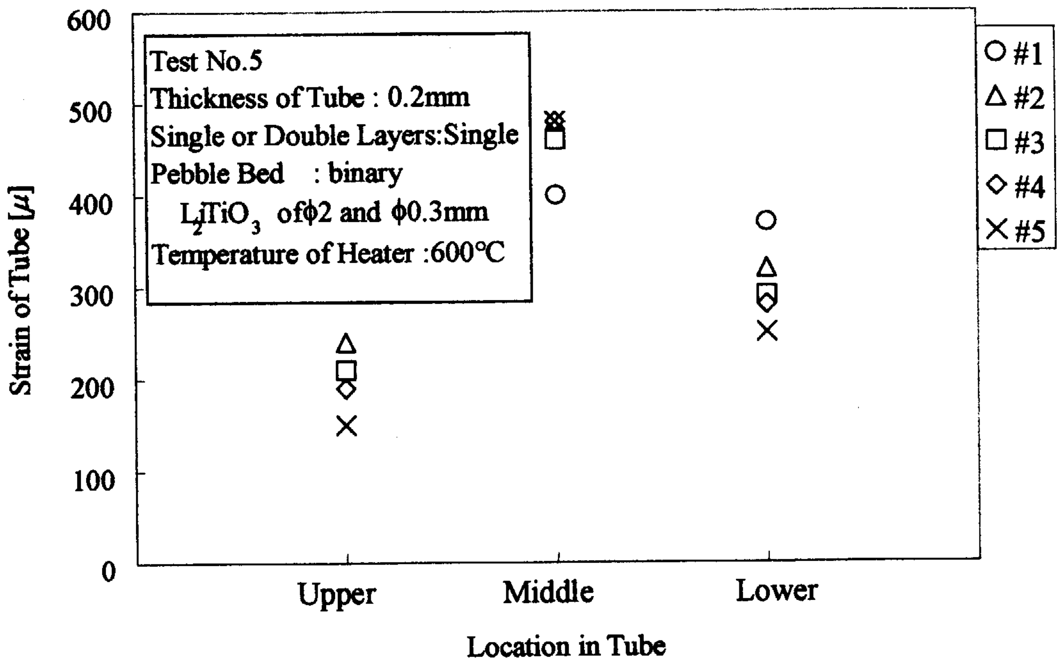
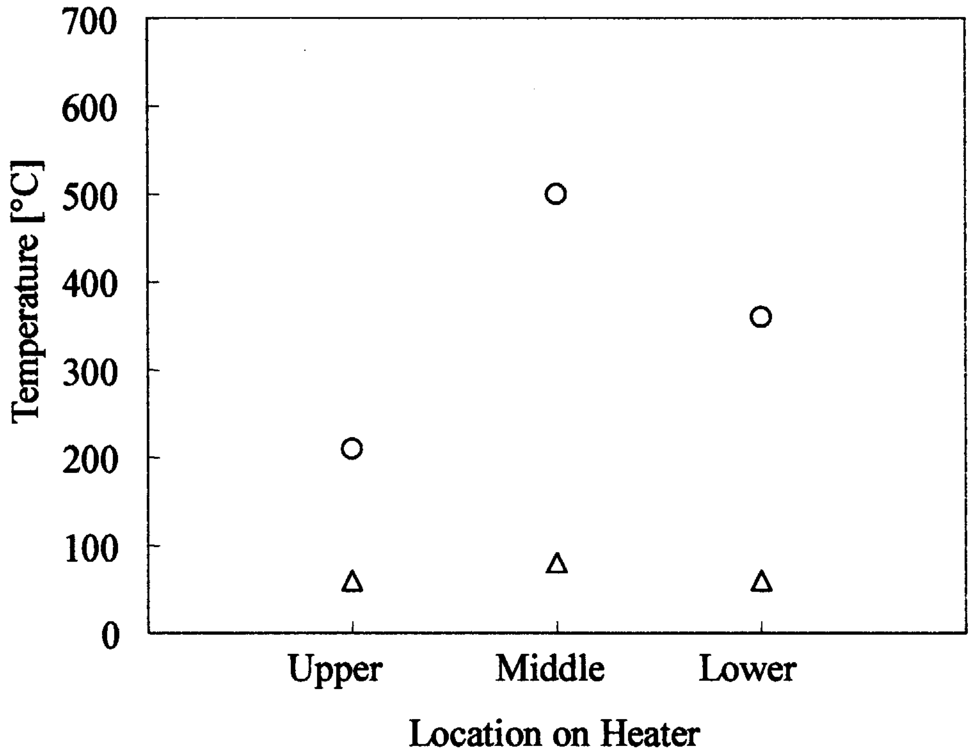


Fig. 5-15 Temperature of Heater and Strain of Breeder Rod Measured in No.5 Test



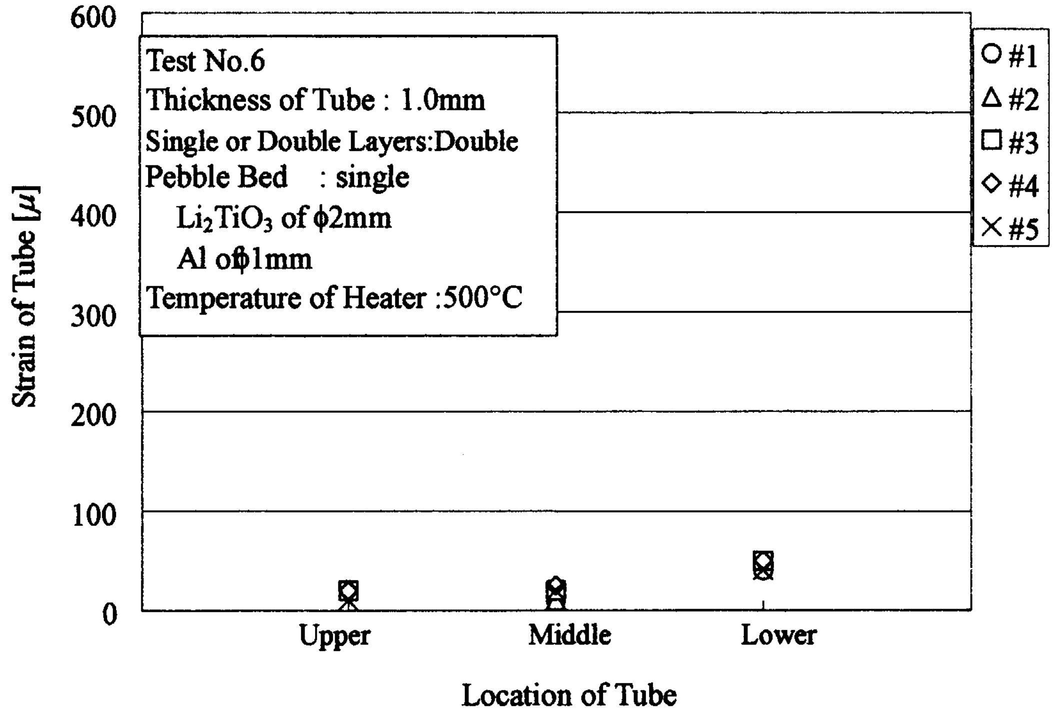


Fig. 5-16 Temperature of Heater and Strain of Breeder Rod Measured in No.6 Test

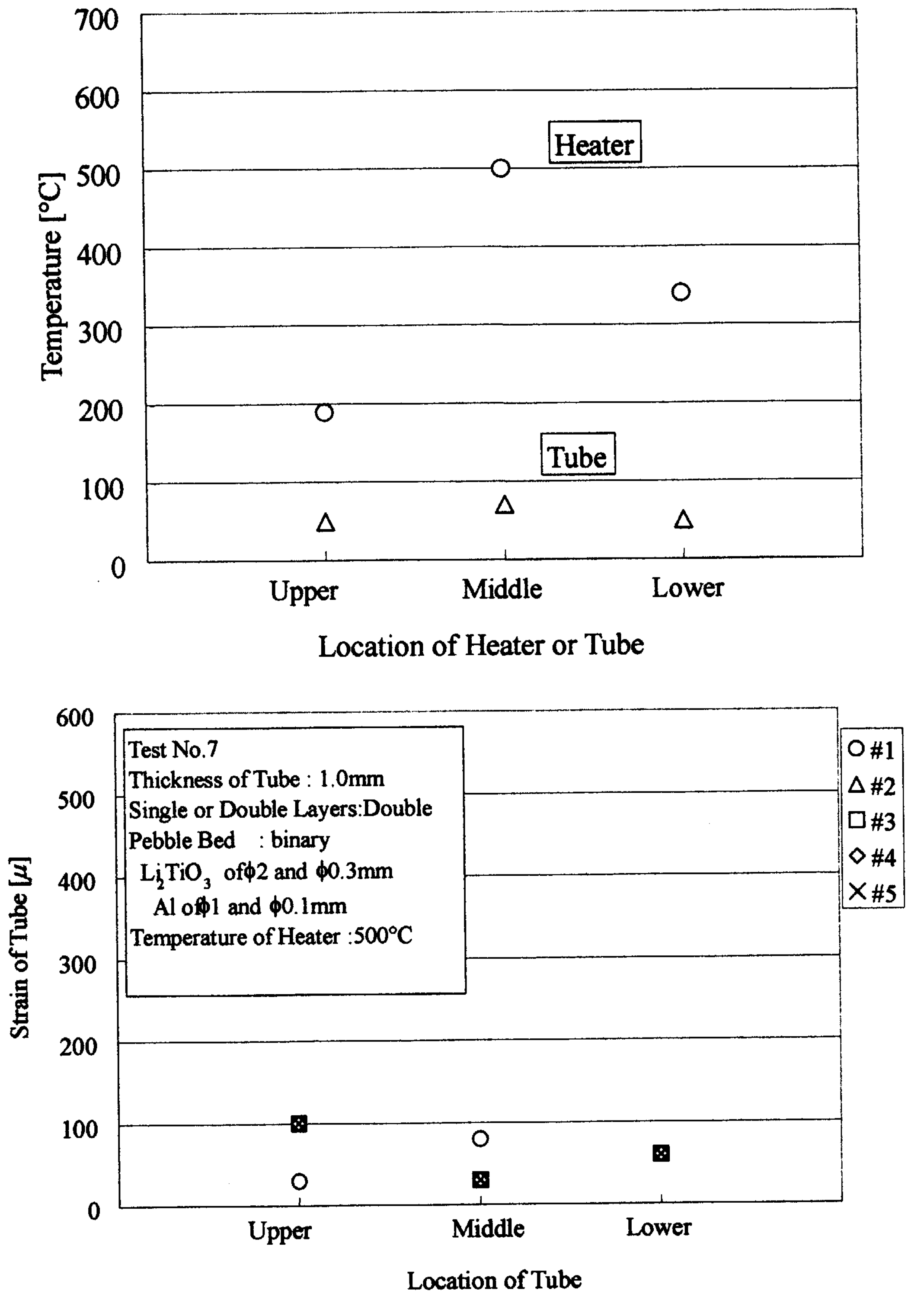


Fig. 5-17 Temperature of Heater and Strain of Breeder Rod Measured in No.7 Test

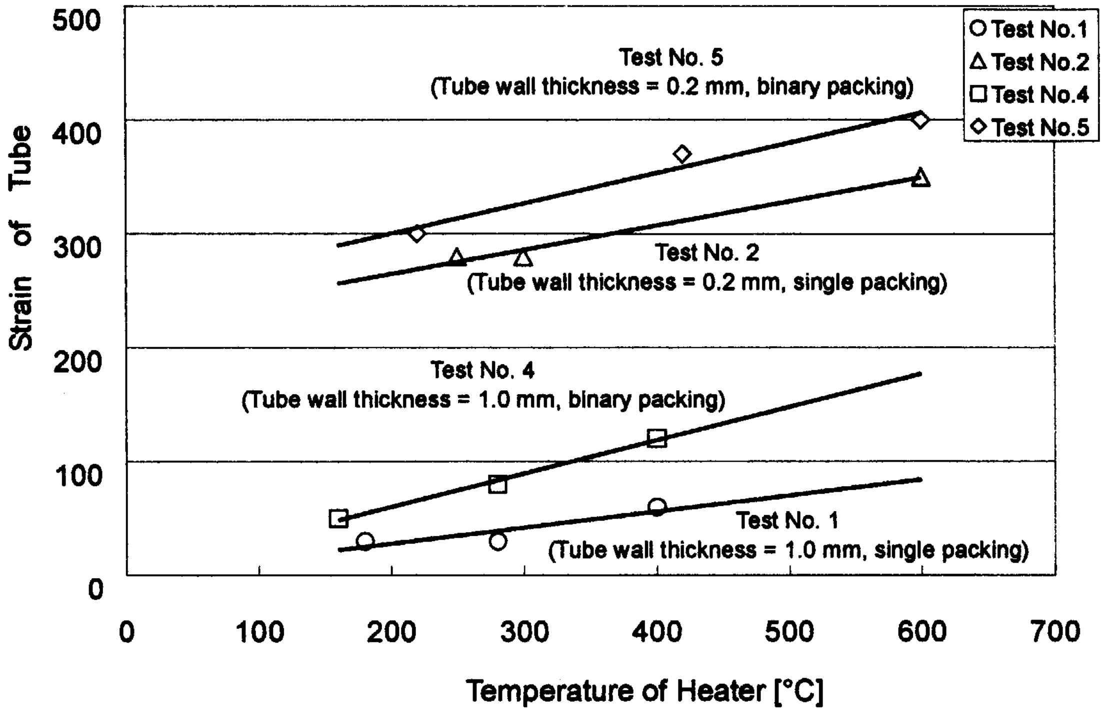


Fig. 5-18 Strain at each Location of Breeder Rod plotted against Temperature of Heater at the same Location during the 1st Thermal Cycle

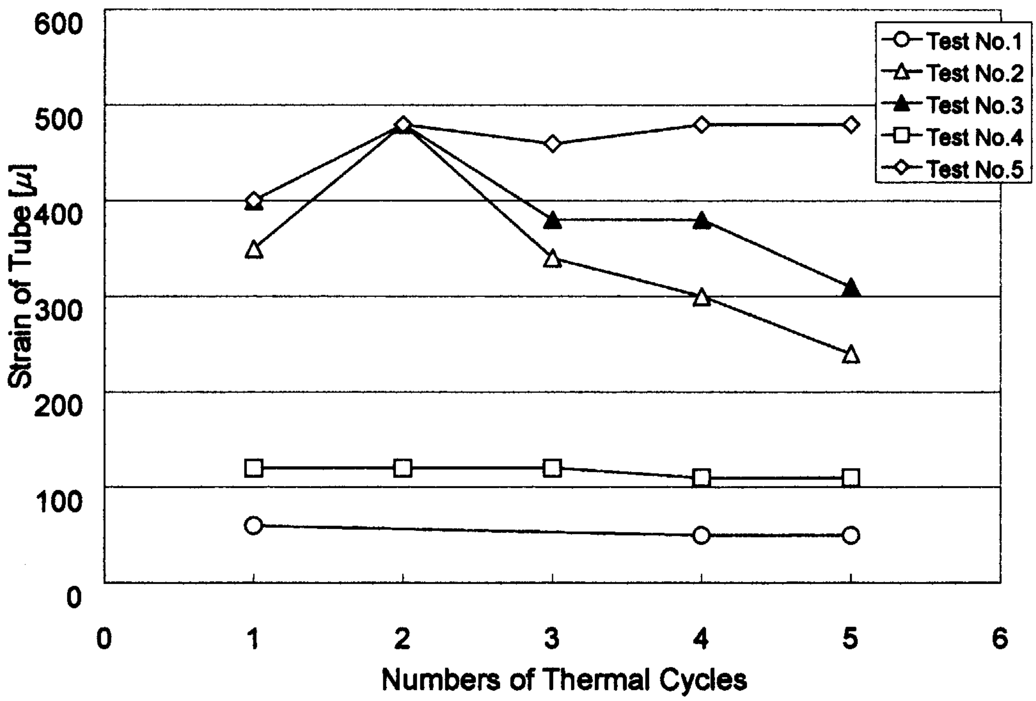
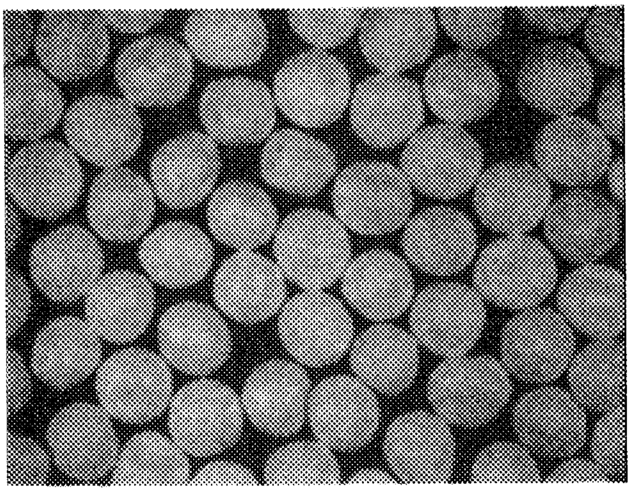
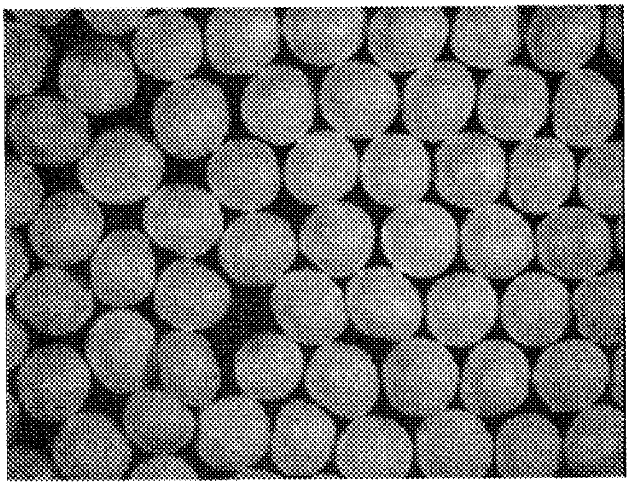


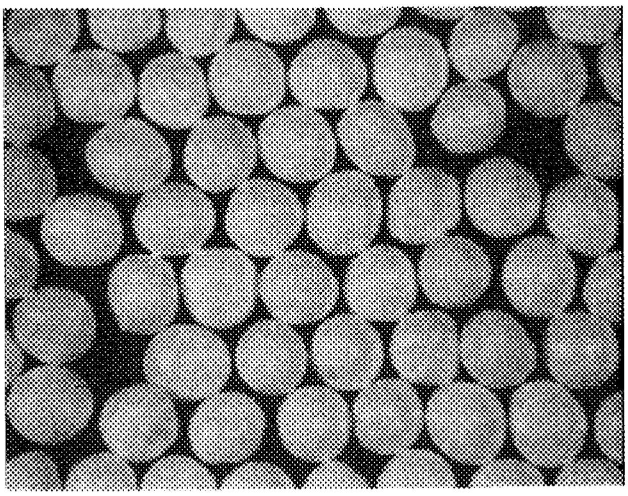
Fig. 5-19 Change of Strains of Breeder Rod at Middle Location during Thermal Cycle Tests



(a) Before tests



(b) After No. 1 test



(c) After No. 2 test

Fig. 5-20　Photographs of Li_2TiO_3 pebbles before and after tests

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国際単位系 (SI) と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長　さ	メートル	m
質　量	キログラム	kg
時　間	秒	s
電　流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光　度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名　称	記　号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19} J

1 u=1.66054×10^{-27} kg

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å= 0.1 nm=10^{-10} m

1 b=100 fm^2=10^{-28} m^2

1 bar=0.1 MPa=10^5 Pa

1 Gal=1 cm/s^2=10^{-2} m/s^2

1 Ci=3.7×10^{10} Bq

1 R=2.58×10^{-4} C/kg

1 rad=1 cGy=10^{-2} Gy

1 rem=1 cSv=10^{-2} Sv

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar, barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	N(=10^5 dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s=10^4 St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)

= 4.184 J (熱化学)

= 4.1855 J (15 °C)

= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)

= 75 kgf·m/s

= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Thermal Cycle Test of Elemental Mockups of ITER Breeding Blanket