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ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

FUEL-ELEMENT VIBRATION AND BEARING PAD TO PRESSURE TUBE FRETTING

VIBRATION DE L'ÉLÉMENT COMBUSTIBLE ET FROTTEMENT PATIN D'APPUI-TUBE DE FORCE

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Chalk River, Ontario K0J 1J0
August 1990 août

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RÉSUMÉ

L'exploitation à des températures d'ébullition provoque une augmentation de la vitesse d'écoulement dans les canaux de combustible, ce qui pourrait conduire à des vibrations excessives des éléments combustibles et au frottement des patins d'appui contre les tubes de force. La base de données actuelle sur les essais d'endurance ne comprend pas toute la gamme des conditions d'exploitation des canaux de combustible. Notamment, après le renouvellement du combustible, certains canaux adaptés à des modèles futurs pourraient demander des conditions d'écoulement diphasique non comprises dans les limites des conditions d'essai d'endurance.

Les essais d'endurance effectués en vraie grandeur dans des conditions eau-vapeur réalistes consomment beaucoup d'énergie. On a donc effectué des essais fondamentaux en laboratoire afin de déterminer une matrice d'essais d'endurance qui engloberait de façon satisfaisante toute la gamme des conditions d'exploitation futures, tout en permettant de réduire le nombre d'essais et la quantité d'énergie consommée par essai. Les études en laboratoire avaient pour but principal la détermination des relations entre : 1) les conditions d'écoulement dans les canaux de combustible et la vibration des éléments combustibles, et 2) la vibration des éléments combustibles et le frottement des patins d'appui contre les tubes de force.

On a mesuré la réaction (vibration) d'un élément combustible particulier dans toute une gamme de conditions d'exploitation englobant des conditions réalistes de canal de combustible et des conditions d'essai d'endurance simulées. À des taux de vide élevés, l'amplitude de vibration mesurée dans un milieu air-eau était beaucoup plus importante que dans un milieu vapeur-eau, alors qu'à de faibles taux de vide, l'amplitude était la même dans les deux cas. Les amplitudes mesurées dans le milieu vapeur-eau ne variaient que légèrement dans la plage des températures et des pressions utilisées pour l'essai.

Les effets de la température, de l'épaisseur de la couche d'oxyde du tube de force, de l'amplitude des vibrations et de l'origine (fabricant) des patins d'appui sur l'usure des tubes de force par frottement ont été examinés. L'usure par frottement est intimement liée à la température. Dans le cas d'amplitudes de vibration trois à quatre fois supérieures à celles attendues dans les conditions que l'on retrouve dans le réacteur, l'usure par frottement la plus poussée a été observée dans la plage de température de 225 à 286 °C. L'usure par frottement était sept fois plus faible à des températures plus élevées (300 et 315 °C) et à des températures plus basses (25 et 150 °C).

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ABSTRACT

Fuel channel operation under boiling condition results in increased flow velocities, which may lead to unacceptable fuel-element vibration and bearing pad to pressure tube fretting. The existing endurance test database does not fully cover the range of future channel operating conditions. In particular, after refuelling, some channels for future designs may operate with two-phase flow conditions outside the range of endurance test conditions.

Full-scale endurance testing at realistic steam-water conditions involves substantial energy costs. Therefore, fundamental laboratory investigations were conducted to define an endurance test matrix which adequately envelops the future range of operating conditions while minimizing both the number of tests and the energy requirement of individual tests. The main focus of the laboratory investigations was to establish the relationships between: (1) fuel channel flow conditions and fuel-element vibration, and, (2) fuel-element vibration and bearing pad to pressure tube fretting.

The vibration response of a single fuel element was measured over a wide range of operating conditions covering realistic fuel channel conditions and simulated endurance testing conditions. For high void fractions, the vibration amplitudes measured in air/water were much higher than in steam/water, while for low void fractions, the amplitudes were similar. The measured amplitudes in steam/water varied very little over the range of temperature and pressure investigated.

The effects of temperature, pressure tube oxide thickness, vibration amplitude and bearing pad manufacturer on pressure tube fretting were investigated. The fretting rate is extremely temperature dependent. For vibration amplitudes about three or four times greater than expected in-reactor conditions, peak fretting rates were observed in the 225 to 286°C temperature range. Fretting rates were seven times less at the higher temperatures of 300 and 315°C, and the lower temperatures of 25 and 150°C.

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1. INTRODUCTION

Fuel channel operation under boiling condition results in increased flow velocities, which may lead to unacceptable fuel-element vibration and bearing pad to pressure tube fretting. The existing endurance test database does not fully cover the range of future channel operating conditions. In particular, after refuelling, some channels for future designs may operate with two-phase flow conditions outside the range of endurance test conditions. Additional endurance testing to envelop future channel operating conditions has been recommended by the Task Group on Boiling in CANDU* Heat Transport Systems.

Full-scale endurance testing at realistic steam-water conditions involves substantial energy costs. Therefore, fundamental laboratory investigations were conducted to define an endurance test matrix which adequately envelops the current and future range of operating conditions while minimizing both the number of tests and the energy requirement of individual tests. The main focus of the laboratory investigations was to establish relationships between: (1) fuel channel flow conditions and fuel-element vibration, and, (2) fuel-element vibration and bearing pad to pressure tube fretting.

2. FUEL-ELEMENT VIBRATION

Turbulence-induced fluid forces that excite fuel elements are affected by changing flow parameters. To determine suitable flow conditions for the endurance test, the relationship between fuel response and flow conditions is required.

All previous fundamental tests in two-phase flow were carried out in support of the Boiling Light Water (BLW) reactor program. Pettigrew and Gorman (1973) [1] performed steam/water tests on a single heated cylinder and Pettigrew and Turner (1973) [2] performed in-reactor tests on fuel elements within an actual fuel bundle. Since flow rates are lower and steam quality is higher in BLW reactor fuel channels, the results from these earlier tests cannot be applied to Pressurized Heavy Water (PHW) reactor fuel bundles.

A test section containing a single fuel element surrounded by "dummy" element sections was designed, assembled and tested in the Chalk River Laboratories (WAFER) air/water loop and the Chalk River Laboratories (MR-1) (FLARE) steam/water loop. The response of a single fuel element was measured over a wide range of void fractions (0 to 90%) and mass fluxes (1250 to 11250 kg/(m^2•s)) in both air/water and steam/water axial flow. The steam/water tests were done at three pressures: 3.47, 5.50 and 9.86 MPa, to investigate the effect of pressure on vibration response. This is necessary, since a fuel channel endurance test must be done at lower pressures to allow for realistic void fraction simulation by flashing.

2.1 Test Apparatus

The test section was designed to maintain close geometric, fluid dynamic and structural dynamic similarity with fuel elements under actual operating conditions. The final design is shown in Figure 1. A description of the test section geometry is given in Table 1. A real fuel element is mounted on a flange at one end and is secured to a zirconium sleeve at the other end. The symmetrically-spaced dummy element sections surround the central fuel element.

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* CANDU: CANada Deuterium Uranium, Registered Trademark

Vibration response of the fuel element was measured using AILTECH weldable strain gauges which are designed for use under high temperature and pressure conditions. Four strain gauges were mounted in diametrically opposite pairs, at 90° from one another, at the midpoint along the fuel-element length.

The strain gauge signals were recorded on magnetic tape and analyzed simultaneously. WAVEPAK, a commercially-available personal computer software package, was used to analyze the data. The frequency spectra were stored and could be accessed for further analysis.

2.2 Test Results

2.2.1 General Fuel-Element Vibratory Behaviour

Within a fuel bundle, each element behaves differently and the vibratory response of a fuel element may change with power level and/or time. A wide variation in fuel-element response with reactor power level was noted by Pettigrew and Turner (1973) [3]. In the present study, obvious differences were found in the response spectra obtained between Series A and Series B steam/water tests. Figure 2 shows the transition from several low-amplitude peaks in Series A to one or two dominant peaks in Series B. Between the two almost identical series of tests, the test section was dismantled and strain gauges were replaced.

The change in the fuel-element response may be explained by a shift in the position of one or more fuel pellets. During Series A, the occurrence of several frequency peaks may have been due to the free movement of the fuel pellets within the fuel sheath. As the pellets move about, the fuel-element mass distribution and stiffness could fluctuate and cause the response frequency to fluctuate accordingly. The moving pellets could also provide some damping and therefore cause reduced peak amplitudes. This is apparent in the broader and lower frequency spectra of Series B, as shown in Figure 2. While removing and replacing the test section, one or more pellets probably shifted so that the pellet(s) could no longer move as freely within the fuel sheath. This lack of fuel-pellet motion should result in the large magnitude, single-frequency peaks found in Series B.

Although the vibration response in the Series A tests is lower than in the Series B tests, the trends with changing flow parameters are very similar. The Series B test results are used to establish the relationship between fuel-element vibration and flow conditions, as discussed in the following sections.

2.2.2 Air/Water versus Steam/Water

It has been generally accepted that air/water flow results in larger vibration amplitudes than steam/water flows. However, in the present study, at low void fractions and for mass flows above 3750 kg/(m^2•s), the steam/water flow resulted in slightly higher amplitudes. Figure 3 shows the change in vibration response as the void fraction is carried at a mass flux of 5000 kg/(m^2•s). Response to steam/water is slightly higher than air/water below 20% void; above 30% void response to air/water flow is much higher than response to steam/water flow.

2.2.3 Effect of Void Fraction

In air/water, the effect of void fraction is rather dramatic. Figure 3 shows that, as the void fraction increases, the vibration response of the fuel element increases rapidly. A maximum is reached at about 80% void.

In steam/water, the void fraction effect is reduced. At the highest temperature and pressure (reactor operating conditions), the vibration response changes by only a factor of two over a range of void fractions from 0 to 80%. Vibration response in steam/water decreases or increases only very slightly up to 60% void.

2.2.4 Effect of Mass Flux

Examples of the effect of mass flux for 25 and 50% void are shown in Figure 4. The air/water results suggest that the vibration amplitudes eventually decrease with increasing mass flux. In steam/water tests, a decrease in response with increasing mass flux was only seen at the lowest pressure (3.47 MPa) and then only at very high void fractions and mass fluxes.

The air/water results also indicate a sharp increase in vibration amplitude at low mass fluxes and high void fractions. Such an increase was not seen in the steam/water results.

2.2.5 Effect of Flow Regime

The trends in vibration amplitude with mass flux and void fraction can change abruptly due to flow regime transitions. The differences between air/water and steam/water trends, as noted above, are due, at least in part, to the fact that their transitions from one flow regime to another do not occur at the same flow conditions (as defined by void fraction and mass flux). In the case of air/water data, it is felt that the decreasing amplitude response with increasing mass flux reflects a transition to an annular- or wall-type flow, which does not provide as turbulent a flow structure next to the fuel element. This transition does not seem to have occurred in the steam/water data except, perhaps, for 3.47 MPa at very high void fractions.

2.2.6 Effect of Temperature and Pressure

In general, the steam/water test results indicate that, in the range of flow conditions that were tested, changing the pressure from 3.47 to 9.86 MPa does not significantly alter the vibration amplitudes. The Test Series B results show that for all three pressures, the present operating range of flow conditions will produce maximum vibration amplitudes of between 6 and 16 µm. These small amplitudes are typical of PHW reactor fuel-element response.

The only notable difference between the results for the three pressures occurs in the low mass flux and high void fraction region. In this region, it appears that the lower temperature flows have slightly higher excitation levels. As one would expect, the lowest pressure steam/water results are the most similar to the air/water results.

2.3 Further Work

In preparation for the full-scale endurance test, a fuel bundle will be tested in a prototype fuel channel. A limited test matrix of flow conditions will be used to determine the vibration response (rocking motion) of the fuel bundle.

3. BEARING PAD TO PRESSURE TUBE FRETTING

As part of the fundamental laboratory investigations to define an endurance test matrix enveloping current and future channel operating conditions, impact fretting testing of fuel-sheath bearing pad and pressure tube specimens was conducted in the Chalk River Laboratories high-temperature impact fretting-wear test facility.

The purpose of these tests was to determine the effect of various parameters on pressure tube fretting. The most important parameter to be studied was temperature, since endurance testing might be conducted at lower temperatures to enable the required void fraction of steam to be achieved via flashing. Therefore, the major purpose of these tests was to determine the difference in pressure tube fretting at the proposed endurance test temperature of 250°C and the CANDU channel outlet temperature of 315°C. Secondary parameters to be studied included vibration amplitude, motion type, pressure tube oxide and fuel sheath manufacturer.

3.1 Test Apparatus and Description

The impact fretting-wear test facility consists of six test rigs connected to a water storage tank and accumulator, and operated in a bleed-and-feed mode. The temperature and pressure inside the rigs are independently controlled so both high-temperature, pressurized water and saturated steam conditions can be achieved.

The test rigs simulate the dynamic interaction characteristic of CANDU components such as fuel channels, steam generators and heat exchangers. Unlike a conventional wear-testing machine, where the contact motion is strictly controlled, the excitation in these rigs is remote from the point of specimen contact. This arrangement allows the wear surfaces to move relatively freely against one another, simulating the motion in real components.

During testing, noncontact transducers mounted inside the rigs monitored the fuel sheath position. Also, interaction forces between the sheath and pressure tube specimens were measured at room temperature before each test using four miniature piezo-electric force transducers.

The environment for all tests was pressurized water at 10 ±0.5 pH, which is typical of the CANDU primary circuit. Hydrazine was added to the make-up water at room temperature to increase the pH level and to scavenge dissolved oxygen. The dissolved oxygen level during testing was typically 30 ppb.

3.2 Dynamic Interaction

Fretting is dependent on the dynamic interaction between the contacting surfaces. Dynamic interaction combines both relative displacement and contact force. An appropriate parameter for expressing dynamic interaction is work-rate, which is defined as the time-averaged integral of contact force and sliding distance.

Fuel-sheath bearing pad to pressure tube vibration occurs at two frequencies: predominantly at 10 Hz due to bundle rocking, and at 30 Hz due to element flexural vibration. In liquid flow, maximum vibration levels generally occur at the side mid-plane of the inlet bundle. Typical maximum inlet bundle vibrations measured in liquid flow during Bruce out-reactor endurance testing were about 30 μm RMS for normal bundle support. In two-phase flow, maximum vibration levels probably occur in the last two or three bundles towards the outlet end. Typical mid-span element displacements measured in fundamental two-phase flow-induced vibration tests were about 15 μm RMS .

Four different sinusoidal vibrations were used in the test program: impacting at 15 Hz, rubbing at 15 Hz, impacting at 25 Hz and rubbing at 25 Hz. These four vibration types are shown schematically in Figure 5. The schematic shows typical fuel-sheath bearing pad to pressure tube motion at about 100 times magnification, so the pressure tube surface appears flat. Typical displacements and forces for each motion type are also included.

The amplitudes of the two motion types at 15 Hz were typically three times greater than the amplitudes at 25 Hz. For both frequencies, the tangential components of vibration were equal, while the normal components were nearly zero for rubbing motion and almost equal to the tangential components for impacting motion. The contact force magnitudes for impacting motion at both frequencies were equal and about two or three times greater than the magnitudes for rubbing motion.

The motion type for the majority of the test program was impacting at 25 Hz. Typical displacements and forces for this motion type were 65 μm RMS and 0.4 N RMS, respectively. Therefore, the test displacements for this motion type were three to four times greater than typical in-reactor displacements.

No experimental measurements of fuel-sheath bearing pad to pressure tube dynamic contact forces or work-rates have been made for CANDU fuel bundles. Therefore, predictions of in-reactor dynamic contact forces were obtained by simulating fuel-element vibration and fuel-element bearing pad to pressure tube dynamic interaction using the VIBIC computer code.

The excitation for the VIBIC simulation was circular sinusoidal at 25 Hz, with the force magnitude chosen to result in fuel element mid-span displacements ranging from 10 to 30 μm when no bearing pad to pressure tube contact was allowed. Typical mid-span displacements and forces with bearing pad to pressure tube contact were 15 μm and 0.25 N, respectively. Therefore, the contact forces for impacting motion fretting tests at 25 Hz were about 1.5 times greater than predicted in-reactor contact forces. Since fretting damage is dependent more on contact force than on relative displacement, the fretting rates in this test program were probably about 1.5 times greater than in-reactor fretting rates.

3.3 Test Results

The test program consisted of about 70 tests of 250 h duration. The effects of temperature, pressure tube oxide, vibration amplitude and fuel sheath manufacturer were investigated. At least three tests were conducted at each condition to increase data reliability.

The results of the test program are summarized in Table 2. The fretting damage is recorded in terms of pressure tube fretting rate, which is defined as the equivalent fretting depth per unit time. The fretting rates were calculated from measured wear volumes, assuming uniform depth over the bearing pad to pressure tube contact area. A typical 3-D surface profile of a fretted area is shown in Figure 6. The arithmetic averages of all tests at each temperature are plotted in Figure 7. Separate symbols and curves are drawn for small and large amplitude motion. A vertical line at each data point denotes the minimum and maximum fretting rates observed at each temperature.

The variation in test results at the same condition was dependent on fretting rate. Conditions which resulted in low fretting rates (0.1 pm/cycle) exhibited standard deviations of about 20 to 30%, while conditions with severe fretting (10 pm/cycle) had standard deviations of up to 100%. Therefore, the large variation in test results observed at temperatures in the 225 to 286°C range where the fretting rates were severe is believed to be characteristic of the fretting phenomenon. The variation attributable to experimental error is 20 or 30%.

No significant difference in pressure tube fretting rate was observed for the two fuel sheath manufacturers, Zircatec and General Electric Canada (GEC).

3.3.1 Effect of Pressure Tube Oxide

The presence of an initial layer of pressure tube oxide slightly reduced the fretting rate at lower temperatures, where the material oxidation rate was low. However, at higher temperatures, the presence of an initial layer did not significantly affect the fretting rate. Overall, the effect of pressure tube pre-oxidation was insignificant in comparison to the effects of vibration amplitude and temperature.

3.3.2 Effect of Vibration Amplitude

The fretting rate was observed to be strongly dependent on vibration amplitude, but only slightly dependent on motion type. More fretting damage was observed for large amplitude motion corresponding to impacting and rubbing at 15 Hz than for small amplitude motion corresponding to rubbing and impacting at 25 Hz. The variation in test results at the same condition was also dependent on vibration amplitude, with greater variation observed for large vibration amplitude motion.

The fretting rate for large amplitude motion at 250, 286 and 300°C was severe. These results agree with the results of previous investigators, who observed that zirconium fretting damage was dependent on oscillation amplitude, and that the amount of damage increased dramatically at amplitudes exceeding 200 µm. For these tests, tangential displacements averaged 200 µm, but ranged from 50 to 270 µm. Generally, tests with displacements greater than 200 µm exhibited fretting rates ten times greater than those with displacements less than this threshold. Severe fretting of this type should not occur in-reactor, where displacement amplitudes are much less than 200 µm.

3.3.3 Effect of Temperature

The effect of temperature on fretting damage was very significant (see Figure 7). Maximum fretting damage for both small and large vibration amplitudes was observed in the 225 to 286°C temperature range. Less damage occurred at lower temperatures (25 and 150°C) and at higher temperatures (300 and 315°C) for both vibration amplitudes. In particular, the fretting damage for small amplitude motion at 300°C was seven times lower than for the 225 to 286°C temperature range, and was about equal to the fretting rate at lower temperatures. The fretting rate at 300°C for large amplitude motion was also lower than for the 225 to 286°C range, but the effect was less pronounced.

A postulated mechanism to explain this fretting behaviour is the competing effect of both increasing fretting and oxidation with increasing temperature. Fretting wear is known to depend on both wear and corrosion processes, with material oxidation acting to accelerate the normal wear process. In pressure tube fretting, oxidation may act to accelerate the wear process in the 150 to 225°C range, but then may act to limit the process at higher temperatures above 286°C by forming a protective film on the pressure tube surface.

3.4 Future Work

Future tests are planned in water of different pH and dissolved oxygen content to investigate the dependence of pressure tube fretting on water chemistry.

4. CONCLUSIONS

The study of axial, two-phase flow-induced vibration of a fuel element has shown that:

1) The vibration response of a fuel element will change due to pellet movement.

2) Vibration response due to air/water flows is an unrealistic estimate of response due to steam/water.

3) The trends due to void fraction and mass flux are different between air/water and steam/water flow.

4) Flow regime can have a large effect on vibration response.

5) Temperature and pressure, in the steam/water range investigated, did not have a significant effect on vibration response.

6) The fuel elements have a maximum amplitude of approximately 17 µm at operating conditions.

The pressure tube fretting study has shown that:

1) Fuel sheath manufacturer (Zircatec or GEC) does not affect pressure tube fretting significantly.

2) Pressure tube pre-oxidation slightly decreases pressure tube fretting. However, this decrease is insignificant compared to the effects of vibration amplitude and temperature. Pre-oxidation does not provide protection against severe fretting damage.

3) The fretting rate is amplitude dependent. Large amplitude motion causes significantly greater fretting than small amplitude motion. This difference is greater at higher temperatures. Severe fretting occurs for large amplitude motion with amplitudes greater than 200 µm.

4) Maximum fretting damage occurs in the 225 to 286°C temperature range. The fretting rate is less at higher temperatures of 300 and 315°C.

5. RECOMMENDATIONS

Due to the complicated nature of a fuel element, it would be useful to do future tests using a solid cylinder with the same mass and stiffness as a fuel element. These tests would provide reliable frequency, damping and excitation force values for use in design guidelines.

Additional fretting tests should be conducted in the future to determine the effect of water chemistry. Important water chemistry parameters that warrant further study include dissolved oxygen content and pH.

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Thanks are extended to P.L. Ko of NRC for performing 3-D surface profilometry of pressure tube fretting samples.

7. REFERENCES

1. M.J. Pettigrew and D.J. Gorman, "Experimental Studies on Flow-Induced Vibration to Support Steam Generator Design - Part 1: Vibration of a Heated Cylinder in Two-Phase Axial Flow", AECL-4514 (1973).
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TABLE 1

TEST SECTION DESIGN PARAMETERS

Fuel Element	— Length,	L	=	0.495 m
	— OD,	D	=	13.075 mm
	— Wall Thickness,	t	=	0.42 mm
	— Mass/unit Length,	m_t	=	1.12 kg/m
Zirconium Sleeve	— ID	R	=	25.1 mm
Test Section	— Flow Area	A	=	205.6 mm^2
	— Equivalent Diameter			
	a) of the Flow Area	d_e	=	7.8 mm
	b) of the Flow Area	D_e	=	16.4 mm
Inlet Section	— Length		=	0.5 mm
End Condition	— approximately Pinned-Pinned			

TABLE 2: PRESSURE TUBE FRETTING RESULTS

Temperature (°C)	Small Amplitude Impacting and Rubbing				Large Amplitude Impacting and Rubbing			
	Test	Fretting Rate (pm/cycle)	Arithmetic Average	Standard Deviation	Test	Fretting Rate (pm/cycle)	Arithmetic Average	Standard Deviation
25	PT-17	0.1	0.11	0.02	PT-20	0.21	0.26	0.08
25	PT-25	0.13			PT-22	0.22		
25	PT-26	0.13			PT-23	0.35		
25	PT-15	0.12			PT-19	0.15		
25	PT-16	0.11			PT-21	0.35		
25	PT-18	0.078			PT-24	0.26		
150	PT-29	0.14	0.15	0.05	PT-27	0.94	0.38	0.28
150	PT-30	0.13			PT-28	0.34		
150	PT-32	0.23			PT-31	0.22		
150	PT-50	0.076			PT-47	0.23		
150	PT-51	0.15			PT-48	0.23		
150	PT-52	0.2			PT-49	0.29		
225	PT-66	0.32	0.75	0.40				
225	PT-67	1.1						
225	PT-68	0.83						
250	PT-56	0.1	0.38	0.33	PT-53	0.71	10.23	10.01
250	PT-57	0.32			PT-54	6.40		
250	PT-58	1			PT-55	9.60		
250	PT-60	0.12			PT-59	24.20		
250	PT-61	0.26						
250	PT-62	0.49						
275	PT-63	0.26	0.92	0.59				
275	PT-64	1.1						
275	PT-65	1.4						
286	PT-10	0.3	0.64	0.57	PT-2	1.50	9.60	5.86
286	PT-11	0.17			PT-7	2.70		
286	PT-13	1.7			PT-8	14.10		
286	PT-9	0.4			PT-4	13.40		
286	PT-12	0.4			PT-5	13.70		
286	PT-14	0.86			PT-6	12.20		
300	PT-34	0.087	0.11	0.03	PT-33	0.44	4.83	7.79
300	PT-35	0.15			PT-37	0.59		
300	PT-36	0.14			PT-38	1.10		
300	PT-39	0.078			PT-40	6.20		
300	PT-41	0.081			PT-42	0.28		
300	PT-44	0.12			PT-43	3.40		
300	PT-45	0.11			PT-46	21.80		
315	PT-69	0.16	0.17	0.12				
315	PT-70	0.06						
315	PT-71	0.3						

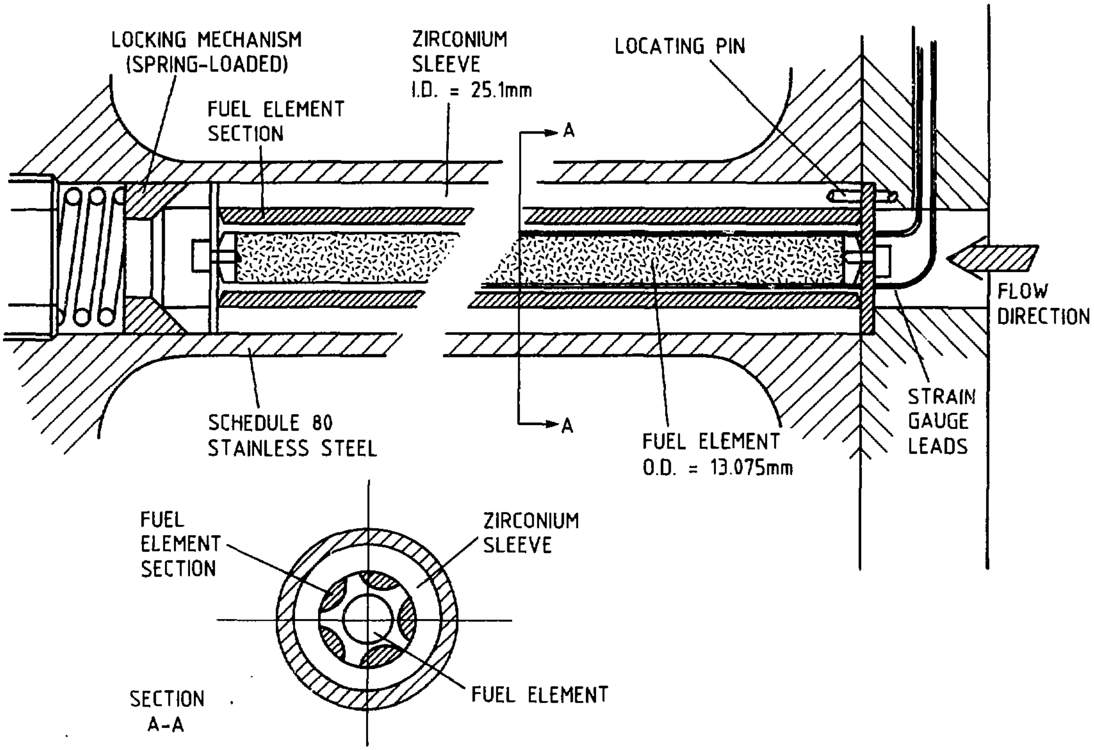


FIGURE 1: Test Section Cross-Sections

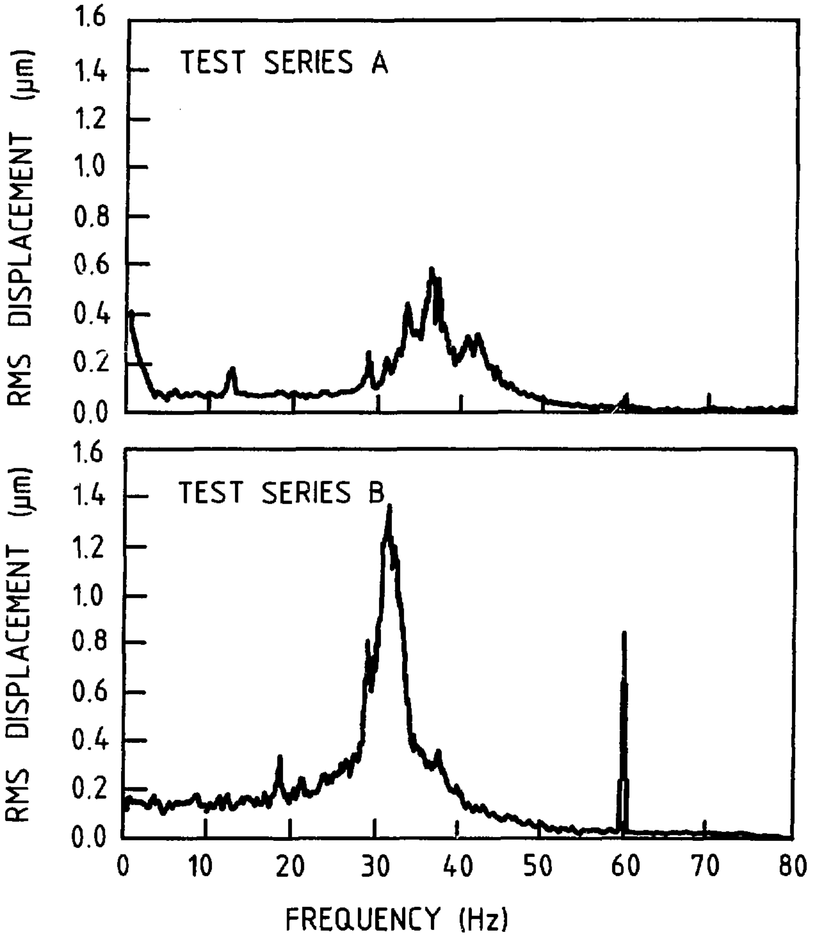


FIGURE 2: Comparison of the Series A and Series B Response PSD for Steam/Water at 5.50 MPa (Void Fraction = 50% and Mass Flux = 5000 kg/(m^2•s))

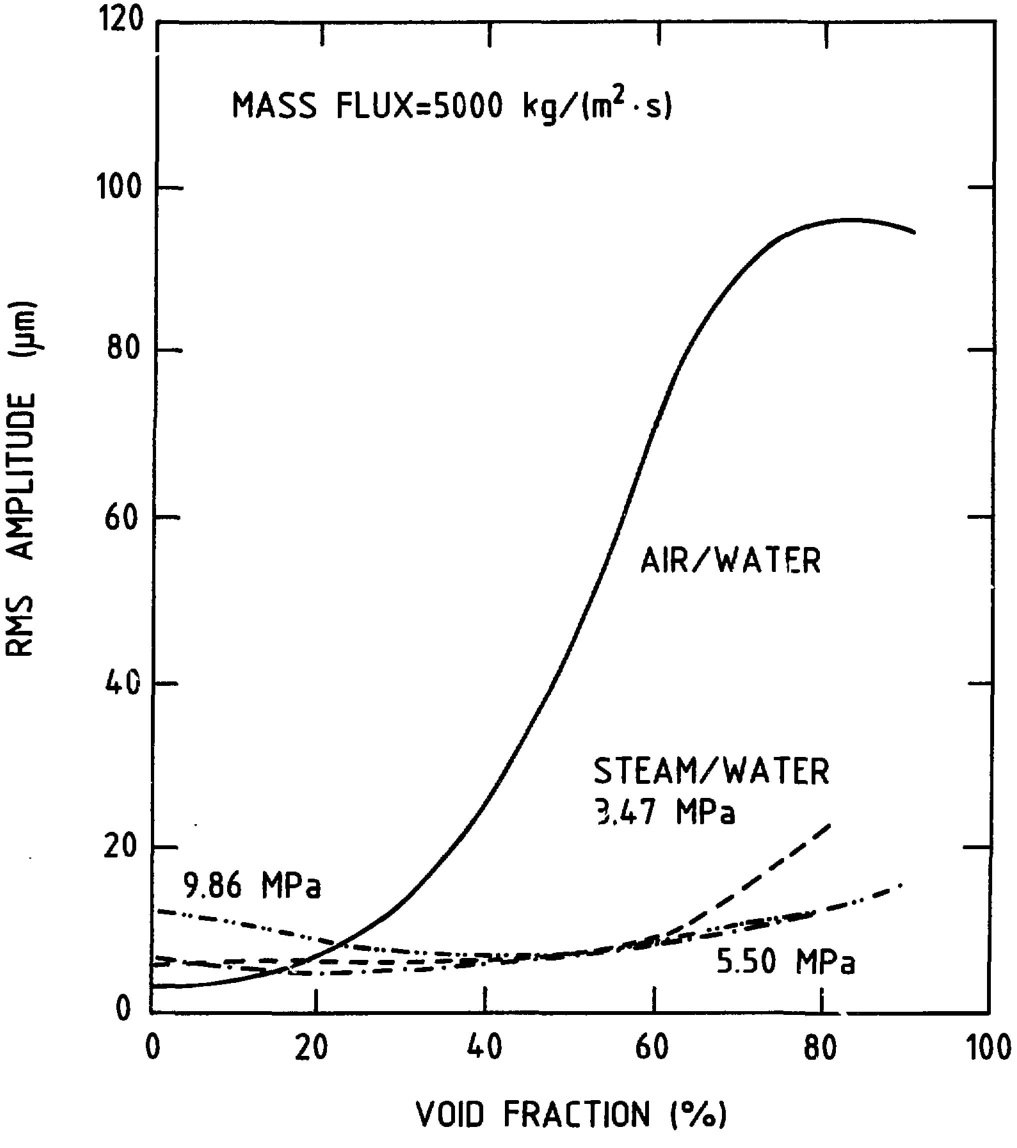


FIGURE 3: Comparison of the Effect of Void Fraction on Vibration Response at Mass Flux = 5000 kg/(m^2•s))

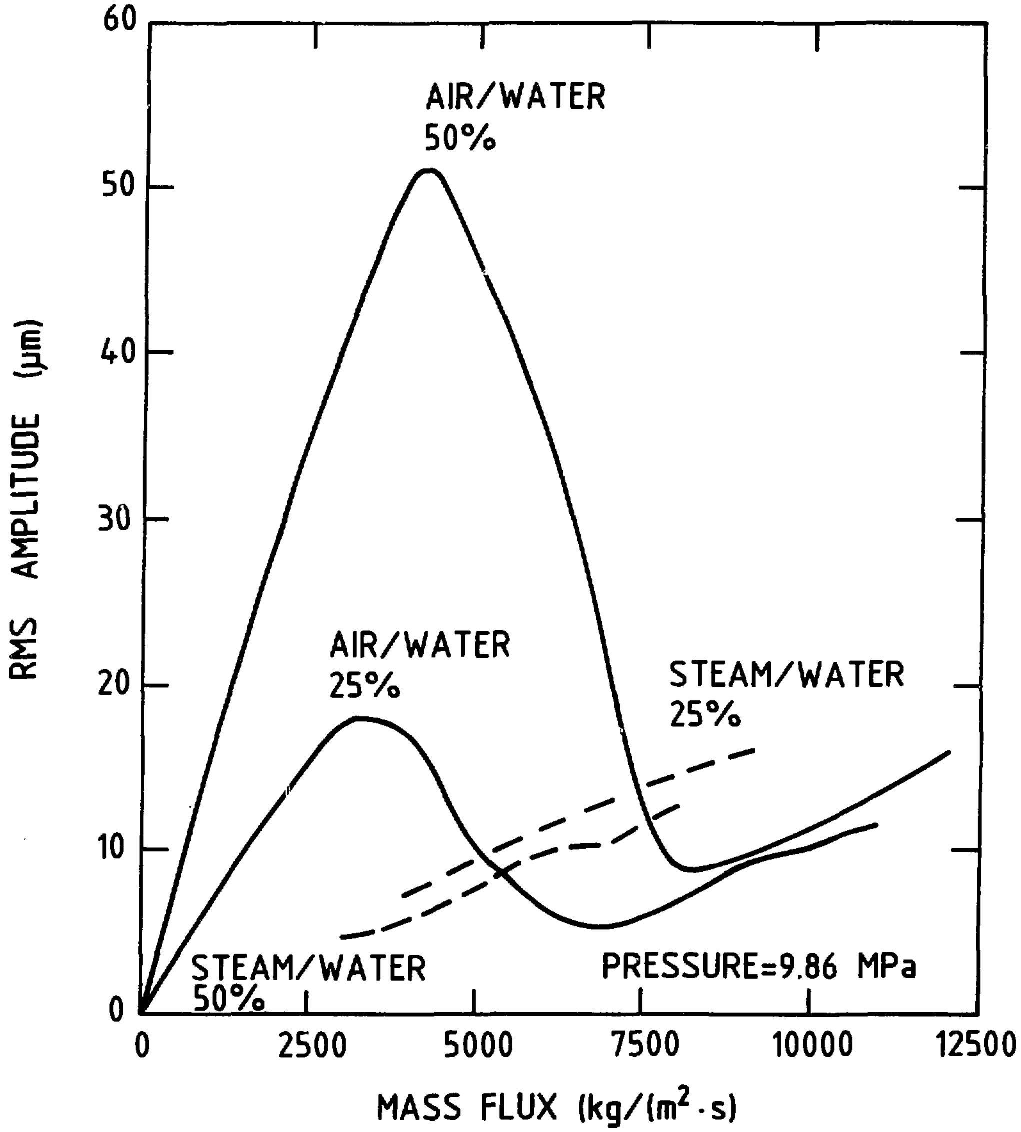
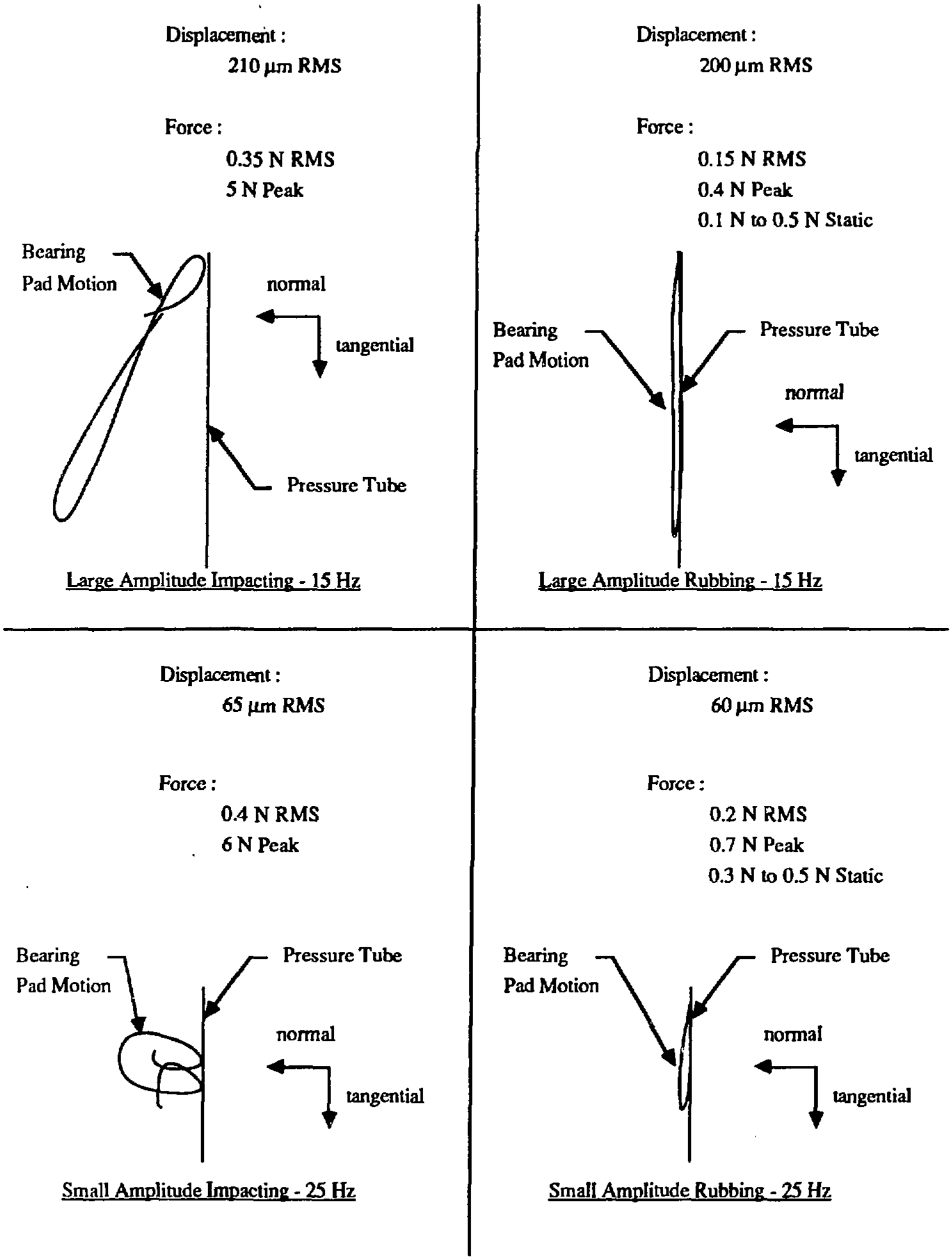


FIGURE 4: Comparison of the Effect of Mass Flux on Vibration Response at Void Fractions of 25% and 50% with Steam/Water at 9.86 MPa



Large Amplitude Impacting - 15 Hz

Displacement :
210 μm RMS

Force :
0.35 N RMS
5 N Peak

Large Amplitude Rubbing - 15 Hz

Displacement :
200 μm RMS

Force :
0.15 N RMS
0.4 N Peak
0.1 N to 0.5 N Static

Small Amplitude Impacting - 25 Hz

Displacement :
65 μm RMS

Force :
0.4 N RMS
6 N Peak

Small Amplitude Rubbing - 25 Hz

Displacement :
60 μm RMS

Force :
0.2 N RMS
0.7 N Peak
0.3 N to 0.5 N Static

FIGURE 5: Schematic of Typical Motion

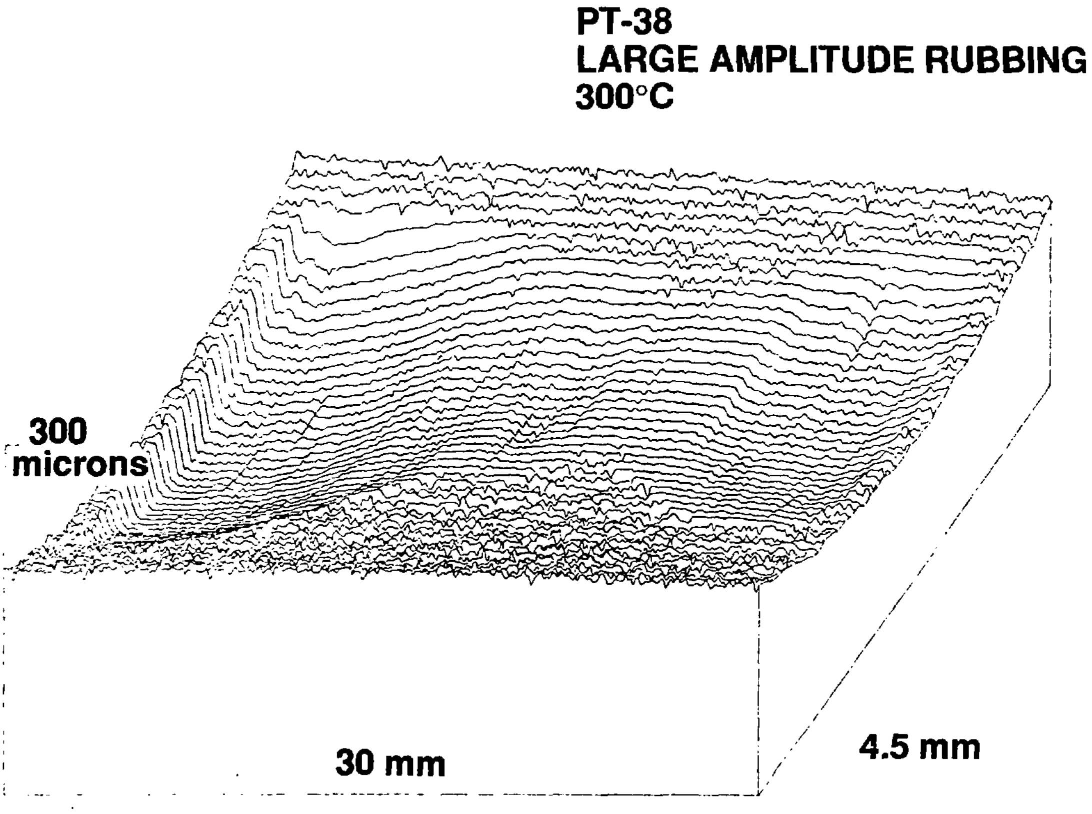


FIGURE 6: Typical 3-D Surface Profile of Fretting Scar

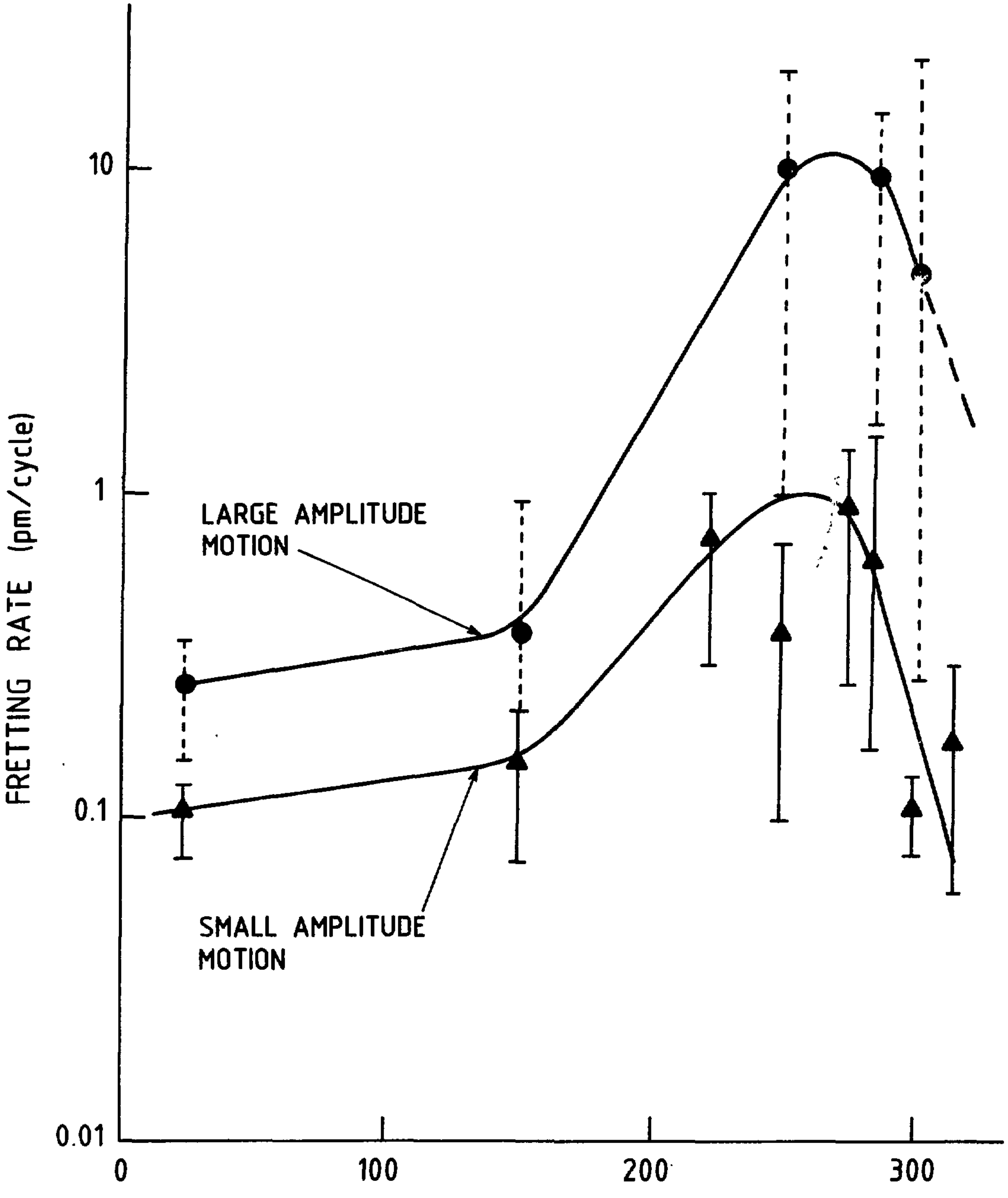


FIGURE 7: Pressure Tube Fretting Results

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