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FUEL BUNDLE TO PRESSURE TUBE FRETTING IN BRUCE AND DARLINGTON

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Abstract

As the fuel channel elongates due to creep, the fuel string moves relative to the inlet until the fuel pads at the inboard end eventually separate from the spacer sleeve, and the fuel resides on the burnish mark of the pressure tube. The bundle is then supported in a fashion which contributes to increased levels of vibration. Those pads which (due to geometric variation) have contact loads with the pressure tube within a certain range, vibrate, and cause significant fretting on the burnish mark, and further along at the midplane of the bundle.

Inspection of the pressure tubes in Bruce A, Bruce B, and Darlington has revealed fret damage up to 0.55 mm at the burnish mark and slightly lower than this at the inlet bundle midplane. To date, all fret marks have been dispositioned successfully without the need for tube replacement but a program of work has been initiated to understand the mechanism and reduce the fretting. Such understanding is necessary to guide future design changes to the fuel bundle, to guide future inspection programs, to guide maintenance programs and for longer term strategic planning.

This paper discusses how the understanding of fretting has evolved and outlines a current hypothesis for the mechanism of fretting. The role of bundle geometry, excitation forces, and reactor conditions are reviewed along with options under consideration to mitigate damage.

INTRODUCTION

Fretting wear of the pressure tube caused by fuel element vibration of the bearing pad against the pressure tube is an integrity concern in Bruce and Darlington reactors. Significant fretting does not occur in the 600 MW reactors. This is believed to be due to differences in channel design, bundle design, and primary heat transport (PHT) conditions. Two primary locations where fretting has been observed in Bruce and Darlington is at the pressure tube inlet end near the burnish mark and at the midplane of the inlet fuel bundle. Considerable effort has been made to understand the mechanism of fretting and to develop solutions to the problem. Analysis of fret marks from reactor inspections, extensive lab testing and modelling of reactor conditions indicates that, for the majority of the channels, the main excitation causing mid-plane fretting appears to be moderate level acoustics in the PHT system with some contribution from flow turbulence (1). An understanding of the mechanism, as outlined below, is fundamental to optimizing design solutions and is also beneficial in planning inspection strategies.

FRETTING RESEARCH BACKGROUND

The element vibration amplitude has been determined to be about 25μm RMS through fuel bundle tests in hot loops. Gross bundle motion is also this magnitude with peaks possibly two to three times the RMS value. Flow induced turbulence was considered largely responsible for this vibration and the in-reactor fretting behaviour was attributed primarily to this effect. During the fuel bundle endplate cracking investigations, however, acoustic excitation which caused pressure pulsation (~40 kPa) in the fuel channel was also found to contribute to fuel bundle axial vibration causing the endplates to fail through a fatigue mechanism. The vane passing frequency of the PHT pumps initiated the acoustic response in the PHT system. Pressure pulses propagated through the feeders, with possible pulse amplification under some conditions, and into the fuel channel. Acoustic excitation, which was established to cause endplate cracking, was also associated with incidents of very severe fretting in the Darlington test program. This observation has evolved into a belief that pressure pulses in the fuel channel contribute significantly to the fretting mechanism through enhanced fuel bundle/element vibration even at low pulsation amplitudes.

A wear model applied in fretting research (2) correlates volumetric wear rate (V) with the product of a wear coefficient (K) times the work rate (W).

$$\text{Wear Rate (V)} = \text{Wear Coefficient (K)} \times \text{Work Rate (W)}$$

A nominal wear-depth rate of 1 μm/day (based on full pad area of contact) was considered a representative average value over the fuel residence time from several in-reactor observations of fret depths. The wear coefficient was determined experimentally using reactor simulated conditions and representative vibration amplitudes and frequency. A value of 10^{-12}/Pa (measured at 265°C which is the temperature at the inlet end) was taken as a reference value. Using these reference conditions, a work rate of about 0.8 mW was calculated to be necessary to cause a wear rate of 1 μm/day. However, work rate determination by vibration tests of bearing pads against pressure tube material indicated somewhat of a paradox. Test data, summarized in Figure 1, indicated that vibration amplitudes of 25μm are completely damped at a load of 1 N and do not give a high enough work rate to cause the damage rate of 1 μm/day. These tests suggested vibration amplitudes of about 100μm were needed to give the required work rate but this magnitude of vibration had never been observed in any representative tests of fuel bundle behaviour. Taking acoustic excitation into account, research efforts at Chalk River have confirmed some key information which supports the role of acoustics in the fretting process. Firstly, bounding calculations indicate that energy transmitted to the fuel bundle from acoustic excitation is sufficient to explain the deep fret depths observed in reactor while random turbulence excitation cannot account for the deep frets. Secondly, when acoustic excitation is present, the load required to damp 25μm fuel element vibration is considerably higher than 1 N. This is significant since static load measurements suggest very few pads have loads less than 1N, therefore, to be consistent with the frequency of frets observed in reactor, fretting must be able to occur at loads greater than 1 N.

IN-REACTOR FRETTING OBSERVATIONS

Fretting has been observed along the entire length of the pressure tube although the intensity and severity decreases rapidly from inlet to outlet end. Inspections at the outlet end have shown frets occur, but the depths have never been substantial. The most severe damage occurs at the inlet end of the pressure tube in the burnish mark area of the rolled joint. Fretting occurrence at the burnish mark is influenced by the fuel support condition in Bruce and Darlington reactors. The effect of channel type and pressure tube creep on fuel support is illustrated in Figure 2. Initially, the fuel bundle bearing pads rest on the spacer sleeve (except for type A channels). During pressure tube creep, however, the inlet bundle bearing pads move off the spacer sleeve until, eventually, the outer ring of bearing pads are no longer in contact with it. This results in 'abnormal' fuel support (AFS) with the inner row of bearing pads in contact with the burnish mark. Frets at the burnish mark are a particular concern since this area is subject to reduced notch toughness due to deuterium uptake. Fretting at the midplane position (of the inlet fuel bundle) has also been found, on numerous occasions, to a depth which is reportable (>0.1mm) and to a depth (>0.15mm) requiring a disposition assessment.

Figure 3 shows inspection results on a moderate and a severely fretted channel in Bruce Unit 8. Observations made from analysis of this type of inspection data are:

- fretting propensity is not the same in all channels
- no correlation of burnish mark and midplane frets
- not all fuel bundles cause frets; not all pads fret
- pattern of frets is random
- more than one element on a bundle can cause frets

Several factors which have been examined to assess possible correlation with the fretting behaviour are discussed below:

Channel type: The dished installation of the end fitting results in different fuel support conditions at any point in time for the four channel groups (type A, B, C, and D channels of different initial lengths). Figure 4 shows a chart of the maximum fret depth in the channels inspected in B8 grouped by channel type. The chart shows that there is more variation in fret depth within any single type than there is among the four channel types. Consequently, channel type does not seem to have a predominant effect on the depth of fretting. It does influence when burnish mark fretting begins in the different channel types.

Fuel bundle geometry and pad loads: Profilometry of new fuel bundles indicates they are mostly barrel-shaped with individual element bow up to 600 um outward convexity. The bundle shape changes considerably during reactor operation due to hydraulic, thermal and radiation effects but cannot be measured in the 'hot' condition. Nevertheless, bundle shape is an important factor in fretting. Shape deformation of the bundle explains how one bundle can cause fret marks both at about the 4 and 8 o'clock position in the pressure tube. In addition, the bundle shape determines the load on pads in contact with the pressure tube and also affects which elements can or cannot fret depending on the gap between interelement spacer pads. Bearing pad loads measured in a static frame for a straight and sagged pressure tube are shown in Figure 5. A key observation drawn from this data is that a very low proportion of pad loads are <1N. In fact, at the bottom (6 o'clock position) of the pressure tube, no pad load were measured to be 1 N or less. This suggests that fewer frets should be observed in-reactor if turbulence is the main excitation which causes frets.

Coolant flow rate: The degree of turbulence at the channel inlet varies with the flow rates. The expectation, therefore, is that higher flows would correlate with deeper frets since flow turbulence is higher and fuel element vibration should be enhanced. The flow variation among channels of the same type is small but the wide variation in maximum depth observed within a single type (Figure 4) is difficult to understand solely on the basis of tubulent flow-induced vibration. A pronounced flow dependence was shown in a 40 day zero power hot (ZPH) test at D3, however, the fret depths were all relatively shallow (<0.08mm). In addition, the flow range over which this was apparent ranged from 15 to 28 kg/s. Bruce data does not support a correlation between flow and fret depth as shown in Figure 6. It should be noted that this data represents a narrower flow range (24-26.5 kg/s) but it is possible that the effect saturates at higher flows.

Fuel bundle dwell time: The A type channels experience lower fuelling rates so a fuel bundle remains at the inlet position for a longer period of time in type A channels. It is interesting to note, however, that type A channels do not show the deepest occurrence of frets despite the fact that the fuel residence time is longest in this channel type. Thus, dwell time does not appear to be a factor and this has been supported in other inspection data.

Acoustic excitation: Since a correlation had been observed between pressure oscillation and fretting in Darlington, some measurements were undertaken for Bruce B. Acoustic pressure pulses measured in some channels of B6 were about 20 kPa (half the amplitude at Darlington). An extensive modelling evaluation was also conducted (3) to rank channels based on a predicted disposition to acoustic excitation and quite a good correlation was established between the extent of fretting damage and the predicted rank. Those channels shown in Figure 4 which had fret depths >0.3 mm also had a high rank in the acoustic model prediction. Data collected from Bruce and Darlington stations show many differences which can be explained by acoustic phenomena. Maximum fret depths from inspections up to about mid-1994 for Bruce and Darlington reactors is given in the Table 1. Data from D1 and D2 is excluded since very severe fretting was observed in these units when they were operating with 5-vane impellers on the PHT pumps. As a result of the endplate cracking investigation, 7-vane impellers were installed in order reduce the pressure oscillation amplitude by changing the frequency away from the 150 Hz resonant node of the PHT system. This change eliminated end plate cracks and has also been effective in reducing the severity of frets although it has not, as originally thought, eliminated the occurrence of 0.15mm deep frets. A number of observations related to the Bruce reactors can also be supported when viewed in the context of acoustic response and this is summarized in the following discussion.

Bruce A Reactor Data: Bruce A inspections on Units 1,2,4 were done within a span of 82000-93000 EFPH and the frequency and severity of fretting was less than observed on Bruce B. Despite a longer period of service, fretting at Bruce A is less severe than Bruce B and this is believed to be due to lower level acoustics attributable to differences in system hardware and operating conditions. Lower acoustics in Bruce A is also supported by the fact that no endplate cracking has been observed on fuel inspections. Although the acoustics at Bruce A have not been modeled, it is expected that pressure pulsation amplitudes at Bruce A are less than Bruce B due to slightly lower PHT pressure, temperature, and flow rates as well as a different HT system configuration. All these factors influence the extent to which channels are susceptible to acoustic phenomena and could account for the reduced fretting. Lower channel flows might diminish fretting due to less flow turbulence but it is more likely the reduced inlet header temperature, together with HT system differences, dominate the trend to reduced fretting due to lower acoustic conditions.

Bruce B Reactor Data: Bruce Units 5, 6, & 7 were inspected at about 60000 EFPH and unit 8 at about 45000 EFPH. A notable trend appearing in this investigation is an increase in fretting in the outer zone channels compared to the inner zone channels (4). At Bruce, the PHT system is split to inner and outer zones where the flow streams of the outer zone channels bypass a feedwater preheater. This effectively changes the acoustic characteristic between the two zones. Another main difference is that the outer channels have a higher inlet header temperature (269 C vs 256 C) which exerts a strong influence on acoustic tendency. Outer channels, which have been shown to have higher pressure pulses, also differ from inner channels in the following aspects: higher average flow (24.9 vs 24.6 kg/s; min/max difference is about 3 kg/s between inner and outer zone) and higher pressure (10.73 vs 10.57 MPa) both of which also influence the acoustic response.

Table 2 gives a comparison of the number of dispositioned midplane frets found in B5/B6/B8 for inner and outer zone channels and the outer zone (higher acoustic) channels consistently have an increased incidence of frets. This variation in fretting behaviour at the inlet ends of channels cannot be explained by flow induced turbulence alone since the flow variation is quite small. There are differences in fuel support between inner and outer channels (A, B, C, D type channels) but all channels of the same type do not exhibit the same severity of fretting (Figure 5). Fuel bundle dwell time also varies considerably in the different channel types but there is no correlation with the depth of fretting observed. Low-level pressure pulsation is considered to be a significant parameter in fretting which can account for many of the observations in Bruce B data. Pressure pulsation amplitudes of 20-25 kPa have been measured in the outer-zone reactor inlet header and lower amplitude pulses (10 kPa or less) are predicted for the inner zone based on modelling results and end-fitting laser vibrometry measurements.

Figure 7 and 8 show a frequency distribution of burnish mark and midplane fret depths for 'acoustic' and 'non-acoustic' channels which were inspected in Bruce 8. In both cases, the number of deep frets decreases rapidly but the non-acoustic channels seem to have a depth limit around 0.3mm. Acoustically active channels, however, show depths up to 0.45mm at the midplane and 0.55mm at the burnish mark with no indication of a depth limit.

A number of other factors, such as bundle manufacturer, feeder diameter, rosette location on header, were examined for possible correlation with fretting but none was established.

FRETTING MECHANISM HYPOTHESIS

The following factors are considered key aspects in the fretting process:

- an initial outward bow of a fuel element and adequate clearance with adjacent spacer pads
- a bearing pad load within a critical 'fretting' range (4N-10N)
- flow turbulence which results in light fretting (depths up to about 0.1 mm)
- acoustic excitation for moderate to severe fretting (moderate up to 20 kPa and severe up to 40kPa pressure oscillation)

- abnormal or transition fuel support in the case of burnish mark frets
- initially, if conditions are conducive to fretting, the wear depth rate is quite high and diminishes with time such that most of the fretting occurs in the first 100 days of fuel dwell period

The mechanism hypothesis suggests that fretting depends on the bearing pad load and the amount of flow and acoustic energy in the system which follows a relationship illustrated in Figure 9. In this model, fretting will not take place at very high loads because frictional forces completely damp vibration. At loads below a critical value, which varies depending on the excitation, fretting will occur until wear has reduced contact loads to zero or minimal levels. A model of the postulated wear rate and fret depth progression is shown in Figure 10 which was developed using the wear equation and typical known values about element excitation and stiffness.

With a fuel bundle resting in the pressure tube, there is a distribution of fuel bearing pad loads, only some of which will be in the "critical" range for deep fretting at the start of the dwell. Not all of these may have other pre-conditions for fretting to occur (eg. sufficient inter-element space to allow vibration; an element which has developed an outward bow (from initial manufacture or during residence at previous bundle positions) and has been bowed inward due to placement in a new location in the pressure tube. Figure 11 and 12 show a schematic illustration of the sequence which is postulated to produce frets much deeper than the 25 μm vibration amplitudes of the fuel element. As the fuel bundle passes along the fuel channel (Figure 11), it deforms in the sagged channel under the influence of radiation and thermal effects; initial bundle shape may also affect the deformation response. When the bundle arrives at the inlet end, its shape relative to the pressure tube geometry causes inward deflection of some fuel elements which results in bearing pad loads within a critical range. As the vibration produces wear of the pressure tube and the bearing pad, the fuel element relaxes to an outward bow (Figure 12) until the loads are insufficient to cause fretting. Considering the fuel element stiffness is about 15 N/mm and assuming that the wear ratio of the pressure tube and bearing pad is 1:1, this hypothesis suggests a load of about 4N-5N would be needed to preload the fuel element in order to fret to a depth of 150 μm. With only low level acoustics and flow turbulence, the element vibration occurs in a lateral, normal or combined plane of motion. With high level acoustics, however, axial components of motion are also considered to occur, possibly through flexing of the endplates, and fretting becomes very aggressive under this condition. A critical load range for fretting to be active is postulated to be about 4N-10N; this load range is about 10% of the population of pad loads shown in Figure 5 (for a sagged PT) which corresponds approximately to the average number of fuel bundles which result in pressure tube frets.

SOLUTIONS TO FRETTING DAMAGE

A number of potential solutions to mitigate or eliminate fretting damage are presently under consideration and/or implementation. The main control strategies are summarized as follows:

1) Rounded bearing pads: This comprises a design change to the fuel bundle bearing pad. The objective is to achieve a larger notch radius in fret marks by rounding off the sharp edges on the standard bearing pad. Fretting incidence may not be reduced, but stress concentrations would be diminished with resultant improvements in dispositioning fret indications on the basis of notch toughness assessment.

2) Longer fuel bundles: This bundle design change can eliminate bearing pad frets since the inlet fuel bundle is re-positioned to a normal support condition with the pads resting on the spacer sleeve. It does not address the potential for midplane fretting and has some disadvantage in requiring a complex fuel management program to maintain the correct mix of 'long' and 'short' bundles in the pressure tube in order to adhere to minimum gap requirements with respect to the shield plug.

3) Fuelling with flow & 12 bundle string: A 12 bundle fuel string (instead of 13) is an option which would eliminate burnish mark frets. Unfortunately, this is unacceptable from a safety perspective since current refuelling practice introduces new fuel at the outlet end (fuelling against flow) and under certain conditions can

result in a power pulse. Thus, a 12 bundle option also requires that fuelling with flow be implemented which invokes other component design changes (eg. shield plugs) and also has an impact on channel power rating and fuel management operations.

4) Resonator Inlet Shield Plug: While the solutions mentioned above will mitigate fretting damage, the RISP attempts to address a root cause of fretting. The RISP, shown schematically in Figure 13, is designed to reduce pressure pulses in the channel by providing an alternate acoustic path within a cavity designed in the shield plug. This will result in amplitude cancellation by virtue of the fact that the alternate path is a half wavelength of the 150 Hz acoustic pulse. Preliminary test results of this design have shown substantial reduction of the 150 Hz pressure pulsation and it appears to have a promising future as a strategy for reduced fretting.

5) Inter-element spacer height: Increasing the height of inter-element spacers on the fuel bundles may be a means of reducing element vibration amplitudes and tests are underway to assess the benefits of this approach.

Other possible solutions which have been under consideration involve feeder length addition, reduced PHT flow, and fuel bundle design changes (eg. add more bearing pads, manufacture bundles with elements bowed inward).

FUTURE DIRECTIONS

A sufficient understanding has been acquired over the last several years on the phenomena of pressure tube fretting in Bruce/Darlington reactors and this has enabled some practical solutions to the problem. Several fundamental aspects of the mechanism are still not well explained, however, and further work is needed to explore issues in order to define long term strategic plans to prevent fretting in future stations. A few topics which do not have clear answers are:

- how does acoustic excitation enhance fretting at higher pad loads
- what is the role of changing bundle geometry and PT geometry due to creep and other effects
- do material property changes due to irradiation effect fretting
- are alternate material compositions or coatings for the bearing pad beneficial to fretting reduction

The role of acoustics in raising the damping load of a vibrating fuel element is not completely understood; conjecture suggests it could be related to very small cyclic straining of the pressure tube caused by the acoustics which affects the frictional loads during contact with the bearing pads. Material hardness is another factor which may warrant some study to clarify whether this aspect plays a role in fretting. Indications of this were first observed in tests at DNGS where inspection results obtained from the ZPH tests showed much shallower frets than were obtained later after some time of reactor operation. This difference has been attributed to the fact that the ZPH tests used new unirradiated fuel while subsequent inspections were performed after irradiated fuel had passed through the inlet bundle position. If irradiation hardening of the bearing pads is a factor in fretting damage, then it could also lend support to a fuelling with flow option which retains a 13 bundle fuel string. The underlying rationale is that, with present conditions, the hardness ratio of bearing pad to pressure tube (BP/PT) is <1 at the outlet end but is likely >1 at the inlet end due to greater irradiation hardening of the BP than on the inlet end of the PT. A fuelling with flow scenario reverses the hardness ratios so that pressure tube wear susceptibility due to hardness effects is reduced at the inlet. It would increase susceptibility at the outlet end but fretting would not occur because other factors dominate the process at the outlet (eg. lower wear coefficient due to temperature). Hardness may be an additional factor to explain the lack of fretting in the 600 MW reactors since all the pads on the inlet bundle are within the core and the BP/PT hardness ratio always favours wear of the bearing pads instead of the pressure tube. While hardness could be an issue, there are other factors which appear to dominate the absence of fretting in the 600 MW including no abnormal fuel support condition as well as the differences in fuel design and operating conditions.

SUMMARY / CONCLUSIONS

A hypothesis to describe the midplane fretting mechanism has been developed which appears to be consistent with the behaviour observed in pressure tubes of Bruce/Darlington. The mechanism relies on both flow turbulence and acoustic excitation forces to produce deep frets at the inlet bundle locations and it is characterized by high wear rates during the initial fuel dwell period. Some pre-conditions need to be fulfilled before fretting occurs and these relate to a bowed element geometry and contact loads in the range of 4N - 10N. When fretting is active, most of the damage occurs in the first several weeks until the bearing pad load is out of a critical range and loading is distributed to other pads which may or may not fall within the range required for fretting to occur on these pads. Practical solutions to reduce fretting damage have been realized which address root cause factors or impose design changes to reduce susceptibility. Further research to establish basic characteristics of fretting, especially when acoustics exist, could expand the design options for control of fretting.

ACKNOWLEDGEMENT

This paper has drawn from the experience of many groups and organizations involved in fretting investigations including Ontario Hydro, AECL Research, Stern Laboratories and AECL SPEL and these contributions are gratefully acknowledged.

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3) R.E. Pauls et al, "ABAQUS Acoustic Modelling of the Bruce NGS 'B' System and Assessment of Pressure Tube Damage", Draft Report, OH-NSD, July 1994.

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TABLE 1: Maximum Fret Depths at Bruce/Darlington

Unit	Burnish Mark Max. Depth mm	Midplane Max. Depth mm
B1	0.18	0.23
B2	0.29	0.19
B3	0.17	<0.10
B4	0.28	0.16
B5	0.51	0.31
B6	0.43	0.29
B7	0.44	0.37
B8	0.55	0.41
D3	<0.10	0.23
D4	<0.10	<0.10 (new fuel only)

TABLE 2: Comparison of Bruce 'B' Inner/Outer Zone Fretting Incidence

	Range of No. of Fuel Dwell Periods @ Inlet Position	Avg. No. of Dispositioned Frets per Channel at Burnish Mark	Avg. No. of Dispositioned Frets per Channel at Midplane	Flow Range (kg/s) in Sample Group
BRUCE 5				
Inner Zone *	25-26	0.73	0.8	25.7-26.1
Outer Zone *	7-27	1.71	0.63	24.2-27.2
Outer Zone **	26-27	3.0	1.4	25.1-26.3
BRUCE 6				
Inner Zone *	24-30	1.39	0.14	25.6-26.0
Outer Zone *	6-27	2.8	0.8	24.2-27.2
Outer Zone **	25-28	3.9	1.1	24.2-26.3
BRUCE 8				
Inner Zone *	18-21	0.27	0.1	23.0-25.1
Outer Zone *	5-22	2.8	1.3	24.2-25.8
Outer Zone **	19-21	2.4	1.46	24.7-25.8

* Sample of channels represents all inner or outer zone channels inspected in this unit

** Sample of channels represents only outer zone channels which have refuelling frequency equivalent to inner zone channels. In some cases the calculated average is based on only one or two outer zone channels.

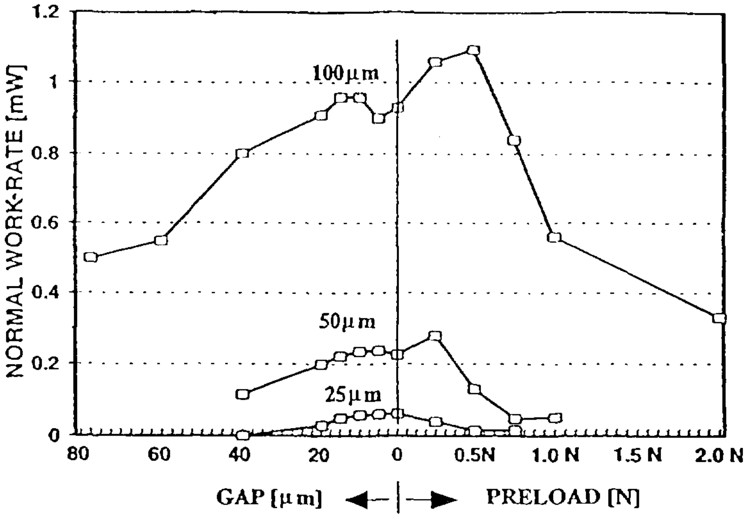


FIGURE 1: Effect of Gap and Pre-load on Work-Rate for Different Vibration Amplitudes.

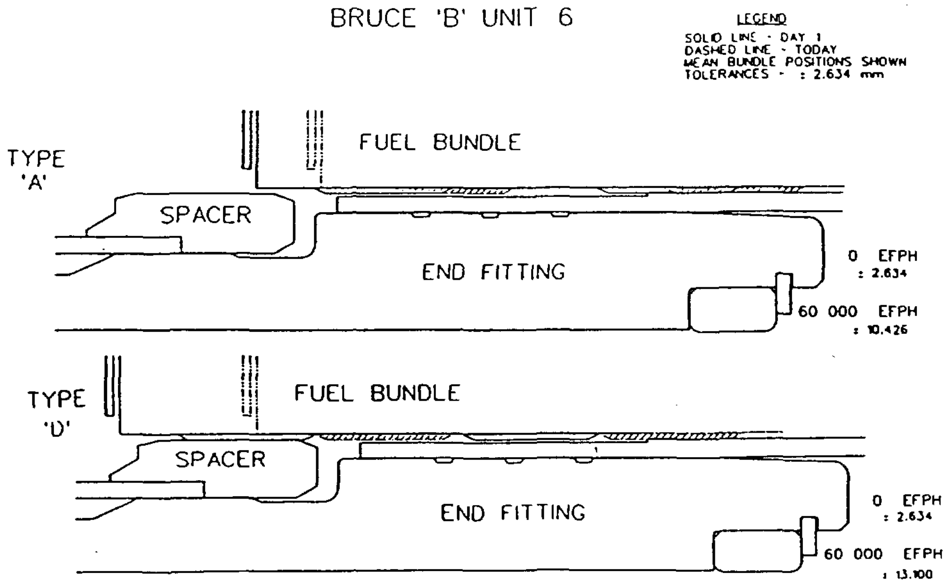


FIGURE 2: Fuel Support Condition for Type A and Type D Fuel Channels.

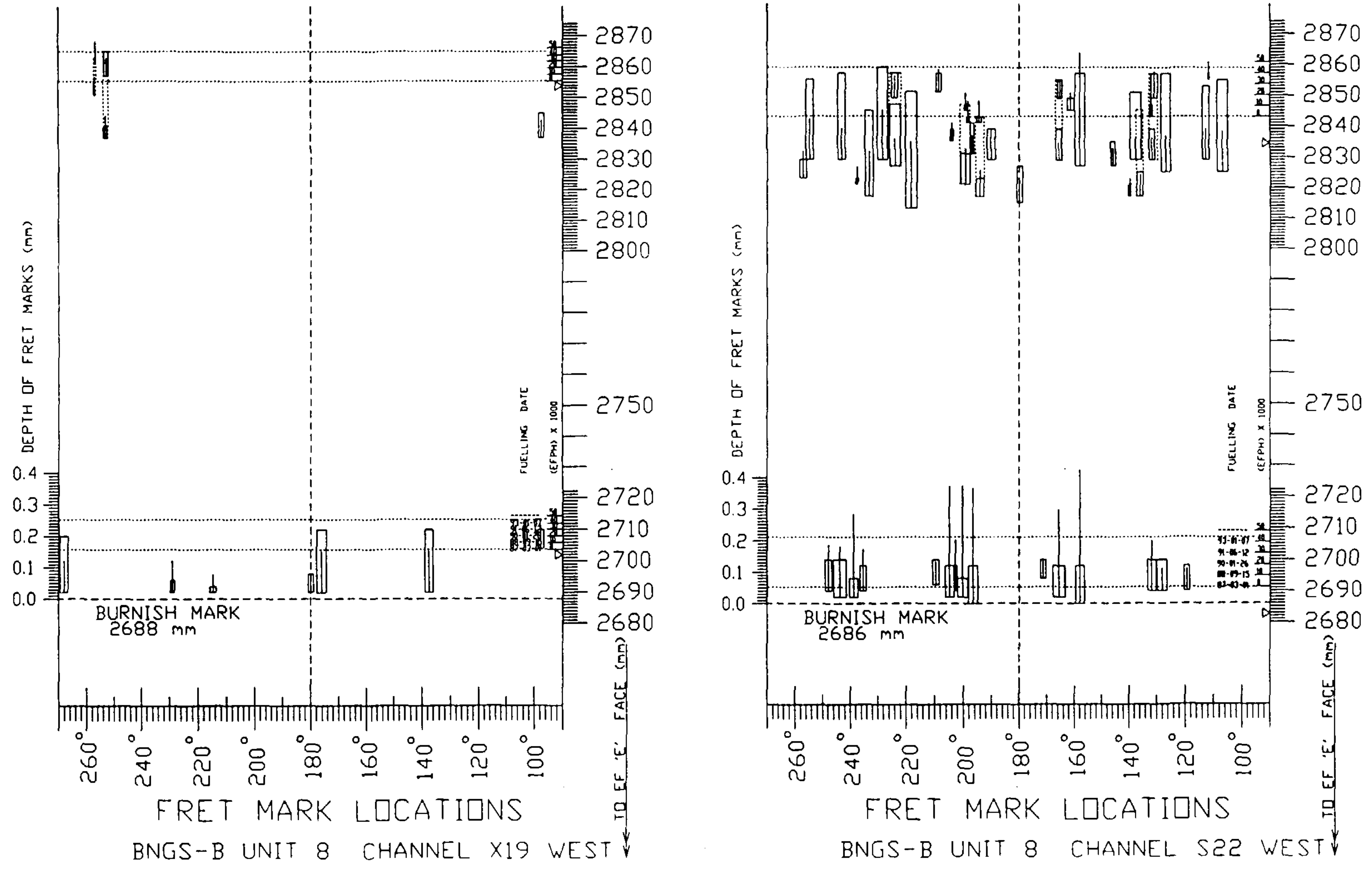
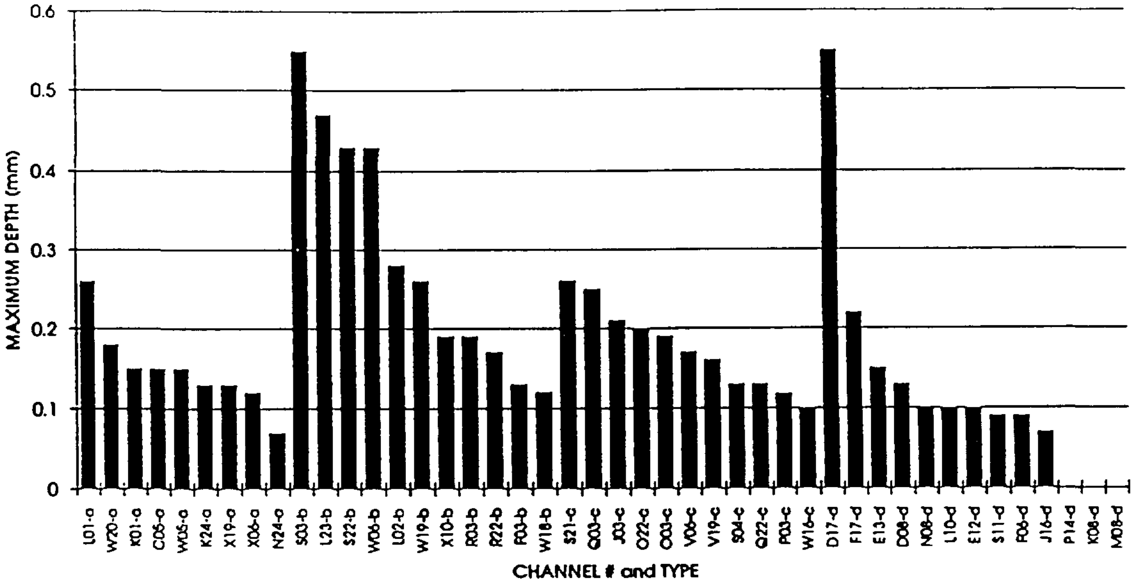


FIGURE 3: Moderate (X19) and Severe (S22) Fretting In BNGS 8.

BNGS-UNIT 8 P/T FRETTING RANK BY MAXIMUM DEPTH
@ BURNISH MARK FOR CHAN. TYPES A-D



BNGS-UNIT 8 P/T FRETTING RANK BY MAXIMUM DEPTH
@ MIDPLANE FOR CHAN. TYPES A-D

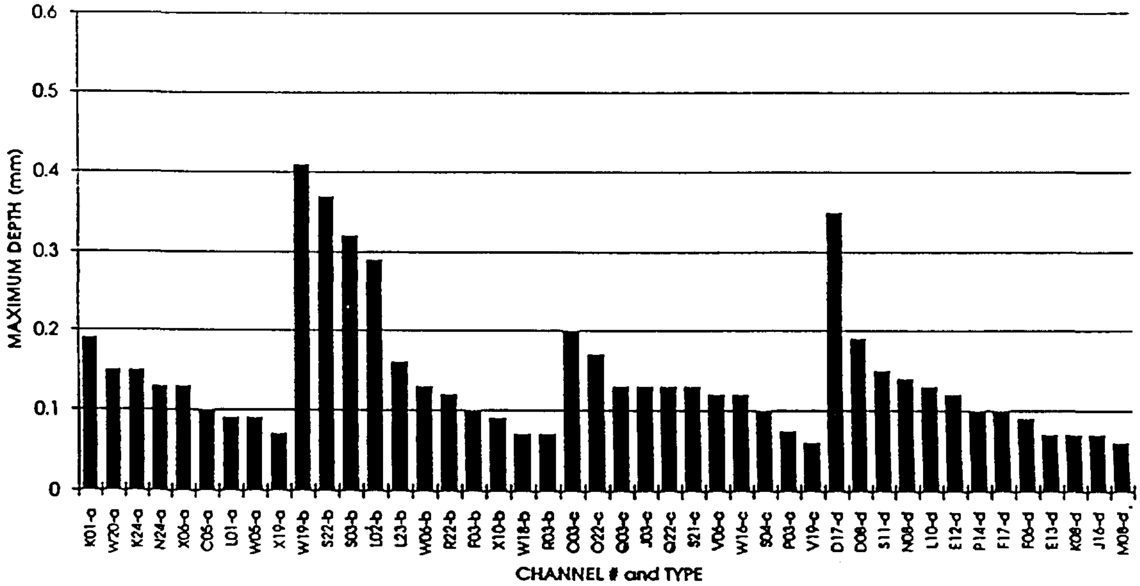
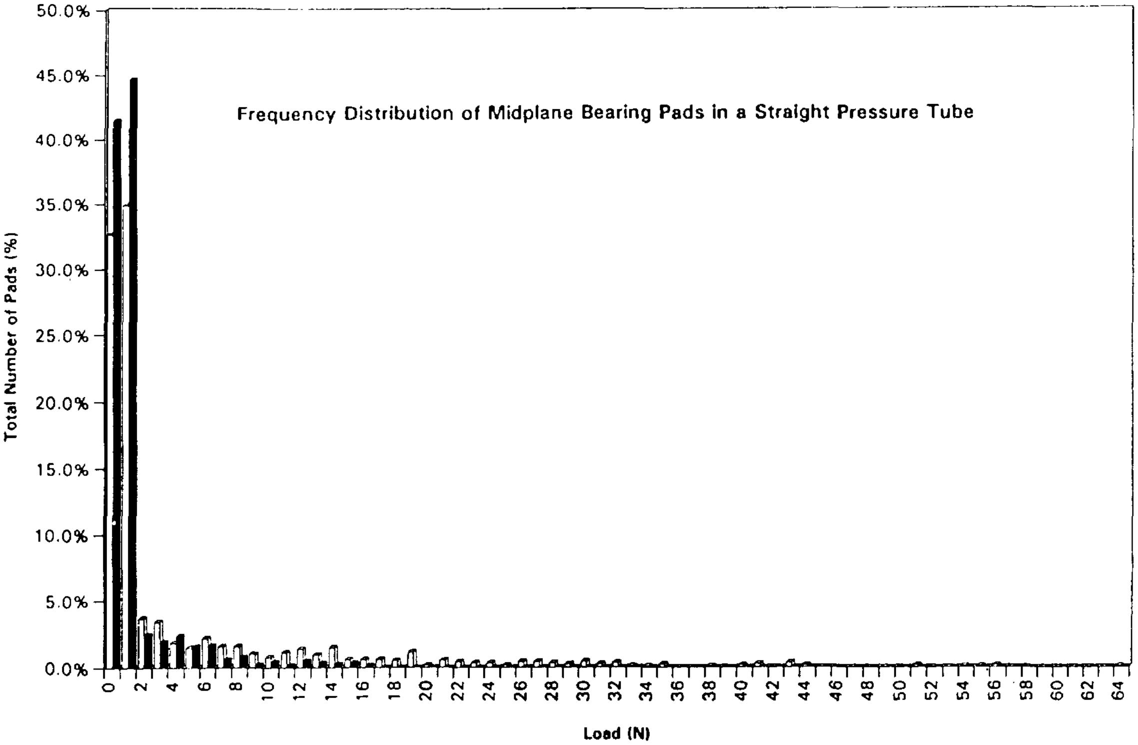


FIGURE 4: Maximum Fret Depth in BNGS 8 Sorted by Channel Type



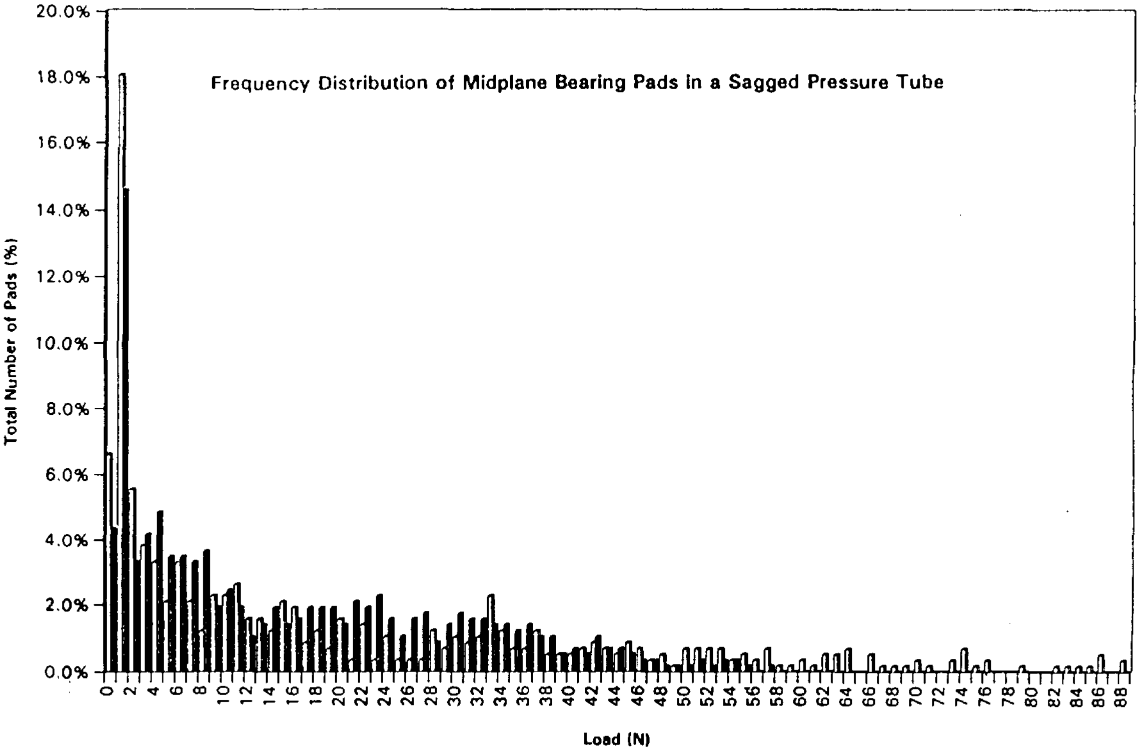


FIGURE 5: Frequency Distribution of Midplane Bearing Pad Loads

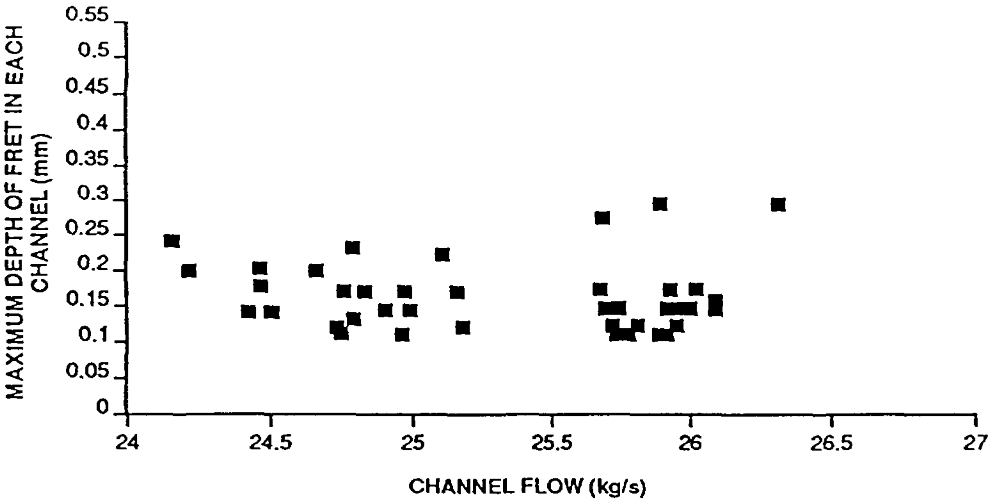


FIGURE 6: Effect of Channel Flow on Fret Depth in BNGS 6

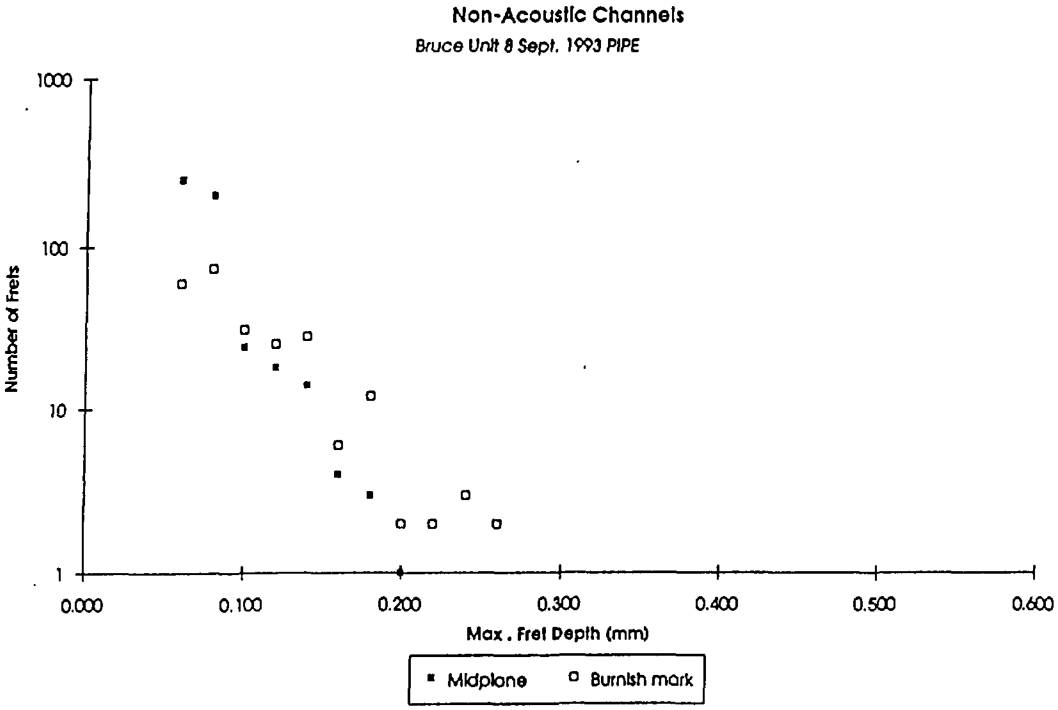


FIGURE 7: Fret Depth Frequency Distribution for Non-Acoustic Channels In BNGS 8

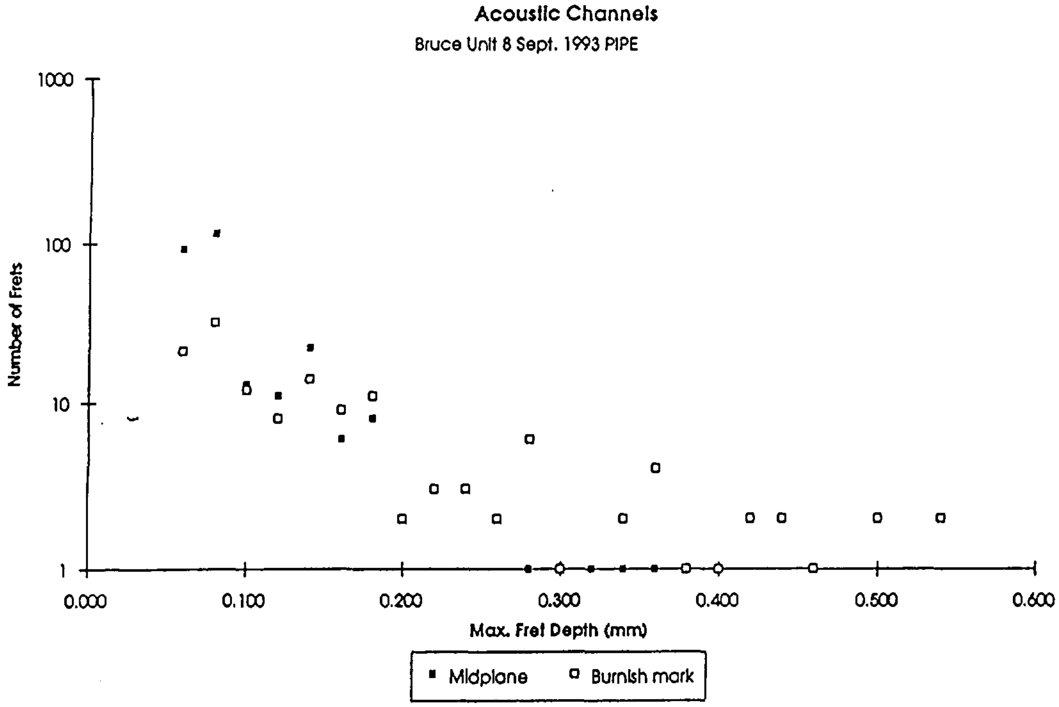


FIGURE 8: Fret Depth Frequency Distribution for Acoustic Channels In BNGS 8

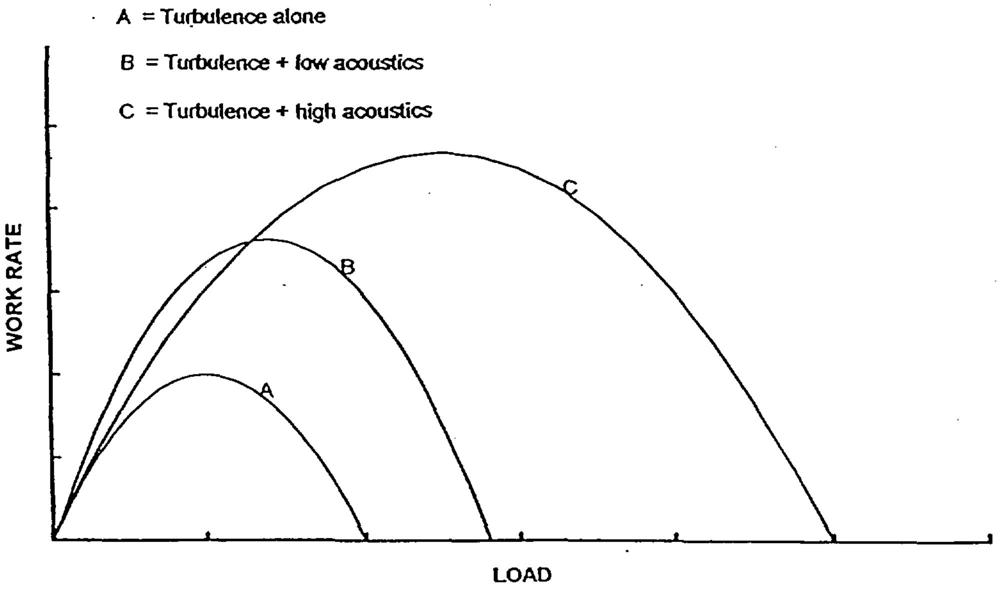


FIGURE 9: Hypothetical Work Rate Versus Bearing Pad Load For Different Excitation

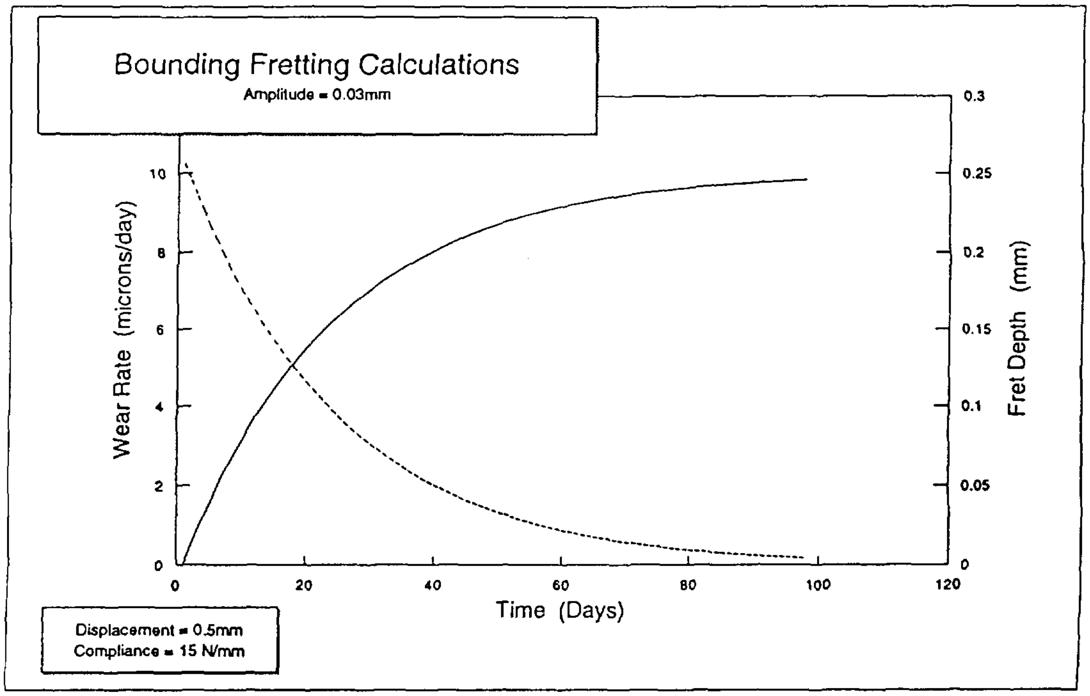


FIGURE 10: Simulation of Wear Rate and Fret Depth Using the Wear Rate Equation

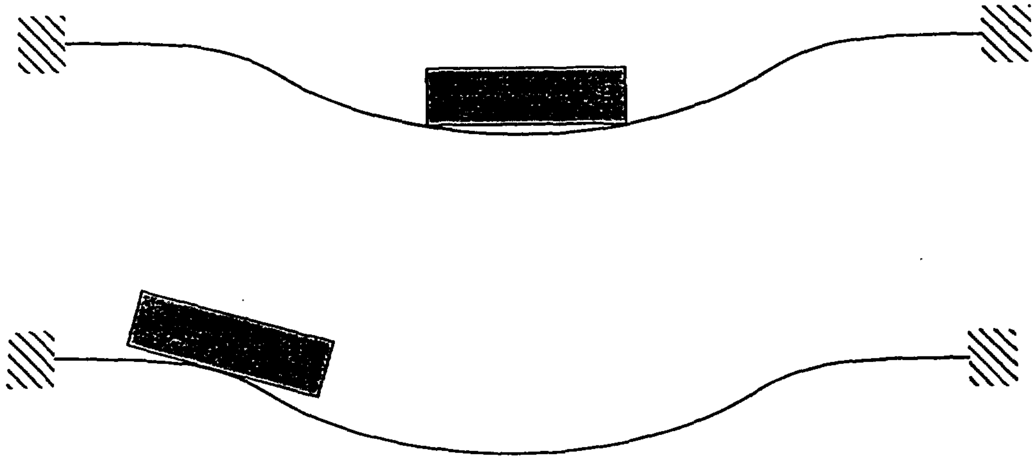


FIGURE 11: Idealized Schematic of Bundle Support Conditions When Fuel Moves From Mid-Channel to Inlet End Causing Bundle to Pressure Tube Interaction Loads and Bundle/Element Deformation

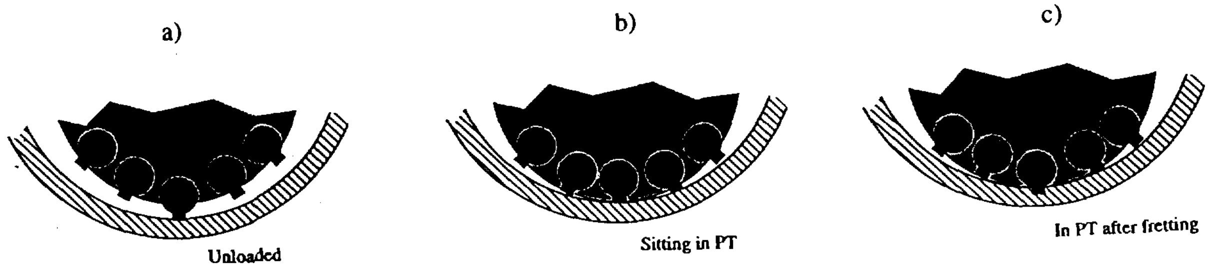


FIGURE 12: Idealized Schematic of Fretting Sequence; a) Bundle with Convex Bowed Fuel Element Moves to New Location, b) Element Deflects Inward and Preload Established, c) Bearing Pad Frets into Pressure Tube and Element Relaxes to Unloaded State

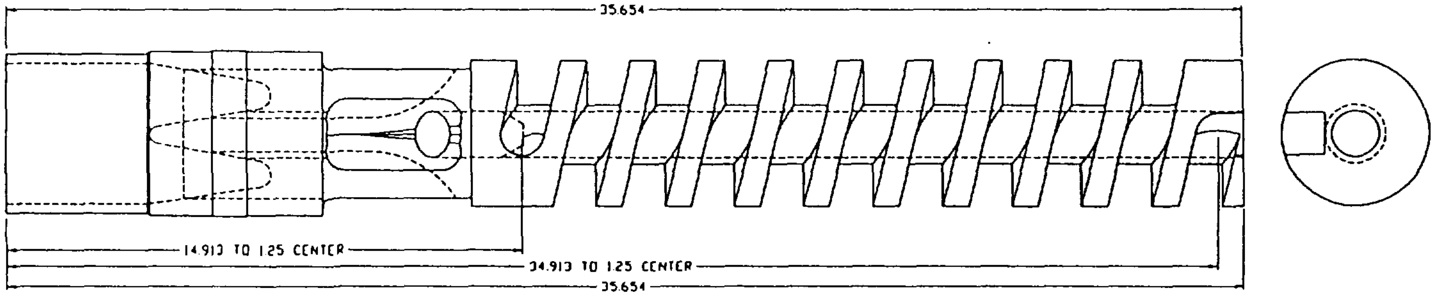


FIGURE 13: Resonator Inlet Shield Plug