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INVESTIGATIONS OF FUEL-BUNDLE MOTION AND FRETTING-WEAR IN THE CHALK RIVER SINGLE-CHANNEL TEST RIG

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Abstract: Out-reactor tests of fuel components have been performed with AECL's VIBFLO hydraulic loop at Chalk River, in support of design improvements to HANARO research-reactor fuel. Vibration frequencies and amplitudes were measured in and out of flow, and the effect of various design features on vibration levels was determined. Component wear was measured following endurance tests, and the fretting-wear performance was predicted for extended periods of time in operation. Basic hydraulic properties of the fuel were also determined. Various aspects of this work are applicable to similar tests of CANDU-type fuel.

I. INTRODUCTION

A knowledge of the hydraulic and vibrational characteristics of nuclear-reactor components is essential to ensure high levels of performance and reliability. Many reactor components, for example fuel bundles in the core and tube bundles in heat exchangers, are subjected to relatively high flow velocities. Flow-induced vibration, and the possibility of associated fretting-wear of reactor and heat-exchanger components, are two areas of particular concern.

Within the nuclear industry the most common, and potentially costly, mechanisms causing flow-induced vibration can be categorized as follows [1,2]:

1. *fluidelastic instability*, usually related to tube bundles in cross flow,
2. *turbulence-induced vibration*, for a variety of components both in axial and in cross flow,
3. *acoustic resonance*, often associated with acoustic pressure pulsations generated by pumps or acoustic noise generated by valves,
4. *vortex-induced vibration*, for simple geometries also referred to as periodic wake shedding, occurring in cross flow, and
5. *annular/leakage flow-induced instability*, usually involving small flow volumes in confined channels.

These topics have been reviewed by a number of authors, including Pettigrew et al. [1] and Au-Yang [2]. The first three, namely fluidelastic instability, turbulence-induced vibration and acoustic resonance, have attracted considerable attention within the nuclear industry and become the focus of research and development programs. Concerning fuel bundles placed in high rates of flow, the two most common excitation mechanisms are random forces due to turbulence, particularly in the entrance region of the fuel channels, and dynamic pressure fluctuations, particularly pressure pulsations originating with the heat-transport pumps. The resulting possible fuel vibration, and the associated potential for fretting-wear, continue to be important issues.

In the core of MAPLE-type reactors such as HANARO, the fuel bundles are mounted vertically, each one on a bayonet locked into a receptacle in its own flow tube with the coolant flowing axially (upwards). Two types of fuel are used: 36-element bundles with a hexagonal cross-section and 18-element circular bundles. A 36-element fuel bundle is shown in Figure 1. Within each fuel bundle the 36 or 18 finned fuel elements are fastened to endplates at the bottom, with clearance supports at the top endplate and at three spacer plates along the bundle. Depending on geometry, dynamic stiffness, clearances and straightness, the fuel elements may be in contact with the endplates and/or spacer plates at a number of locations. Similarly, the endplates and/or spacer plates may be in contact with the fuel channel (flow tube) in several places. There may be a preload in some cases. The end result is that the fuel elements and bundles are complicated, highly non-linear, poorly defined systems. Although computer modelling can be used to some degree [1], out-reactor testing of new or re-designed fuel bundles is a very useful approach to minimizing potential problems, before such components are placed into service.

This paper describes a series of tests carried out by the Vibration & Tribology Unit at AECL's Chalk River Laboratories, in support of design improvements to fuel bundles intended for MAPLE-type research reactors [3]. The primary purpose of the tests was to investigate the potential for fuel-bundle vibration and associated fretting-wear, as the design of MAPLE-type fuel bundles has evolved. The tests were designed to provide the following information under realistic operating conditions:

- vibration frequencies and amplitudes of various fuel-bundle components,
- measurements of component wear, so that predictions could be made of fretting-wear performance over an extended period of time in operation, and
- basic hydraulic properties of the fuel, for example, the pressure drop across the bundle and fuel channel.

II. DESCRIPTION OF TESTS

A single-channel section of the VIBration in FLOw (VIBFLO) hydraulic test loop at AECL's Chalk River Laboratories was used, enclosed by a clear exterior tube in which a single fuel channel consisting of an inlet, flow tube and fuel bundle could be mounted. The inlet region at the entrance to the flow tube was modified to reproduce the main features of the MAPLE-type reactor fuel-channel geometry. Prototype fuel bundles, of the kind used in the HANARO research reactor [4], were supplied by the Fuel Fabrication Branch at Chalk River.

Three different kinds of tests were performed, as follows:

1. *Modal tests*, in which the vibration of various components was measured in response to well defined forces applied by a shaker, in air and (still) water,
2. *Vibration tests in flow*, in which the vibration of fuel-bundle components was measured for single-phase flow at various flow rates, up to 23.5 kg/s for the 36-element bundle and 15.2 kg/s for the 18-element bundle, and
3. *Endurance tests*, in which the 36-element and the 18-element bundle were subjected to flow at 110% the respective design flow rates for an extended period of time.

In the modal and vibration tests, the motion of various components was measured by a combination of accelerometers, displacement probes and a laser Doppler vibrometer. In some tests, dummy fuel elements containing miniature accelerometers and pressure transducers were installed in the test bundles, located in such a way as to minimize disturbance to flow. Vibration data were recorded on tape and subsequently analyzed to determine the magnitude and direction of component motion as a function of frequency, and to interpret the overall motion of the bundle in terms of possible transverse and/or axial modes of vibration. In the first phase of the tests, a number of different design features were altered and the effect on vibration levels was measured. During tests in flow, the pressure drop across the fuel channel was also measured.

The endurance tests lasted for 40 days, with frequent inspections to monitor the location and rate of growth of wear marks on the exterior fuel-bundle components. Following each test, interior and exterior surfaces were examined and wear marks having any visible depth were analyzed using close-up photographs and/or profilometer measurements. The measured dimensions of representative wear marks were used to predict the fretting-wear behaviour of components up to and beyond the proposed lifetime of fuel in the reactor.

III. RESULTS

These tests led to rather extensive amounts of data, which have been analyzed and interpreted in a series of AECL reports. Selected results from each of the three different kinds of tests follow.

III-1. Modal Tests.

Sample vibration-response spectra for the 18-element fuel bundle in water are shown in Figure 2. The three lower panels illustrate the lateral response of the bundle, as measured by displacement probes aimed at the three spacer plates, to a broad-frequency-band excitation applied to the grapple head. The clearest peaks in all three cases occur at a frequency of approximately 17 Hz and correspond to the approximately in-phase motion of the bundle and flow tube. Apart from this motion, which is interpreted as the fundamental transverse bending mode of the bundle/flow-tube structure, it is difficult to establish clear modes of vibration of the bundle or of individual components, due to the complicated structure of the bundle and the many possible combinations of clearance/preload conditions.

III-2. Vibration Tests in Flow.

Vibration spectra for the 18-element bundle in flow, at 100% of the reactor design flow rate, are shown in Figure 3. The fundamental bending mode observed in the vibration-response tests is also clearly observed in flow at a frequency of approximately 18 Hz.

Figure 4 shows the grapple head displacement measured as a function of flow rate. At flow rates below 5 kg/s, the majority of the vibration is not flow-induced but is rather due to rig vibration, caused by the VIBFLO pumps operating in a hydraulically "noisy" bypass mode in order to maintain such low flow rates. At higher flow rates, the vibration levels gradually increase in a manner typical of flow-induced vibration due to modest levels of random turbulence. By contrast, a response due to fluidelastic instability would exhibit a dramatic increase in vibration with flow rate.

Figure 4 also shows the dominant frequency obtained from the grapple head spectra. The consistency of the frequency as a function of flow rate reflects the fundamental-mode nature of the vibration.

III-3. Endurance Tests.

In principal, in any situation where there is relative motion between different fuel-bundle components, or between bundle components and the fuel channel, and contact occurs, there is potential for fretting-wear. The fuel bundles tested in the present work have a number of (anodized) aluminum components, and so following the endurance tests, and at various intervals during the tests, these components in particular were closely examined for wear.

One such component, a wearpad on the 36-element bottom endplate, is shown in Figure 5. The visible wear mark is due to the endplate coming into contact with the Zircaloy flow tube. Such a fret mark can be categorized as modest wear, and in this case the degree of wear is considered acceptable. The measured wear damage is slight, compared to the considerable volume of material available for wear before the function of the component is compromised in any way.

The spacer-plate wearpads are thinner and have less volume to spare for wear, so a "worst case" of spacer wear was selected for thorough analysis. The profile was traced with a mechanical profilometer to an accuracy of ±10 μm and compared to profiles obtained from unworn areas. Following the approach used by Pettigrew and co-workers [1], the wear volume obtained from the dimensions of the wear mark was then used to calculate the product of a wear coefficient, K, and work-rate, $\dot{W}$, for this test.

The work-rate represents the dynamic interaction between two contacting surfaces. Assuming that this interaction remains constant - and knowing the geometry of the spacer wearpad - the product $K\dot{W}$ was used in a calculation which modeled the dimensions of the wear mark as a function of time. To determine whether or not the fretting-wear performance of the bundle was acceptable, the observed wear after 40 days was extrapolated to twice the reactor design residence time.

Results for the 36-element-bundle spacer wearpad are illustrated in Figures 6 and 7. Based on this analysis, the extrapolated maximum wear depth falls well short of the specified wear criterion. Therefore, for this type of fuel bundle under the hydraulic conditions present during the test, external wear of the wearpads due to flow-induced vibration is not expected to affect spacer function.

IV. Application to Tests of CANDU-Type Fuel

Out-reactor vibration and fretting-wear tests have been performed with CANDU fuel bundles in the past, and tests similar to those described here are being proposed for new designs. Various aspects of the present work are directly applicable to such tests. For example, the technology of installing miniature instruments within fuel elements has recently been used for tests carried out in support of the Fuel Development Branch at Chalk River. Out-reactor tests can also be designed to simulate reactor-like fuel conditions, for example by fabricating dummy elements filled with Pb/Sn pellets (of the correct density) that are sized to simulate the dynamic characteristics of fuel pellets at high temperature and pressure. Pressure pulsations that are typical of reactor pump acoustic noise can be introduced into the fuel channel. In addition, the tests can be designed to obtain reliable values for basic hydraulic parameters such as overall pressure drop, or friction factors, information that is often desired before fuel is loaded into a reactor.

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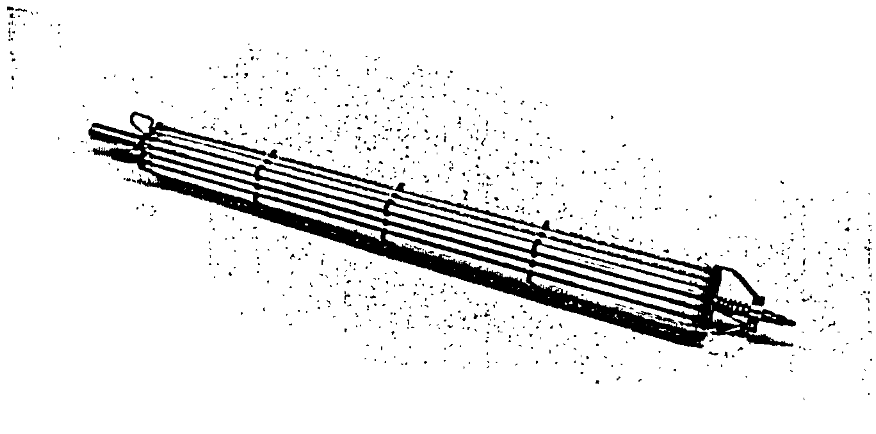

FIGURE 1. A 36-ELEMENT HEXAGONAL FUEL BUNDLE OF THE TYPE USED IN THE HANARO RESEARCH REACTOR. THE GRAPPLE HEAD (TOP) IS ON THE LEFT AND THE BAYONET MOUNT (BOTTOM) IS ON THE RIGHT. THREE SPACER PLATES APPEAR AS DARK BANDS SITUATED AT EQUAL INTERVALS ALONG THE LENGTH OF THE BUNDLE.

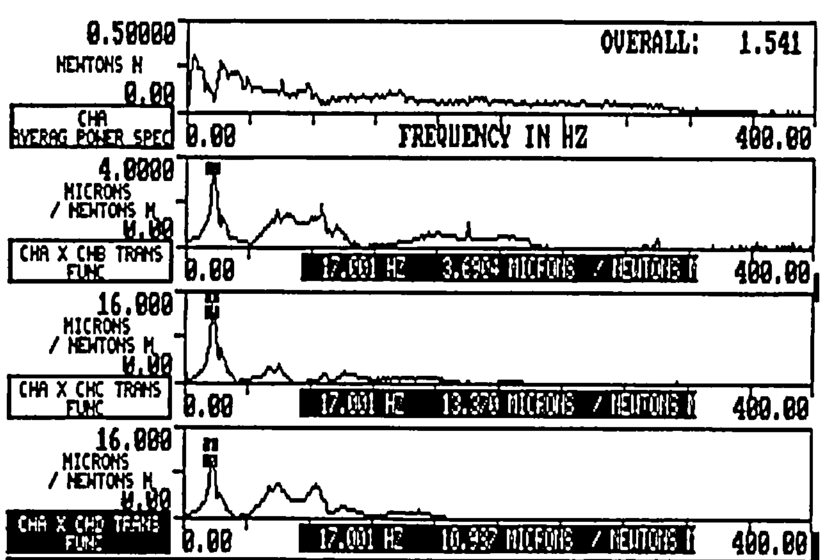

FIGURE 2. VIBRATION SPECTRA FOR THE 18-ELEMENT-BUNDLE MODAL TEST IN WATER, OVER THE FREQUENCY RANGE 0-TO-400 HZ. THE TOP PANEL SHOWS THE FORCE APPLIED (AT THE GRAPPLE HEAD), WHILE THE REMAINING THREE PANELS SHOW TRANSFER FUNCTIONS OF THE LATERAL DISPLACEMENTS OF THE THREE SPACERS WITH RESPECT TO THE FORCE.

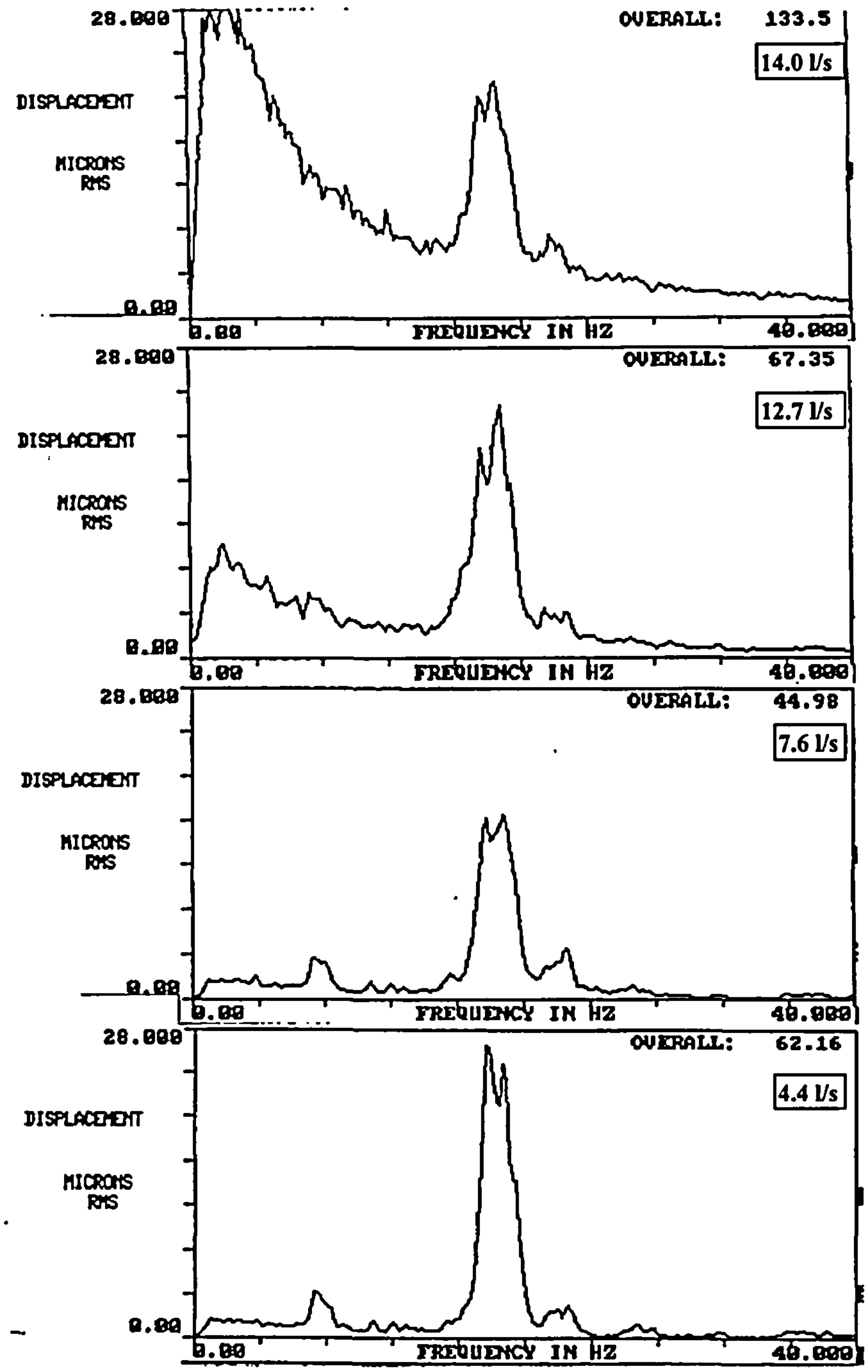

FIGURE 3. RMS-DISPLACEMENT OF THE GRAPPLE HEAD AS A FUNCTION OF FREQUENCY IN THE Y-DIRECTION, AS MEASURED WITH THE LASER VIBROMETER DURING THE 18-ELEMENT-BUNDLE VIBRATION TEST IN FLOW.
THE DESIGN FLOW RATE IS 12.7 LITER/S.

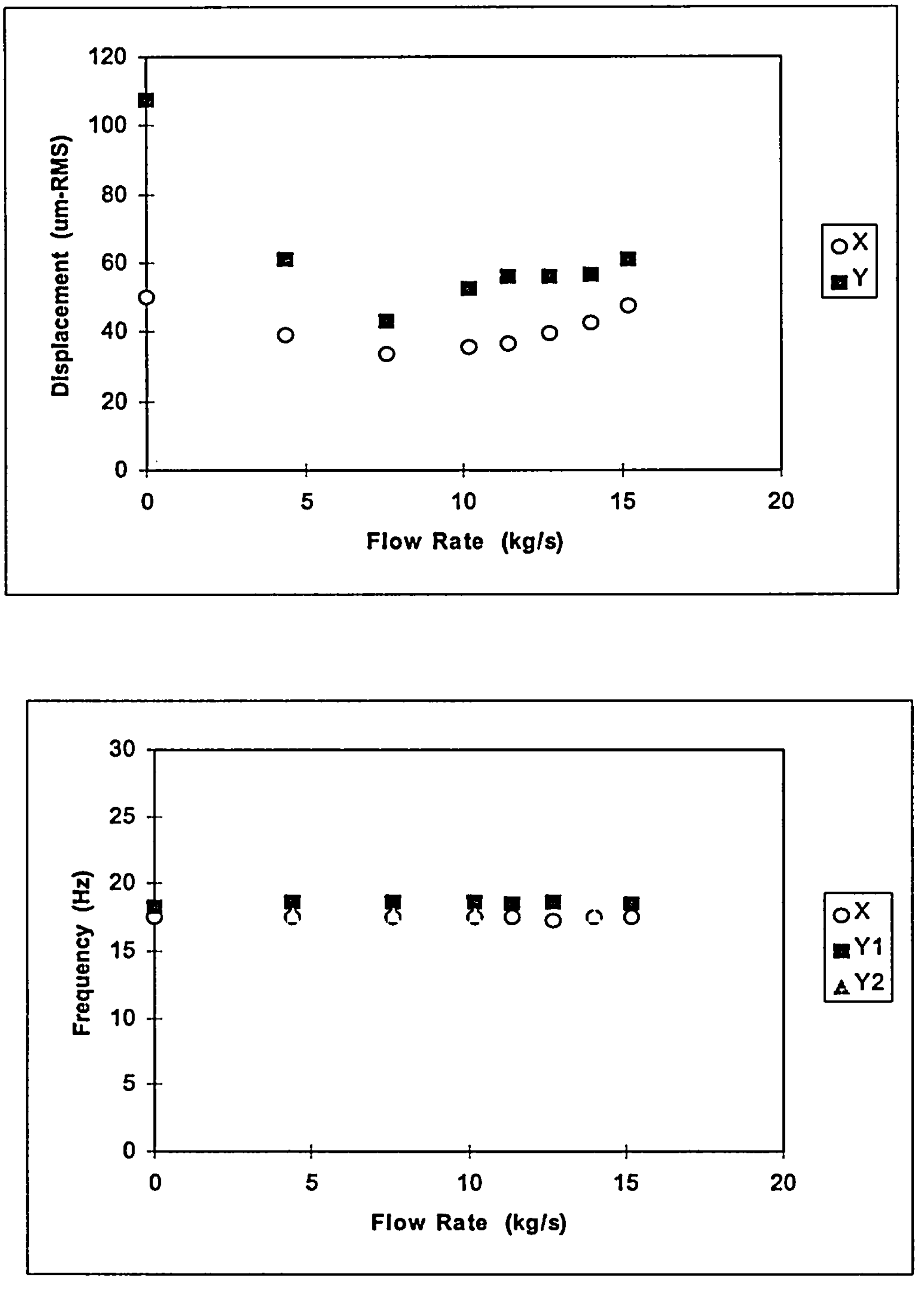

FIGURE 4. GRAPPLE-HEAD DISPLACEMENT AND DOMINANT FREQUENCY AS A FUNCTION OF FLOW RATE, FOR THE 18-ELEMENT FUEL BUNDLE. THE DESIGN FLOW RATE IS 12.7 KG/S. X AND Y ARE REFERENCE DIRECTIONS. SOME SPECTRA FOR THE Y-DIRECTION CONTAINED TWO PEAKS OF APPROXIMATELY EQUAL INTENSITY, LABELLED Y1 AND Y2.

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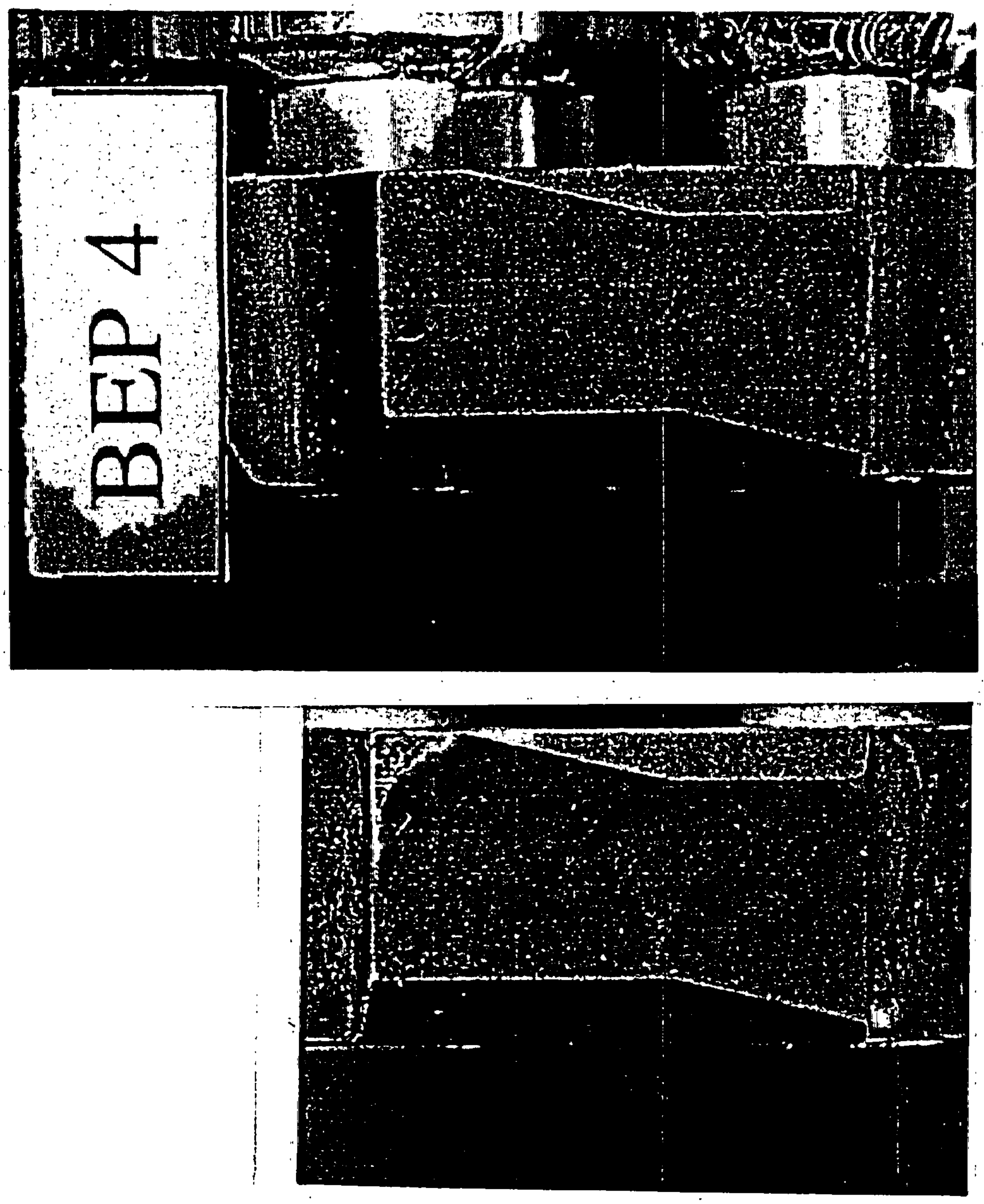

FIGURE 5. BOTTOM-ENDPLATE PAD BEP4 BEFORE AND AFTER THE ENDURANCE TEST OF THE 36-ELEMENT FUEL BUNDLE (TOP AND BOTTOM PANEL, RESPECTIVELY). A WEAR MARK IS VISIBLE AT THE TOP LEFT-HAND CORNER OF THE WEARPAD.

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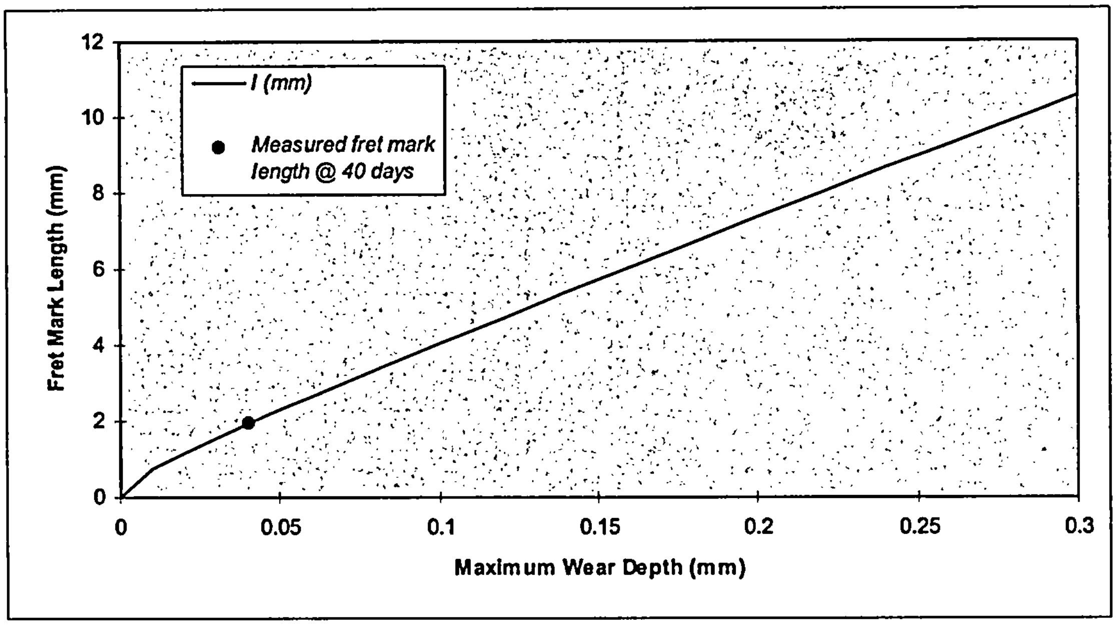

FIGURE 6: VISIBLE FRET-MARK LENGTH VERSUS DEDUCED MAXIMUM WEAR DEPTH.

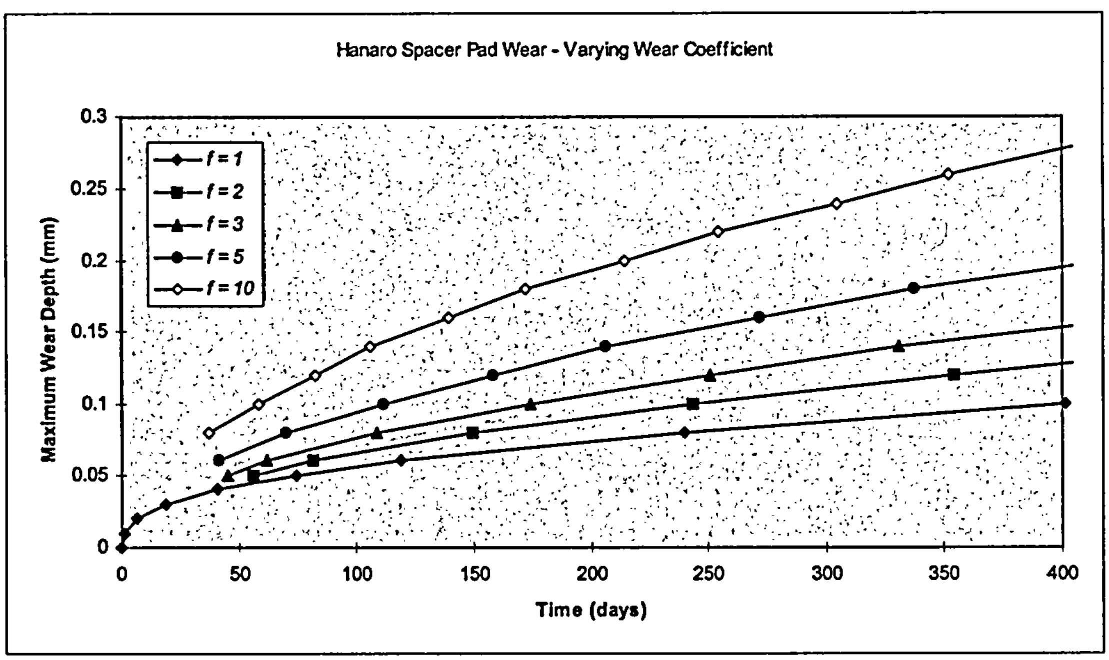

FIGURE 7: CALCULATED MAXIMUM WEAR DEPTH VERSUS TIME. THE DIFFERENT CURVES REPRESENT VARIOUS ASSUMPTIONS FOR FRETTING-WEAR COEFFICIENTS.