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Diagnosis and cure of Dhruva fuel vibration

R.I.K. Moorthy, A. Rama Rao and Anil Kakodkar

Reactor Engineering Division, Bhabha Atomic Research Centre, Trombay, Bombay 400 085, India

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Dhruva is a high flux research reactor with a nominal thermal power of 100 MW. The fuel for the reactor is in the form of seven-pin cluster of metallic natural uranium clad with aluminium. The optimisation from the physics and thermal hydraulic considerations has resulted in this design of small diameter, long pins arranged hexagonally ensuring a minimum specified clearance between the pins. The clearance is maintained throughout the length by a number of spacers located at regular intervals. This seven pin cluster is assembled inside an aluminium flow tube and the assembly goes into coolant channels made of zircaloy. The fuel assembly is constrained radially (i.e. in the horizontal plane) by the bulges at the two ends of the flow tube.

The fuel was endurance tested in an out-of-pile flow test facility for many thousands of hours without any visible damage. However, on loading them in the reactor, many of the fuel pins failed due to fretting wear at the spacer locations. The maximum wear- was on the outer pins near the mid-length of the fuel assembly. The paper gives the details of the measurement and analysis carried out to understand the causes. The solution adopted was to make the supporting bulges flexible – the bottom one by cutting axial slits to obtain a collet type fixture and the top by a sleeve with slits to obtain leaf spring type support. With these design changes, the fuel performs satisfactorily.

1. Description of Dhruva reactor

Figure 1 shows the general arrangement of the reactor schematically. It consists of an 11 m diameter × 12 m high cylinder of heavy concrete. The water-filled cavity inside the cylinder houses the reactor vessel and the various shields. The pipings of the primary heat transport system penetrate through the cylinder at appropriate locations. The heavy water coolant passes through more than a hundred identical coolant channels. The fuel assemblies are located inside each of these coolant channels. Three independent loops circulate the coolant through the reactor and the heat is rejected to a secondary fluid in the heat exchanger.

In addition to the penetrations for carrying the coolant, many structural connections and fluid conduits from various components of the reactor penetrate through the concrete cylinder. The relevant ones from these are also represented schematically in fig. 1.

1.1. Description of the fuel

The general assembly of the fuel is shown schematically in fig. 2. Seven uranium pins clad with finned aluminium tubes are assembled inside an aluminium flow tube. The inter-element spacing is maintained with the help of a number of spacers along the length of the assembly. At the lower end of the fuel assembly a bulge is provided which is closely dimensioned to the coolant channel dimensions at that location. This provides a bearing type horizontal support at the bottom end of the fuel assembly and also reduces the flow of coolant through paths bypassing fuel. Another bulge at the top end of the fuel cluster provides for the same mechanical and hydraulic functions. The seal and shield plug assembly which is pinned to the cluster assembly fill up the remaining length of the coolant channel to the top of the reactor.

1.2. Proof testing of the fuel design

The fuel design had been verified using the several correlations available in the literature for flow induced vibration [1–7]. For confirmation, the fuel was tested at the design pressure and flow on a full-scale out-of-pile flow test facility. The fuel assembly could endure the design life with no apparent damage.

1.3. Performance of the fuel in-pile

Such an endurance tested design of the fuel, when loaded in the pile, was found to vibrate severely. Severe vibrations caused the fretting wear of the clad in a very short time. On an examination of the failed assembly – i.e. 1 mm thick clad worn off completely at the point of maximum wear – it was seen that significant wear had occurred at those spacer locations near the mid lengths of the fuel pins. It was also seen that the wear on outer pins was larger than that on the central pins.

2. Vibration measurement and analysis

To understand this unexpected vibration phenomenon, measurements were carried out as detailed below:

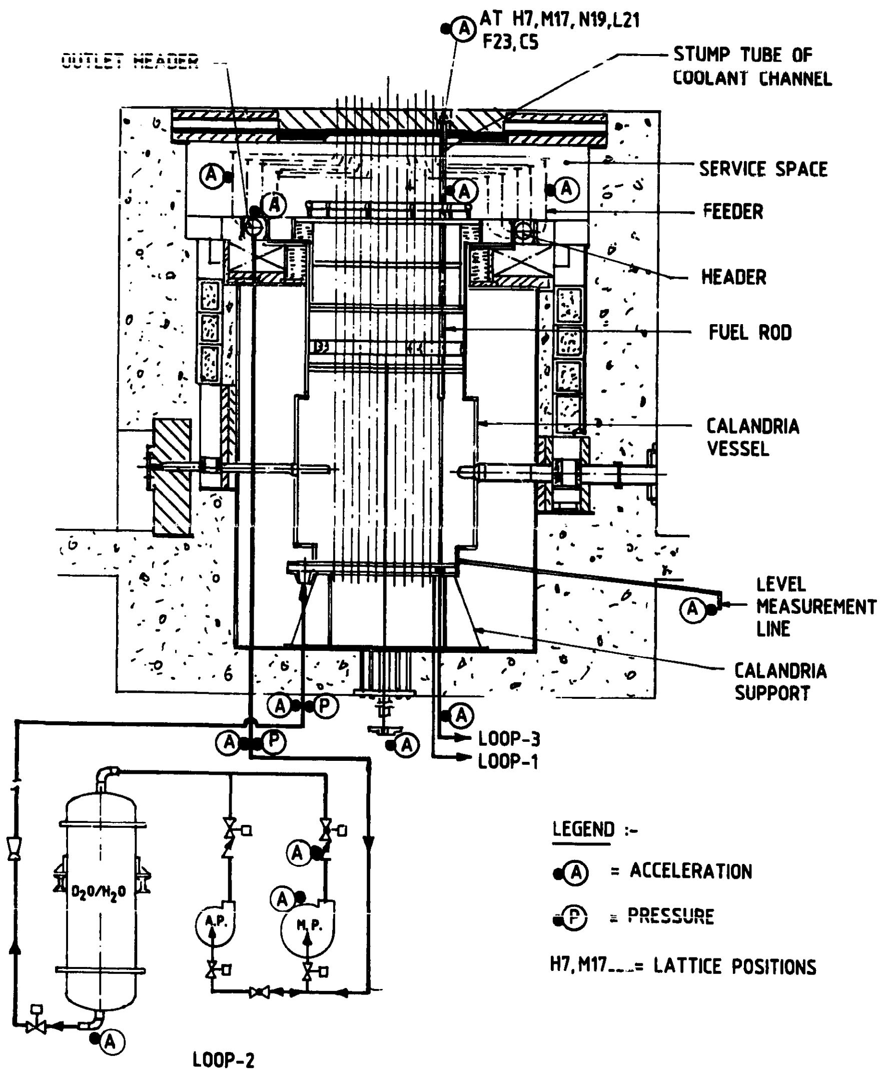

Fig. 1. General arrangement of Dhruva reactor showing the components covered for the vibration study.

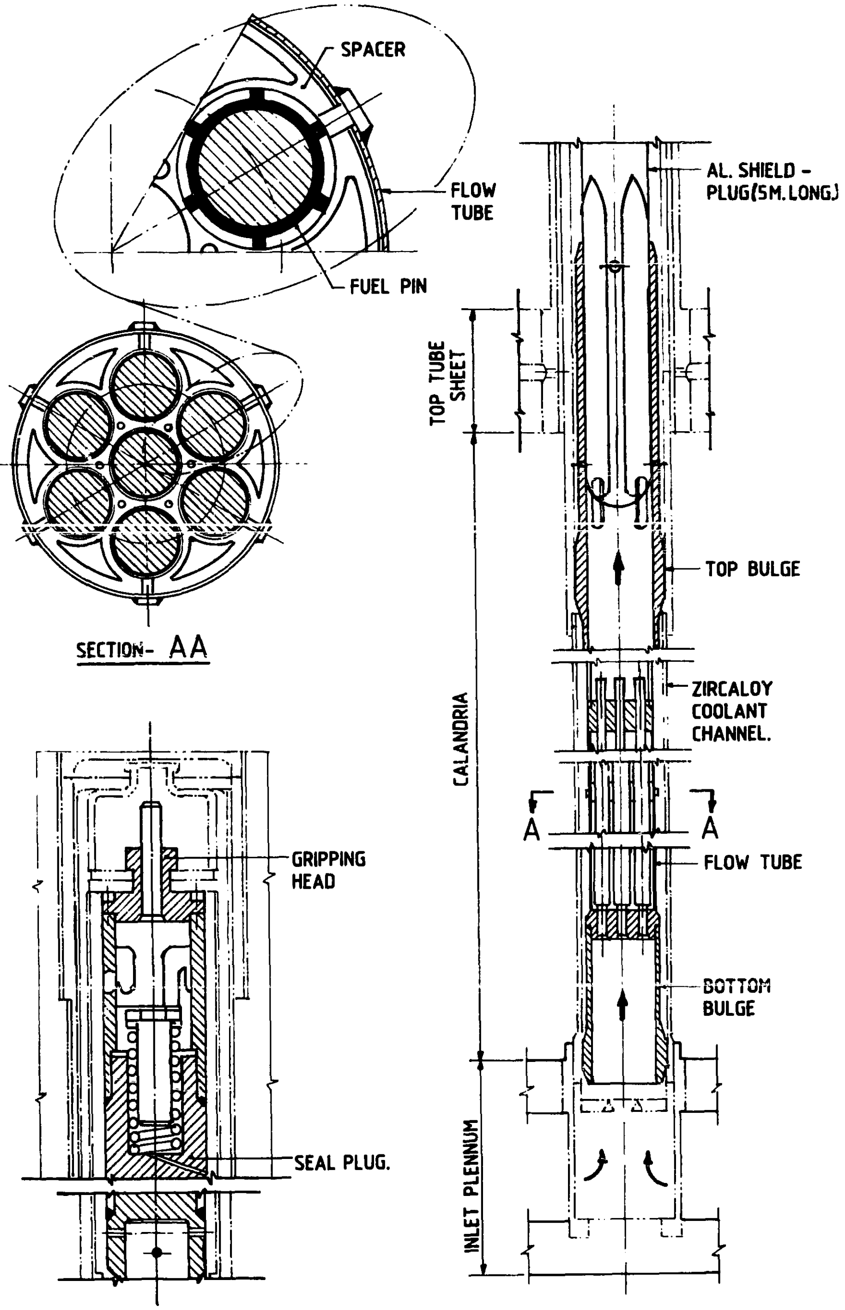

Fig. 2. Dhruva fuel assembly.

Fuel vibration was measured at the top of the reactor from where the gripping head at the top of the fuel assembly is accessible. The vibration was measured in two perpendicular horizontal directions and in the vertical direction. Fig. 1 gives the lattice locations where these measurements were carried out.

Since the reactor structure is inaccessible, measurements were taken on the various accessible structures and piping connections which penetrate the reactor cavity. The level measurement line coming out directly from the lower subshell of calandria and the Engineering loop sleeve which come out directly from the top tube sheet of calandria, were monitored to get an idea of the vibration of calandria. Fig. 1 shows these two points schematically. The vibration tests were conducted with two of the three primary loops working. The vibration of one operating and the non-operating loop was monitored during the test. See fig. 1 for measurement locations.

To obtain the characteristics of the coolant channel the accessible portions of the same in "service space" (see fig. 1) were monitored. So also the "main header" which collects the heavy water from individual coolant channels and the feeders were monitored.

The vibration at all these locations were measured using piezo-electric accelerometers. These locations have been identified in fig. 1 by (A). In addition to the vibration, the pressure fluctuations at the pump outlet, reactor inlet and reactor outlet were also measured. These locations are identified in fig. 1 by (P).

The vibration and pressure fluctuation signals were recorded on multichannel FM tape recorders for laboratory analysis.

2.1. Analysis and interpretation of the signals

The recorded signals were laboratory analysed for their power spectral densities (psd). The psd of pressure fluctuations were not useful for the diagnosis. The most striking feature of all the vibration psd's – from the various pipings, loop components, structural connections from the reactor and the fuel top – had been the presence of 13.2 Hz and its higher harmonics. Refer to fig. 3 for a typical psd of the fuel top. In addition, the fuel top is found to have a very high broad band noise which increases with frequency. A broad band (0.2 Hz to 1 kHz) peak to peak acceleration of more than 10g had been recorded on the top of many fuel assemblies.

The huge peak at 110 Hz in fig. 3 is the response of the fuel pins in a beam mode. This frequency is close to the theoretical estimate of the natural frequency of the

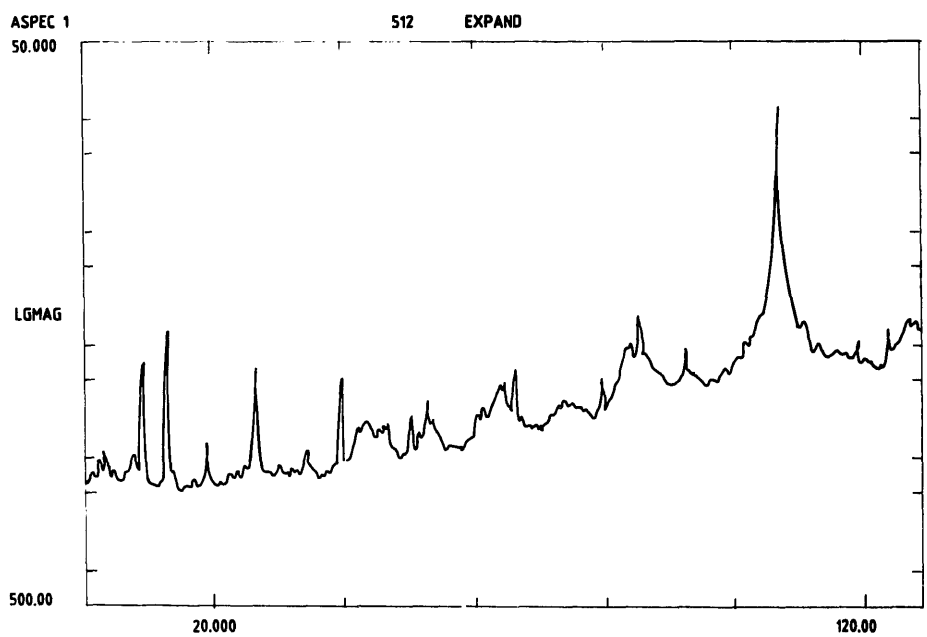

Fig. 3. PSD of vibration acceleration of the fuel-top.

individual fuel pins of the cluster, assuming the pin to be supported at the spacer locations.

In order to identify the source of these 13.2 Hz and harmonics, the coherence and crosspower spectral densities (cpsd) between various combinations of measurement locations were computed. It has been found that at these frequencies, heat exchanger is highly coherent with all the other coolant circuit measurement locations including the ones in the non-operating loop.

2.2.

A theoretical estimate of the natural frequency of the heat exchanger mass (weighing 40 tonnes) supported on ISMB-600 girders was made. This estimate was seen to coincide very closely to 13.2 Hz.

2.3.

Though the above study could establish the source of 13.2 Hz on the loop components and piping, the dominance of these at the fuel top could not be explained unless there is resonance within the fuel assembly itself. Calculations of the natural frequencies of the various components of the fuel assembly with refined modelling revealed that the flow tube, if assumed to be simply supported at the bulges, does have a natural frequency close to 13.2 Hz. In the earlier analytical models, the flow tube was assumed to be rigidly coupled to the fuel cluster through the spacers. However, the gap between the spacer ring and the individual fuel pins allowed the flow tube to respond independently of the cluster and behave as an impact oscillator. The presence of super harmonics in the impact oscillator was confirmed experimentally. The analytical confirmation of such a phenomenon is available in refs. [9] and [10].

2.4.

To verify the above, laboratory tests for the flow tube natural frequency were conducted. A full length flow tube was supported on V-blocks and excited with an instrumented hammer. The impulse and the response were analysed to obtain the transfer function [8]. The experiment was repeated with different extent of clamping of the bulges on to the 'v'-blocks. This was done to study the effect of the possible dimensional clearances in the actual reactor. It was seen that a natural frequency range of 12.7 Hz to 14.5 Hz could be obtained from a no-clamp to good-clamp conditions. Even after account-

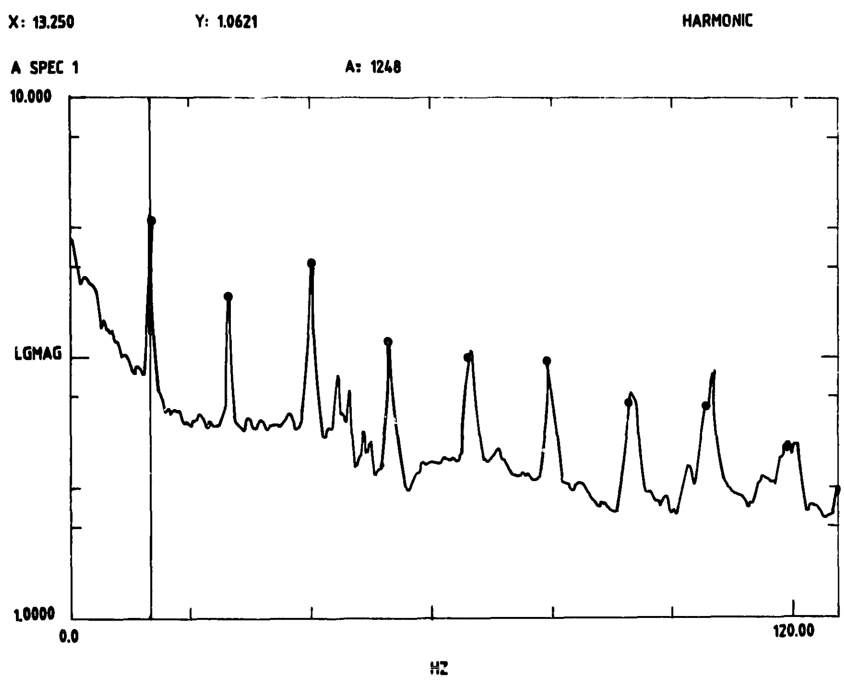

Fig. 4. PSD of vibration acceleration of the fuel-top in the flow rest facility with external excitation.

ing for some difference due to "in-air" and "in-water" values, this range of values could be considered close to 13.2 Hz.

In the out-of-pile flow test station a higher clearance between the supporting bulge and the mating diameter of coolant channel increased the vibration at fuel top. The vibrations also increase when the bulge is lifted up from the mating diameter portion (as during refuelling). But, under these conditions, the wear marks on the bottom bulge could be seen suggesting the possibility of the whipping of the entire fuel assembly by the flow. These trials and observations were necessary to exclude the possibility of the manufacturing tolerances being the cause of vibration and fretting.

The psd of the vibration above 1 kHz showed significant background. Such high background at higher frequencies also pointed to impacting or chattering activity. In conjunction with the super-harmonics of 13.2 Hz, the spacers (which are attached to the flow tube), impacting on the fuel pins could be visualized.

The energy transfer to the higher harmonics in an impact oscillator had been found to be significant by Gandhi [9] and Bhat [10]. As the flow tube with the top and bottom bulge supports is close to an ideal simply supported beam, the higher modes would be integral multiples (4, 9, 16, etc.) of the fundamental. By coincidence, the spacers had been located at the node points of the higher modes. Under these conditions, the higher harmonics manifest with higher energy.

In order to prove such a postulate, the out-of-pile flow test facility was excited externally with an electrodynamic shaker. The excitation was applied to the inlet piping of the facility. An input of less than 10 watts to the shaker at 13.2 Hz was sufficient to double the vibration acceleration recorded on the top gripping head. Figure 4 shows the p.s.d. of the fuel top in the flow test facility with the external excitation. The similarity with the actual in-pile spectra is striking.

The out-of-pile flow test set-up had only two full length assemblies. In the actual reactor, many identical assemblies are located close to each other inside a water filled chamber. Such a configuration could result in higher vibration amplitudes for the same input energy per channel [5,7].

3. Design modifications

Based on the above analysis, it was clear that the natural frequencies of the flow tube and the heat-exchanger-support system would have to be separated adequately. Since the fretting wear is caused by the relative motion between the fuel pins and the spacers on the flow tube, the problem could also be solved by avoiding the relative motion. In other words, the mode-shape should be altered to ensure no relative motion between the fuel pins and the flow tube (with the spacers attached to it). A number of alternative solutions were evolved and reviewed by agencies involved with the design of fuel, design of coolant channel, manufacture of fuel etc. to arrive at an elegant and simple solution. The one finally adopted successfully is as follows.

(a) the bottom bulge was made with a design interference with the coolant channel dimensions at the mating region. The bulge was given radial flexibility by cutting a few 'through-thickness' slits for a sufficient length. In other words, the bottom bulge acts like a collet flexible enough to be inserted into and withdrawn from the coolant channel without much force as well as provide a spring support during the residence in-pile.

(b) at the top location a tapered sleeve with a design interference with the coolant channel dimensions at the mating region was incorporated. This sleeve also has slits to provide the required flexibility during operation and easy insertion into and removal from

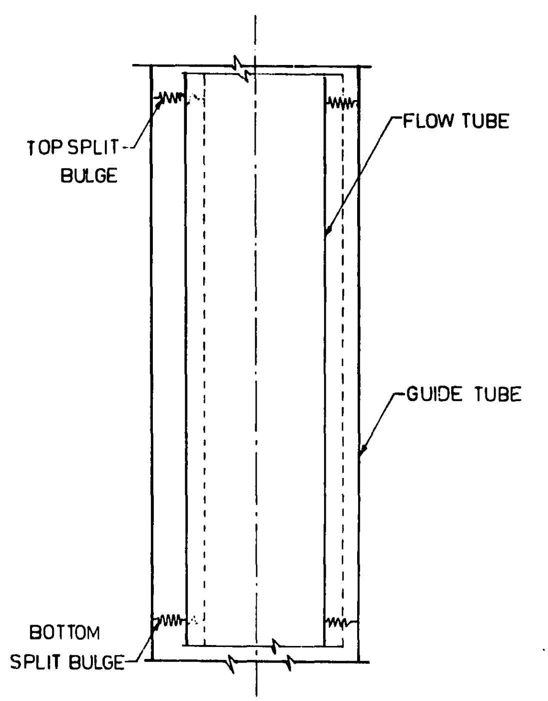

Fig. 5. The first mode of vibration of the fuel assembly with split bulges.

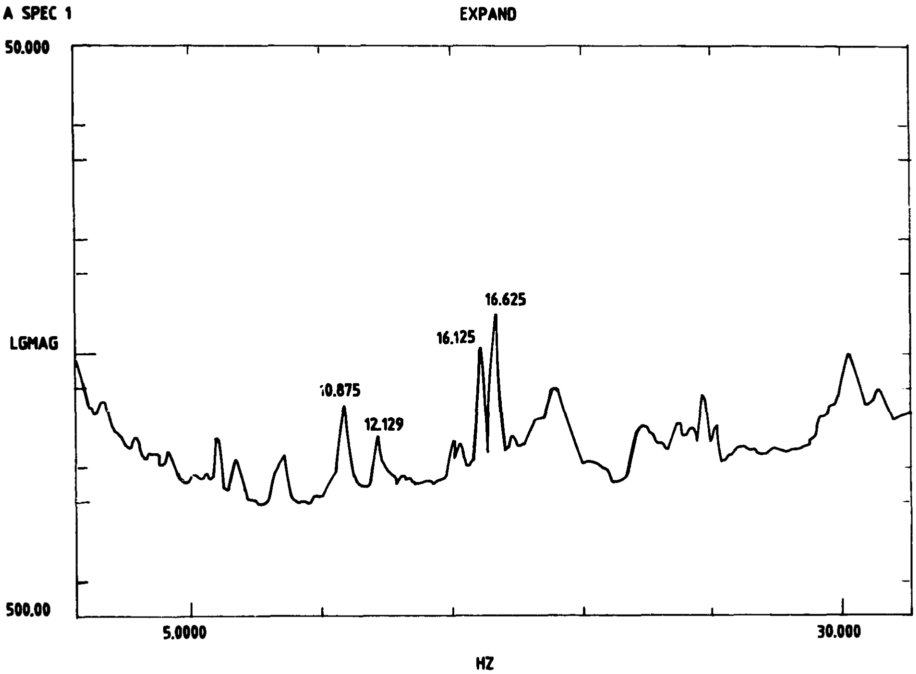

Fig. 6. PSD of vibration acceleration of the modified fuel in the reactor.

the channel. The additional sleeve was necessary to realise hydraulic requirements.

The advantages of such a supporting system have been (a) the first mode of vibration is a "free-free" mode of the flow tube along with the fuel pins as schematically shown in fig. 5, thus avoiding any fretting at the spacer-pin interface, (b) the amplification is also reduced as the first mode of vibration is at a frequency lower than 13.2 Hz and the second mode which would be a bending mode, is adequately higher than 13.2 Hz. Further, the higher modes are not integral multiples of the fundamental.

This scheme has an additional advantage. When the bulges leave the seat, as during refuelling, lateral supports are available to avoid whipping.

3.1. Performance of the modified fuel

Figure 6 shows the spectrum at the fuel top in the reactor after incorporating the above design changes. The drastic change in the spectrum is quite apparent.

The fuel assembly with the above design changes is in use in the reactor for many months now with no problem of fretting. The vibration levels of the fuel at the top of the reactor has also been extremely small throughout its residence in the pile.

Further optimization of the fuel design from nuclear and thermal hydraulic considerations is being carried out by the concerned agencies.

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