# VIBRATION AND WEAR OF LOOSELY SUPPORTED HEAT EXCHANGER TUBES

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Heat exchanger tubes must be loosely supported to allow for thermal expansion and ease of construction. Consequently the tubes are not fully restrained at their supports and they may rattle, impact and slide producing wear. A further problem is that the loose supports may not prevent low frequency vibration and this makes the tubes particularly susceptible to flow excitation.

A support can be fully effective if the friction force between the tube and its supports prevents any sliding motion. This however requires a large static force to press the tube against its supports. This paper will consider what static force is necessary in order to prevent any sliding motion. The factors the designer must manipulate to achieve an effective support are the magnitude of the fluid loading, the tolerance in construction and the location of the supports. This paper considers these factors.

If the friction force is not sufficient to prevent motion, then the tube will slide until its motion is limited by impacting against a support. This situation is much more difficult to analyse but theoretical and experimental considerations show that very low frequencies of vibration are possible. Recent work which investigates the natural frequencies an damping of loosely supported tubes is described. This work includes theoretical simulations of the vibration of an impacting tube and experimental measurements of loose tube motion.

In summary, this paper examines the link between the excitation forces which cause a tube to vibrate and the wear mechanisms which cause damage.

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# FLOW INDUCED VIBRATION IN LMFBRs

## Development Work in Support of the UK Programme

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## 1. INTRODUCTION

Techniques for the assessment and avoidance of flow induced vibration problems employed for the Dounreay Fast Reactor (now closed down) and the Prototype Fast Reactor PFR are being continued for development of the Civil Demonstration Fast Reactor (CDFR) and are also being used for components of SPX2 and SNR2. It is usual to assess (theoretically initially) flow distribution, fluid forcing functions, structural response and the potential for wear or other harmful effects. Prediction of resonance or instability is required at an early stage in design. Endorsement tests have been carried out to confirm theoretical approach or to provide realistic simulation of vibration in cases where available data or techniques are insufficient to give reliable results.

Design aspects are discussed by Bolton(1) in a separate paper, to be presented alongside this one.

The 1.5m$^3$/s water loop at Risley Nuclear Laboratories has been extensively used to generate basic data and for endorsement tests on large prototypic models.

Considerable effort has been devoted to understanding flow interaction in tube bundles as these feature prominently in heat exchangers (Steam Generator Unit, SGU and Intermediate Heat Exchanger, IHX) also in CDFR core support and above-core structure. Excitation data has been obtained at Reynolds Numbers Re 0.4-4x10$^5$ for a range of triangle pitch geometries appropriate to heat exchangers and at Re up to 2x10$^6$ for above core structure.

In this paper basic tube-bundle development work is described first, to be followed by application to the various parts of the reactor to which it is appropriate, along with other vibration experimental work and future intentions.

## 2. BASIC CROSS-FLOW EXCITATION OF TUBE BUNDLES

Multi-tube test-sections (as shown in Figure 1) have been used to investigate flow-induced forces for equilateral triangle geometries. (Square pitching is to be examined in the near future). Test bundles had pitch-to-diameters p/d of 1.3, 1.65 and 2.0, corresponding with IHX, core-support diagrid and SGU geometries respectively. Length-to-diameter ratio was 18 in all cases, behaviour in both normal and rotated triangle geometries being monitored. Most of the tubes were fixed to the tube-plates, but selected tubes could be mounted on triaxial force transducers as shown in Figure 1, allowing comparison of behaviour at various parts of the bundle. Test-sections were assembled in a water test-loop designed to give a uniform upstream velocity profile with low turbulence level.

Test Reynolds number Re was in the range $4 \times 10^4$ to $4 \times 10^5$ (appropriate to heat exchangers). Transducer output was processed to give Strouhal numbers (St), fluctuating lift coefficients ($C_L$') and fluctuating drag coefficients ($C_D$') based on tube diameter and the mean velocity in the minimum gap between tubes. Tube surface pressure fluctuations were correlated with end forces and pressure fluctuations along tube axes are presently being correlated.

Figure 2 is a typical example of results obtained, showing features for a normal triangle geometry (with flow entering the bundle perpendicularly to rows of tubes) with p/d=1.3. The main points of interest are

i. There are distinct peaks in the tube response frequency spectrum, which are flow-induced, for virtually all geometries and tubes. The peaks are sharpest for tubes close to the inlet (ie rows 1 and 2), becoming wider and flatter deeper inside the bundle.

ii. Tubes close to the inlet exhibit a transition at Re of about 1.4 to $1.8 \times 10^5$ at which the Strouhal number ($f_{peak}.d/V_{min\ gap}$) changes. For Figure 2 St fell from 0.57 to 0.13. The transition led to a widening of the peaks in the response spectra as flow increased and no transition was apparent for tubes deep inside the bundles. Above the transition peaks became less distinct as Re progressively increased.

iii. Similar frequencies were recorded for lift and drag directions. Fluctuating lift forces were higher than for fluctuating drag.

iv. Below transition there was strong correlation between surface pressure fluctuation and tube end forces, particularly in the lift direction, for tubes close to the inlet. The correlation was less clear at highest Re and for tubes well inside the bundle.

v. The Strouhal peaks were capable of inducing tube resonance.

The inlet tube rows St was maximum (0.58) for p/d=1.3 reducing to about 0.20 for p/d=2.0 for both normal and rotated triangle geometries below the transition Re. Above transition, values of 0.14 to 0.30 were generally encountered. The St range 0.16 to 0.36 encompassed all data well inside tube bundles.

Fluctuating lift coefficients below the transition Re were typically about twice those above it for tubes close to the inlet.

It was concluded that flow-induced excitation in bundles is complex, with differences in excitation mechanism for tubes close to the inlet as compared with those mid-bundle. It is apparent that the first rows of a tube bundle can be particularly prone to narrow- band flow-induced excitation and that the behaviour of tubes well inside bundles also needs to be considered for Strouhal-type excitation. Presence of a transitional Re requires careful assessment of conditions at the inlet to a tube bundle.

Studies are continuing using correlation techniques to study in more detail force response at tube ends and the axial distribution of pressure fluctuations along tubes.

## 3. CORE-SUPPORT AND SUB-ASSEMBLY VIBRATION

The high-pressure plenum of CDFR is shown schematically in Figure 3(a). Sodium enters vertically a perforated inlet duct from whence it passes radially among the tubes which brace the diagrid and supply coolant to individual sub-assemblies. It is important to show that neither the support tubes nor sub-assemblies experience excessive vibration due to cross-flow in the plenum, which can be considered as a large tube bundle with $Re \approx 10^6$.

Flow patterns have been computed for the plenum using the programme PHOENICS and the velocity distribution is being measured using a 1/4 scale 360° water model. Flow-induced forces are estimated using this data in combination with basic bundle excitation behaviour obtained from appropriate tests as described in Section 2. Simple mechanically and flow-induced performance has been measured using a test assembly as shown in Figure 3(b) in which a model sub-assembly was mounted on a support tube to the reactor design. This allowed vibration mode-shapes, frequencies and damping to be recorded along with resulting amplitude per unit input force. Using this data it has been possible to compare forcing and response frequencies and to make an estimate of possible vibration amplitude for various operating and support conditions.

Vibrations of individual fuel pins within sub-assemblies have been measured in water tests, as described in detail in Ref 2. It was concluded that vibration should be minimal provided that pins were well supported without excessive clearance (particularly upstream) and that gross sub-assembly motion did not occur. Endurance tests have been carried out to give indication of potential pin wear, in some cases using enhanced flow to accelerate any damage (see Ref 3). Results have been in line with the observations of individual pin vibration.

## 4. ABOVE CORE STRUCTURE

Figure 4(a) shows schematically the CDFR above-core structure (ACS). The principal feature likely to cause vibration is the deflection of the upward-rising flow from the core by a horizontal baffle to pass radially outwards into the hot pool. In consequence some control-rod shroud-tubes (CRSTs) experience strong cross flow and the whole structure will be buffeted by fluctuating forces induced by the turning flow. Instrument tubes also are subjected to various degrees of cross-flow.

The model sketched in Figure 4(b) was constructed to investigate cross-flow over tubes at high Re ($\approx 10^6$) relevant for the CRSTs. Seven tubes were flexibly mounted on bending bars in a rectangular water channel which had dummy tubes in a curved section upstream to generate the high turbulence which must occur above the core. Vibration amplitudes were measured for a range of flow-rates and natural frequencies for the seven tubes.

Frequency analysis of tube vibration amplitudes showed a strong flow-dependent peak as well as the lowest natural vibration frequency. Strouhal number (based on minimum gap velocity for the normal equilateral triangle geometry) was typically $\approx 0.24$ for Re in the range $10^5$ to $10^6$, for lift forces. The flow-dependent peak was strongly present for the lower part of the range for in-line excitation, but faded out in the upper part. Violent resonance occurred in the lift direction when the Strouhal and natural frequenciues were close to each other. Data from these tests is used to assess CRST forces.

A model is being considered for the investigation of overall ACS forces in which the ACS is approximated by a simple cylinder and the CRSTs by plain tubes. Maximum scale would be between about 0.15 and 0.25, being dictated by the capacity of available water loops. The simple nature of the model would allow easy adaption to European ACS geometries. The model would be constructed to allow changes of basic dimensions and geometry such that the flow features affecting overall forces (ie amplitude, frequencies, statistical variation, etc) can be identified.

## 5. HEAT EXCHANGERS AND STEAM GENERATORS

Designs for UK CDFR steam generator and intermediate heat exchanger are described in Ref 1. Flow induced vibration is most critical for tubes, particularly in zones of cross-flow. The following procedure is generally adopted for the assessment of vibration.

(a) Velocity profiles are computed as are tube natural frequencies and mode-shapes assuming positive support at grids.

(b) Cross-flow data (Section 2) for the appropriate geometry and Reynolds number is applied to give flow-induced forces and narrow-band excitation frequencies.

(c) (a) and (b) are combined to indicate whether resonance is likely and to give estimated tube vibration amplitudes. The possibility of fluid-elastic instability is assessed and parallel-flow induced amplitudes calculated.

(d) The degree of potential tube wear is estimated by the National Centre of Tribology using the calculated vibration amplitudes in combination with wear data obtained by them in sodium from tube-in-bush wear tests for simulated reactor geometries.

This approach assumes 'idealised' support of tubes at grids. In practice the effects of finite clearances, tolerancing of tube straightness and grid alignment results in considerable variation of tube-grid reaction forces, as was the case in the following example. To endorse design for a replacement superheater for PFR, a full scale water sector model was constructed (Fig 5). Vibration was monitored by pulling bi-axial accelerometers through tubes, giving results as shown on Figure 6, important features of tube motions being as follows.

Tube vibration was random, with no sign of resonance at any flow or position (see Fig 6(a)). Whilst the minimum computed frequency with good support at grids was ≈90Hz, in virtually every case response occurred at lower frequencies (Fig 6(b)). In general grids limited the degree of tube movement (Fig 6(c)) but there was usually significant lower-frequency motion within grids. Highest amplitudes were recorded at positions where grids seemed to be ineffective or on some bends (Fig 6(c) and (d)). It was also found that average vibration amplitude for tubes was directly proportional to tube-grid clearance.

The indicated vibration amplitudes for this case (less than 0.2mm peak-to-peak) are very small, the model indicating very satisfactory reactor behaviour.

It is clear that, unless tubes are pre-loaded onto grids, 'loose-tube' motions will be dominant within heat exchangers. Attempts are being made (Ref 4) to gain a better understanding of excitation mechanisms, tube-grid motions and wear for loose-tube vibration. This will ultimately involve characterising tube dynamics for realistic experimental geometries, relating behaviour to theoretical models and performing wear tests under conditions designed to simulate the observed behaviour.

## 6. CONCLUSIONS

In the UK flow-induced vibration of LMFBR components is assessed using a combination of theoretical and experimental approaches. Basic development work is carried out to allow more reliance in the future on theoretical methods, which requires better understanding of mechanisms involved where flow patterns are complex. In particular loose-tube vibration in heat exchangers, and the above-core region are being considered for experimental investigations of a generic nature.

## 7. REFERENCES

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3. JONES C H, RIDEALGH F and BRAMAH P J. The evolution of endurance tests for development of fast reactor core sub- assemblies. Ibid. Paper 6.1.

4. GOYDER H G D. Vibration and wear of loosely support heat exchanger tubes. Paper for IAEA IWGFR Specialists Meeting 'Flow Induced Vibrations in Fast Breeder Reactors' Paris, October 1986.

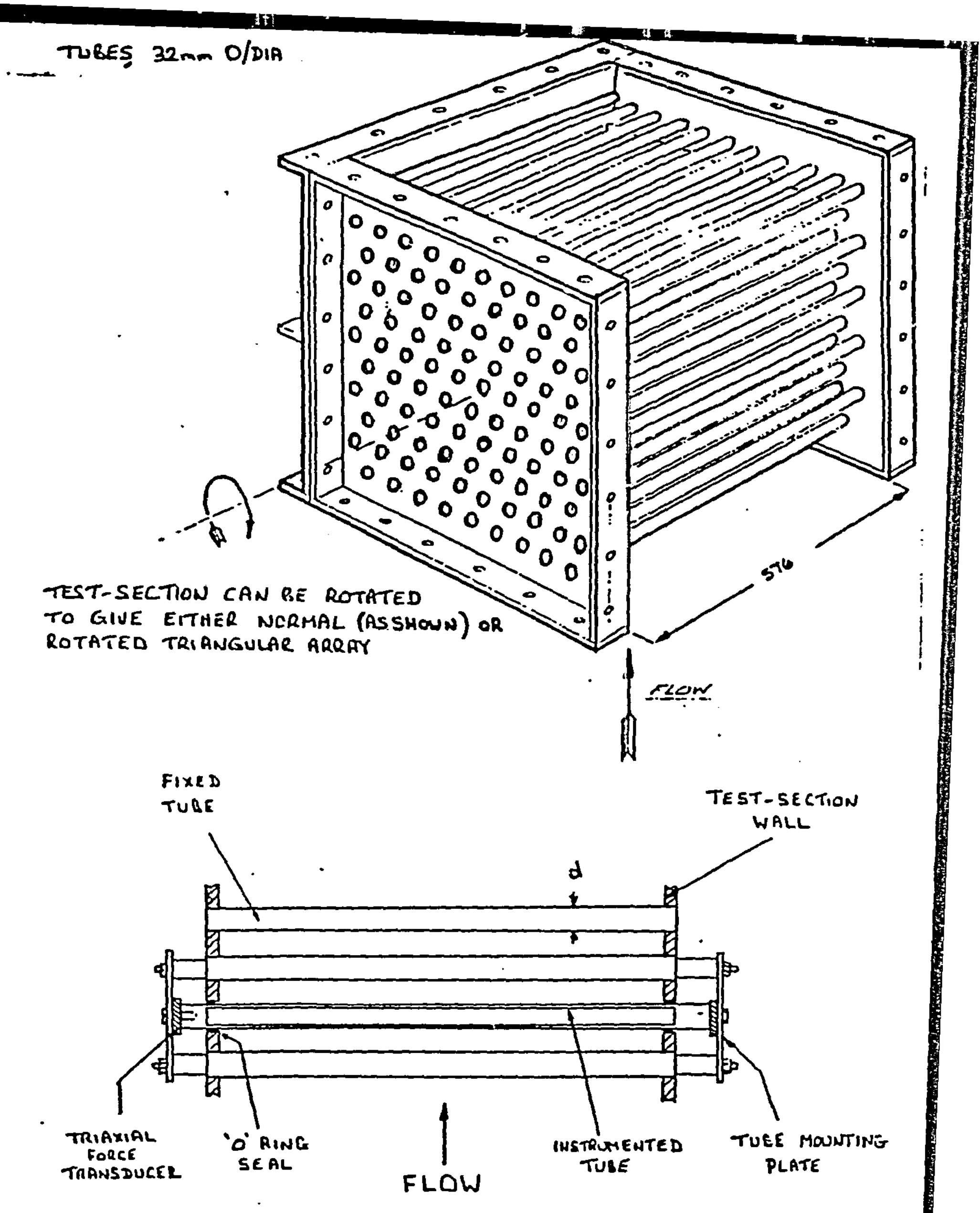
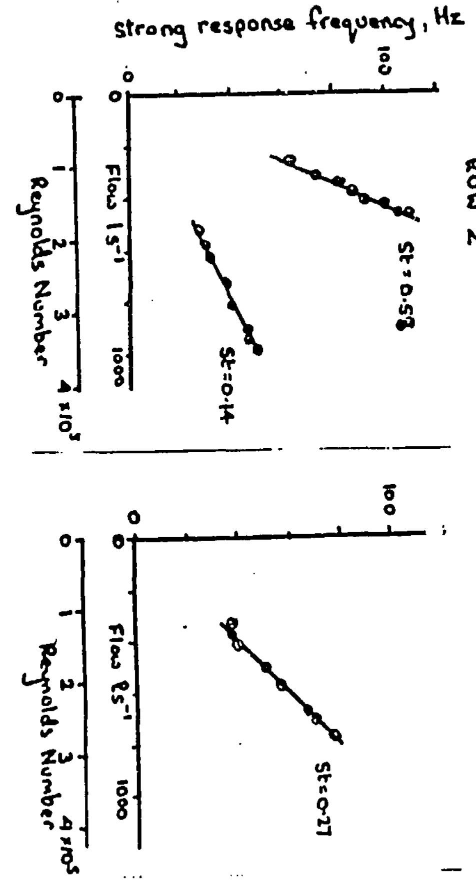
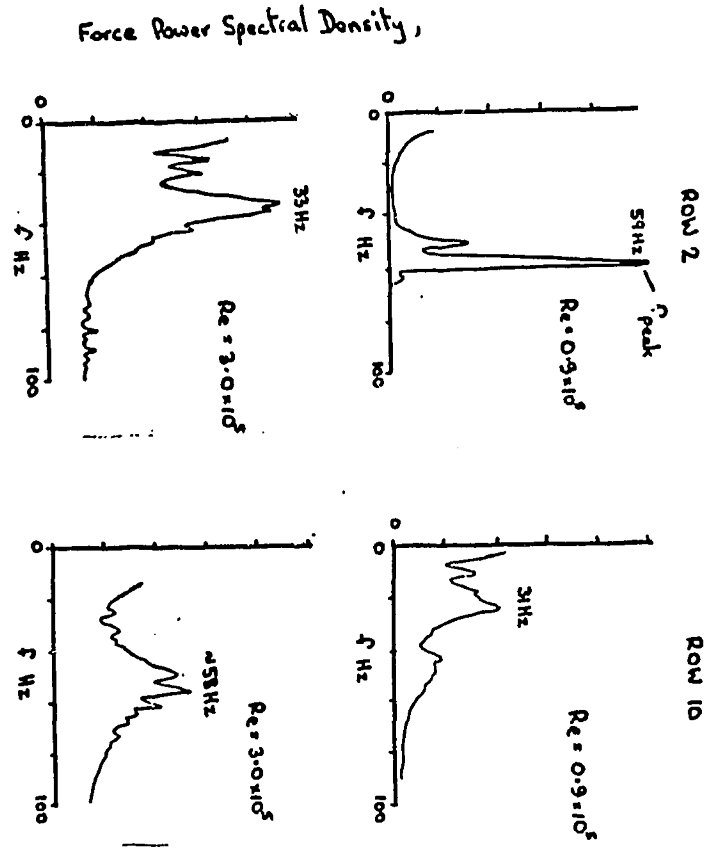


FIG 1 TEST-SECTION FOR MEASUREMENT OF TUBE CROSS-FLOW FORCES

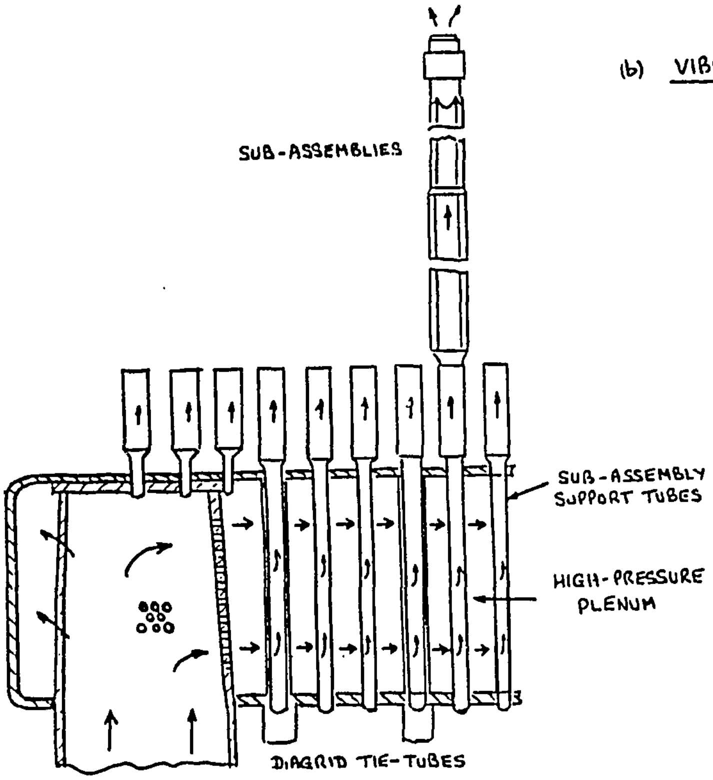


(a) VARIATION OF PEAK RESPONSE FREQUENCY WITH FLOW



(b) TUBE RESPONSE FREQUENCY SPECTRA

FIG 2 VARIATION OF TUBE RESPONSE FREQUENCY AND TYPICAL SPECTRA: PITCH-TO-DIAMETER RATIO 1·3: NORMAL TRIANGLE



(a) SCHEMATIC DIAGRAM OF CDFR HIGH-PRESSURE PLENUM

(b) VIBRATION TEST-RIG

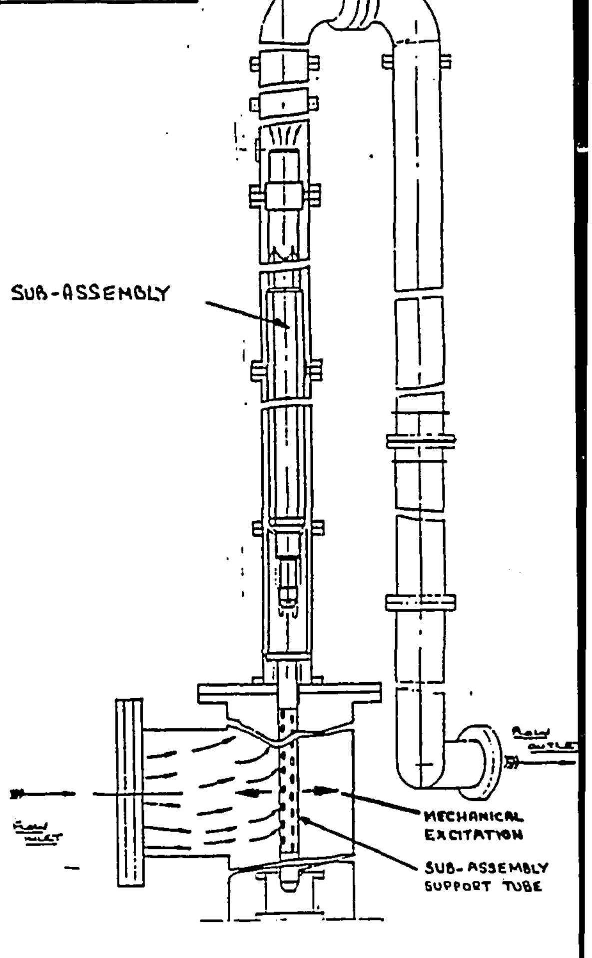
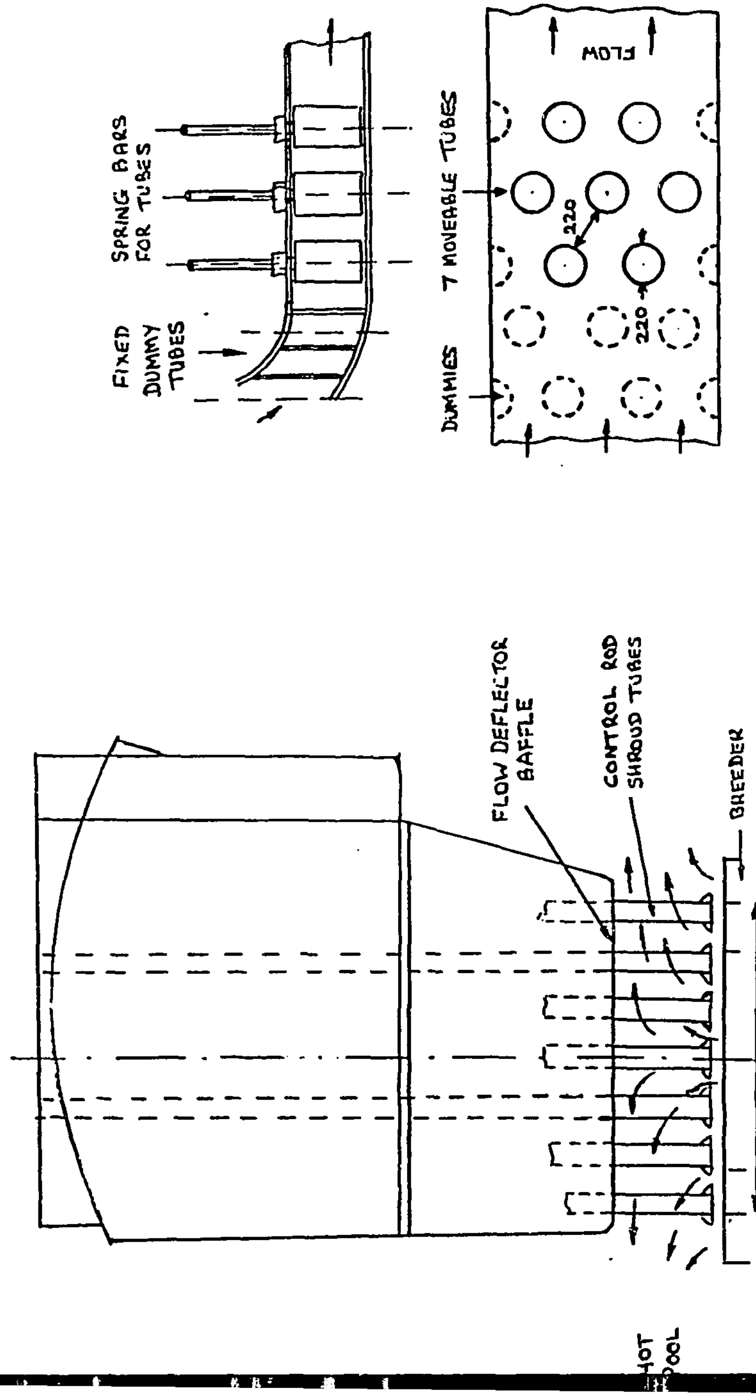


FIG 3 CROSS-FLOW INDUCED VIBRATION IN CDFR HIGH-PRESSURE PLENUM



(b) MODEL TO INVESTIGATE CROSS-FLOW AT HIGH Re OVER CONTROL ROD SHROUD TUBES

(a) SCHEMATIC DIAGRAM OF CDFR ABOVE-CORE STRUTURE

FIG 4 CDFR ABOVE-CORE STRUCTURE

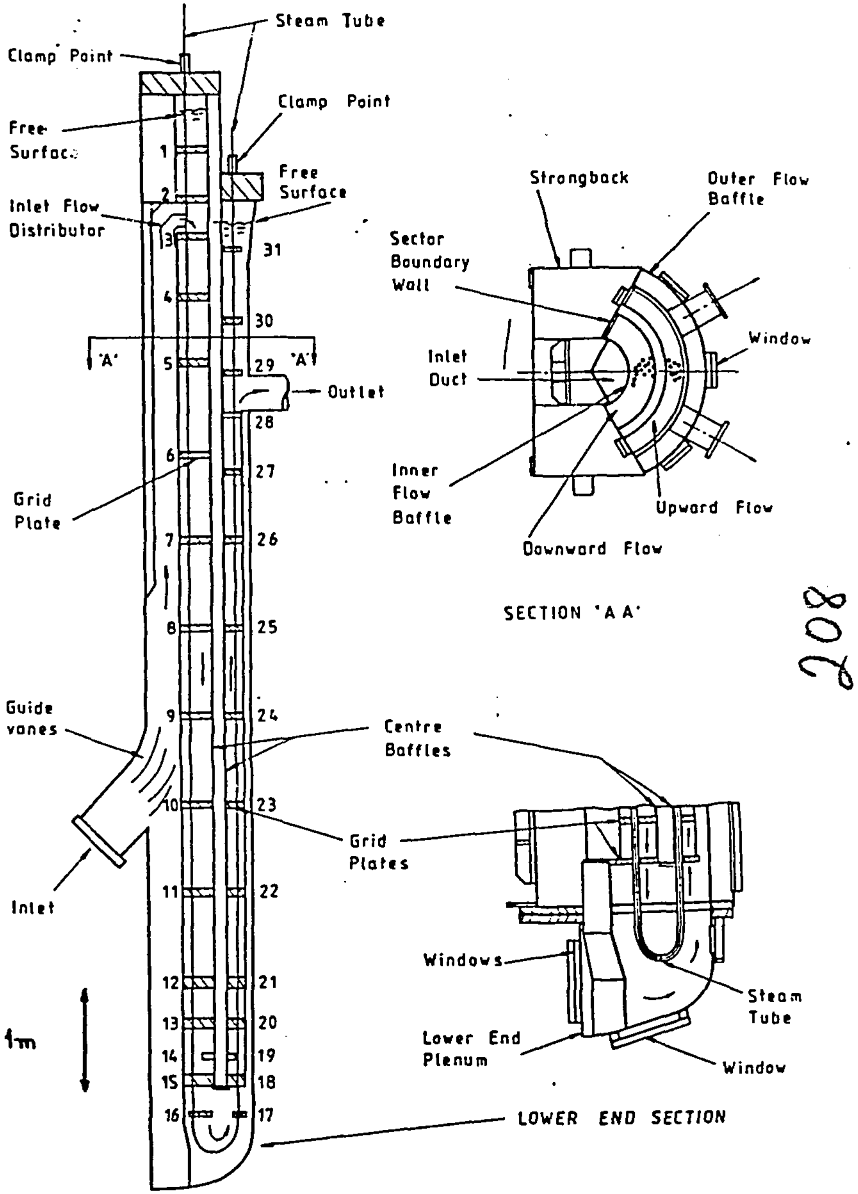
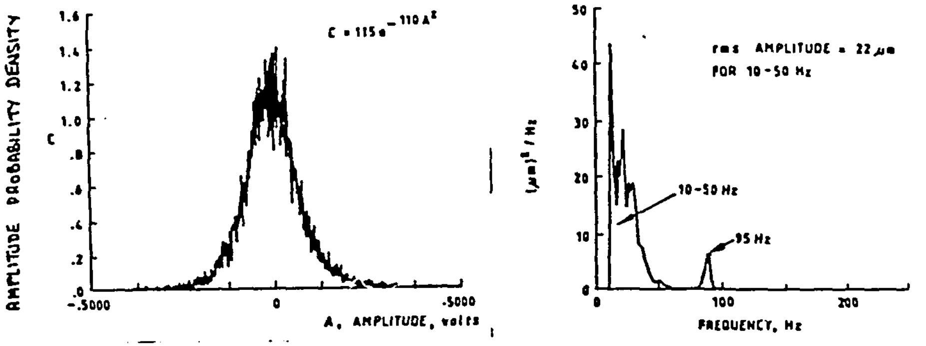
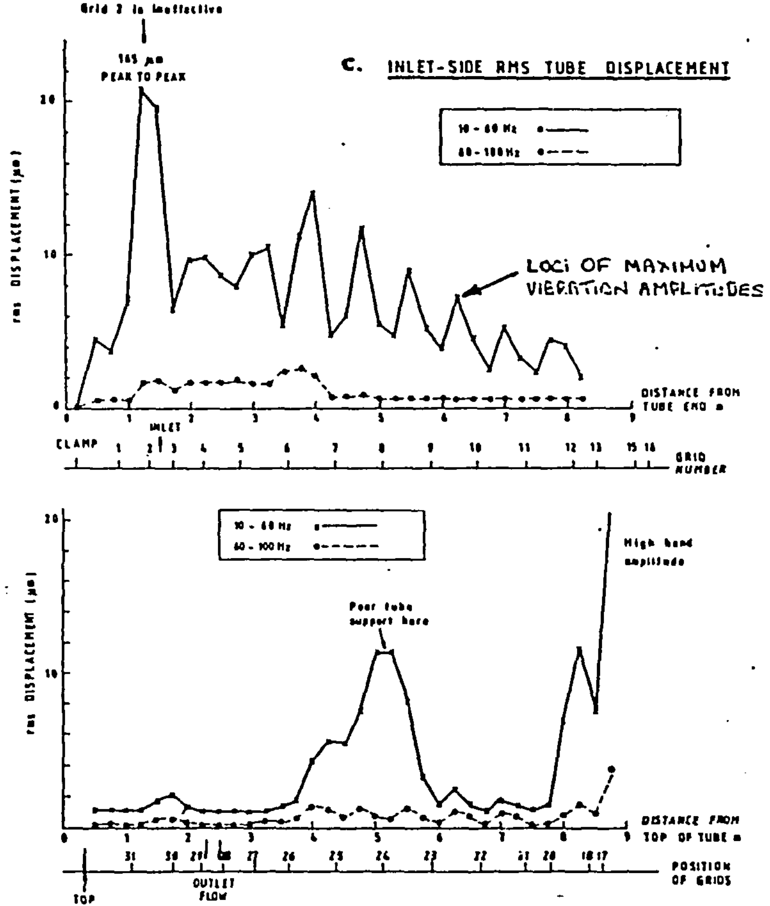


FIG 5 FULL SCALE PFR SUPERHEATER 120° SECTOR WATER MODEL



a. Amplitude Probability Density Distribution

b. Amplitude Power Spectral Density



c. INLET-SIDE RMS TUBE DISPLACEMENT

d. OUTLET-SIDE RMS TUBE DISPLACEMENT

FIG 6 TYPICAL VIBRATION CHARACTERISTICS FOR TUBES IN 120° SECTOR WATER MODEL: TUBE-GRID CLEARANCE 0.5 mm: FLOW = 265 l/s