RESPONSE OF FIBROUS PRESTRESSED CONCRETE PRESSURE VESSEL INSULATION SYSTEMS TO TYPICAL NOISE SPECTRA

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SUMMARY

The object of the paper is to show how the acoustic and flow induced pressure fluctuation spectra have been predicted for the environment within the Advanced Gas-cooled Reactors being built by The Nuclear Power Group, and how these spectra have been used to estimate the vibration responses of vessel thermal insulation containment structures.

Within a reactor, acoustic pressure fluctuations affect all areas and are determined largely by the noise emissions from the gas circulators. Measurements made on early gas-cooled reactors, on model and production circulators, and in the reactors during construction and commissioning have been used to estimate the acoustic spectra under all operating conditions. Flow induced pressure fluctuations are only important in specific areas and the spectra have been estimated from the results of flow tests at atmospheric and at high gas pressure on both fractional and full scale models of the relevant parts of the reactor.

The thermal insulation design for the TNPG AGRs uses a ceramic fibre blanket insulant. A criterion has been derived for the allowable vibration of structures in contact with this blanket and the response of insulation assemblies has been determined either in high intensity noise chambers or under high turbulence flow conditions to ensure that the criterion has been met. Wherever possible, tests have been carried out under conditions as near as possible to those predicted for the reactor and analytical models have been used to corroborate the test results.

1. Introduction

During the past sixteen years, The Nuclear Power Group Ltd. has designed gas cooled reactors for seven nuclear power stations. Five Magnox stations are in satisfactory operation, while at the other two stations, Hinkley Point B and Hunterston B, a total of four Advanced Gas-cooled Reactors are nearing completion. With the growth in the power of gas cooled reactors and the introduction of prestressed concrete reactor vessels have come the problems associated with high intensity noise and with the thermal insulation of the reactor vessel.

A brief outline of the TNPG Advanced Gas-cooled Reactor system is given in section 2, and of the thermal insulation of the reactor vessel in section 3. Section 4 deals with the method of estimating the noise spectra for all parts of the reactor. Since the TNPG AGR insulation system consists essentially of a ceramic fibre insulating blanket, it has been necessary to derive an acceptable vibration criterion which will ensure that the blanket performance remains adequate throughout the reactor life. Work to substantiate this criterion is described in section 5. Section 6 refers to the acoustic testing and analysis of insulation designs. In certain areas, flow induced pressure fluctuations cause further vibration problems and the modelling techniques used in their study are referred to in section 7. Wherever possible tests have been carried out under conditions as near as possible to those predicted for the reactor environment, and simple analytical models have been used to corroborate test results.

2. The Advanced Gas-cooled Reactor (AGR)

In the Advanced Gas cooled Reactors being built by TNPG, the reactor vessel consists of a vertical prestressed concrete cylinder with a steel liner (Fig 1). The temperatures of the concrete and the liner are controlled by a thermal insulation arrangement on the gas side of the liner, and a series of cooling water pipes on the concrete side.

Inside the vessel, a graphite core, supported on a diagrid grillage contains the fuel elements and control devices. It is surrounded by a nuclear radiation shield and covered by a gas baffle designed to provide a re-entrant gas flow to cool the core. The boiler units are located in an annular space between the baffle and the vessel.

Gas is drawn from the bottom of the boilers by the gas circulators, and discharged into an annular duct. From there part of the flow passes up the inside of the baffle to cool the shield wall and core, before rejoining the remainder flowing under the diagrid and into the fuel elements. Fuel guide tubes, located at the top of each fuel channel, duct the hot outlet gas through the space below the gas baffle before discharging it into the space above, from where it flows again into the top of the boiler units.

The AGR is designed for on-load refuelling. When a fuel element is removed from its channel, an intense jet of relatively cool gas is discharged from the guide tube due to the marked reduction in the channel flow resistance. The effect of this "empty channel discharge" jet must be considered in the design of components subjected to its influence. There is a similar effect with the outlet flow from the gas circulator outlet diffusers.

3. Thermal insulation Design

The insulation for AGRs built by TNPG is based on the use of a ceramic fibre insulating blanket. This is held in place by a steel "primary cover plate" clamped to a single central stud which is welded to the liner (Fig 2). The hot side of the blanket is partially sealed by an arrangement of overlapping "hot face foils", which increase the resistance to gas flow and minimise the risk of loss of dust from the insulant. Between the foils and the primary cover plate is a system of "secondary cover plates". These do not overlap but are off-set relative to the primary cover plates in such a way that the foils are covered and protected. The axial position of the cover plate on the stud is set by a backing collar on to which the whole hot face assembly is clamped by the main nut (Fig 3). Loops are welded to each edge of adjacent primary cover plates to provide a secondary retention system in the event of a stud failing.

Insulation arrangements are designed to meet a range of different performance requirements in the various zones of the reactor. These requirements include allowable component temperatures, temperature gradients, thermal shock, thermal cycling performance, heat flux, surface pressure gradients, vessel depressurisation rate, as well as vibration caused by acoustic and turbulent pressure fluctuations. Because of this variety of design requirements, a number of different insulation arrangements have been developed for different areas of the vessel. Each of these arrangements has been development tested at or near the noise levels predicted for the appropriate area of the reactor.

4. Estimation of Reactor Acoustic Spectra

The acoustic spectra in the AGR are determined largely by the noise emissions from the gas circulators. In the constant speed circulators being used in the AGRs, the flow is controlled by means of variable angle inlet guide vanes. Initial estimates of the overall reactor noise levels were based on previous experience with variable speed axial flow machines used in the magnox reactors. Since then a number of tests have been carried out, the results of which improved the original estimates (Fig 4). The variable IGV system was thought to produce a spectrum with high noise levels at low frequency when the vanes were partly closed. This appeared to be confirmed by a one-third speed test (Fig 5 curve A) but as a result of a full speed test and a calibration of the reactor cavities using a loudspeaker with predetermined radiation characteristics, a revised estimate of the worst reactor spectrum was derived (Fig 5 curve B). In these full speed tests, the effect of IGV angle on the sound power generated was also determined (Fig 6). Later the effect of gas pressure on the sound power generation was confirmed in a test with a production circulator running at full load in a pressurised facility. It showed that for a constant Mach Number,

$$\text{Sound Power} \quad \alpha \quad (\text{Density})^{1.0}$$

$$\text{Sound Pressure} \quad \alpha \quad (\text{Density})^{1.0}$$

Because of the compactness of this test arrangement no new spectral information was obtained.

The circulators have now been installed in the reactors and atmospheric pressure measurements taken with a circulator in operation with the IGVs closed. These results in conjunction with those in Fig 6 yield a further estimate shown in Fig 5 Curve C. Mach number effects are eliminated in the extrapolation since the value is similar in atmospheric air to that in carbon dioxide at reactor conditions. The low frequency content is lower than originally anticipated, but since the most representative tests gave this result, they are treated with most confidence. Final confirmation of the spectra will be obtained in reactor commissioning tests in air, in nitrogen, and in carbon dioxide.

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5. Insulation Blanket Damage Tests

Early in the development programme it was found that unprotected ceramic fibre blanket is rapidly detroyed by high intensity noise at atmospheric pressure. However when tested at similar sound pressure levels in a standing wave tube filled with high pressure gas, damage only occurred at positions of high sound particle velocity. In this test, the damage was much less severe because of the lower sound particle velocity in the high pressure gas. In the reactor, the blanket is always contained within metallic structures, so work was done to determine the effect of excessive vibration of these structures on the blanket and to derive an allowable vibration criterion.

A number of types of damage were noted: unblown beads of the ceramic material were caused to vibrate and bored holes in the blanket; surface layers of fibres fractured and compacted together; the size of indentations, formed in the blanket surface during manufacture, increased when local fibres fractured; large unblown inclusions vibrated within the blanket and damaged surrounding fibres.

From the many and varied tests carried out for periods of up to 10,000 hours at a range of temperature, pressure, geometry and vibration amplitude conditions a damage threshold was derived (Fig 7). All inspections 'below the line' had no visible sign of damage at any time during the test. The data is used, with appropriate safety factors, to set allowable vibration criteria for all components in contact with the insulating blanket.

6. Response of insulation to noise

The acoustic performance of an insulation design is normally assessed by carrying out a structural response test on a representative sample of the structure in a high intensity noise environment. Stress and vibration amplitudes on all the components are determined as a function of frequency at an applied noise spectrum, which is sampled by several microphones in the vicinity of the structure under test. In general, the mean noise spectrum is controlled to be as near as possible to that predicted for the arrangement in the reactor. Since it is known that the properties of the gas surrounding the structure can have a considerable influence on the magnitude of the vibration caused by a given spectrum, most of the tests have been carried out in a pressurised high intensity environment. The TNPG facility used for these tests consists of a 2.4 metre diameter pressure vessel, 4 metres long that can operate at gas pressures of up to about 40 bars.

In the development of the insulation designs it was found (Jones, [1]) that with insufficient blanket pressure to force the secondary cover plate on to the primary, the vibration of the secondary was largely controlled by the acoustic stiffness of the space between the secondary and the liner. The one dimensional equation of motion of a fairly limp plate with surface density m and total mechanical stiffness k, backed by a cavity of depth d and surrounded by gas of density ρ_o and sonic velocity c is, for an incident acoustic pressure wave of amplitude p, neglecting damping terms:

$$m \frac{\partial^2 \xi}{\partial t^2} + \rho_o c \frac{\partial \xi}{\partial t} + \left\{ k + \rho_o c \omega \cot \frac{\omega d}{c} \right\} \xi = 2pe^{i\omega t} \qquad (1)$$

The solution of this equation is

$$\xi = \frac{2p}{k - \omega^2 m + \rho_o c\omega \cot \frac{\omega d}{c} + i \rho_o c \omega}$$

The measured responses for a number of different insulation arrangements, normalised against a single spectrum, have been compared with theory and reasonable correlation obtained both at atmospheric and high gas pressure (e.g. Fig 8).

In general it has been found that the stresses induced in the primary cover plates by acoustic or turbulence spectra are too low to cause concern, so no detailed investigations have been necessary.

The "umbrella" mode, in which all parts of the plate vibrate in phase, is of interest because at the resonant frequency, the insulation structure acts as an effective sound absorber.

$$\omega = 3.75 \frac{s}{r^2} \sqrt{\frac{E}{12(1-\nu^2)\rho}} \qquad (2)$$

The 'cover plate rocking' mode is important as it is the major contributor to the stud bending stresses. If the cover plate is considered as rigid body vibrating at the end of a flexible stud, the resonant frequency is given by

$$\omega^2 = \frac{2(\alpha+1)}{\beta} \left\{1 - \sqrt{1 - \frac{\alpha}{(1+\alpha)^2}}\right\} \qquad (3)$$

where $\alpha = \dfrac{a^2}{4l^2}$

and $\beta = \dfrac{b\,\rho s\,a^3\,l}{12EI}$

With a rectangular cover plate, a band of frequencies may be excited because of the variation in cover plate inertia with the direction of stud bending.

Cylindrical insulation arrangements are used in the various vessel penetrations, such as those carrying the steam pipes. It is of interest to note that because of the presence of standing waves in the annulus formed between the penetration liner and the steam pipe, the local sound pressure level may be as much as 10dB higher than the level just outside the penetration. Such increments must obviously be taken into account in calculating operating stresses.

7. Flow induced pressure fluctuations and vibrations

There are three situations where flow induced pressure fluctuations have been considered in relation to the reactor vessel thermal insulation. These are in order of importance, the gas discharge from an empty fuel channel during on-load refuelling, the gas discharge from the circulator outlets, and the gas flow over secondary retention loops. In each case the power spectral density $E(\omega)$ of the fluctuating pressure was considered in the light of a dimensional analysis of the main flow parameters - density ρ_o, a velocity U, a length h, and a frequency ω. The relationship derived,

$$\frac{E(\omega)\;U}{q^2\;h} = F\left(\frac{\omega h}{U}\right) \qquad (4)$$

was used as the basis for comparison of test data and for scaling to reactor conditions.

The various tests in which pressure fluctuations and stresses were measured may now be considered in relation to eq (4).

7.1 Empty channel discharge

Early tests carried out on a one-tenth scale model of the reactor gas circuit indicated that, where the empty channel discharge jet impacted on the model roof, the pressure fluctuations were random in frequency and amplitude. The normalised frequency spectrum of the fluctuations is shown in Fig 9. The root mean square level of the pressure fluctuations was found to be 176 dB re 2×10^{-5} N/m^2 when corrected to reactor conditions using eq.(4). This level was sufficiently high to require further investigation.

Pressure fluctuation measurements were then taken on the roof of a full scale mock-up of the fuel channel which, unlike the one-tenth scale model, had the correct outlet geomtry and roof arrangement. The rig operated at atmospheric pressure and correct volume flow rates could be achieved. The overall pressure fluctuation levels were found to be 170 dB re 2×10^{-5} N/m^2 when corrected to reactor conditions (Fig 10). It can be seen that the normalised frequency spectrum of the fluctuations was similar to that obtained from the one-tenth scale model. This reasonable agreement indicated that the correct scaling parameters were being used. The differences noted are thought to have been due to the over-simplification of the channel outlet geometry in the smaller model.

In the reactor, the Reynolds number is about thirty times higher than that which can be achieved in the full scale air rig. In order to check the magnitude of the pressure fluctuations at realistic conditions, measurements were made on the roof of a high pressure rig containing a full size fuel channel with the correct outlet geometry, in which the correct reactor density and mass flow rates could be achieved. Fig 10 shows that the measured fluctuation spectrum was virtually identical to the extrapolated full scale air rig results. The effect of the flow dynamic head on the overall pressure fluctuation level is shown in Fig 11.

7.2 Circulator Outlet Gas Duct

The turbulent pressure fluctuations on the wall of the circulator outlet gas duct were investigated using a one-fifth scale model representing a section of the duct with geometrically correct circulator outlet diffusers. When the results were extrapolated to reactor conditions, a maximum level of 159 dB (re 2×10^{-5} N/m^2) was indicated at the position opposite the circulator outlet, with a reduction of about 10 dB at a point midway between adjacent circulators. Fig 12 shows that most of the turbulence energy is at low frequency.

7.3 Flow over secondary retention loops

The possibility was considered that pressure fluctuations caused by the gas flow over secondary retention loops on the insulation cover plates may have significantly augmented the pressure fluctuations due to noise from the gas circulators. A literature survey at the outset of the project failed to reveal any data relevant to the reactor geometry, so a dynamic modelling study was set up. While the programme was under way Fricke [2] was published which gave the results of spectral measurements of pressure fluctuations downstream of a single 'fence' mounted on the wall of a wind tunnel. That reference also quoted previous work by Fricke and Stevenson [3]. When their results are compared with those from our own slightly different geometry, a relatively small difference in non-dimensional spectrum is noted (Fig 13). Under normal operating conditions, loop induced pressure fluctuations are only comparable in level to acoustic pressure fluctuations at low frequencies, typically 20 Hz and below.

7.4 Flow induced vibration

Williams [4] showed that the stresses induced by turbulent pressure fluctuations due to flow are related to the flow dynamic head. Drake's presentation [5] of his data indicated a relationship approximating to

$$\sigma = Aq^{3/2} \tag{5}$$

During the investigation of empty channel discharge effects, stresses were measured on an insulation sample subjected in turn to the atmospheric and high pressure gas flows. The overall dynamic strain induced in the main studs was proportional to the dynamic head of the flow, as was the fluctuating pressure level. No unique dependence is expected for all situations, since the index is dependent upon the shape of the pressure fluctuation spectrum and the frequencies of structural resonances relative to the peak of the pressure spectrum.

At the circulator outlet, the turbulent pressure energy was found to be mainly at low frequency. Since the structural components of the insulation in that area are extremely robust and have no low frequency resonances, the bending stresses induced in the studs were due to sub-resonant forcing of the 'cover plate rocking' mode. For a rectangular plate, a x b, fitted to a stud, diameter d, and subjected to turbulent pressure fluctuations of magnitude p and correlation length L (<< a,b), the maximum stud stress is given by

$$\sigma = \frac{D.paL}{I} \sqrt{\frac{ab}{12}} \tag{6}$$

The response depends on the magnitude of the pressure fluctuations and the correlation length. The stresses expected under reactor conditions may therefore be estimated by scaling measurements on a full scale structure tested at atmospheric pressure in realistic flow conditions.

When insulation with relatively flexible secondary cover plates is exposed to turbulence the responses are again stiffness controlled at low frequencies. Typical spectra of secondary cover plate rms displacements, normalised to a flat one-third octave band spectrum, are shown in Fig 14. The response is essentially stiffness controlled an octave below the first resonance. The measured stresses were found to give a similar relationship. This normalised low frequency response can be related to measurements of the local static stiffness of the component using a probe designed to indicate the local deflection under a standard applied load. These static stiffness probes are used during site erection to ensure that the secondary cover plate stiffness is adequate in critical areas.

8. Conclusions

Methods have been discussed for estimating reactor acoustic and flow induced pressure fluctuation spectra and the resulting vibration of pressure vessel insulation systems. It has been shown that small models of the correct geometry give a good indication of fluctuating pressure spectra to be expected under reactor conditions. The results of tests to derive a criterion for the allowable vibration of components in contact with the ceramic blanket insulant have been indicated. The response of insulation structures has a varying dependence on gas properties, the most sensitive component being an unsupported secondary cover plate. Its response is influenced considerably by the properties of the space between the plate and the vessel liner. The response of structures to low frequency turbulence is generally stiffness controlled, and vibration is therefore dependent only upon the magnitude of the pressure fluctuations and their effective correlation length. Static stiffness probes are used during site erection to ensure the secondary cover plate stiffness is adequate in critical areas.

9. Acknowledgements

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10. References

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[2] FRICKE, F.R., 'Pressure Fluctuations in Separated Flows' J. Sound Vib 17 (1) July 1971.

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11. Nomenclature

a	major surface dimension of plate
b	minor surface dimension of plate
c	sonic velocity
d	insulation thickness
e	exponential
h	characteristic dimension
k	effective stiffness of secondary cover plate (per unit area)
l	length of stud
m	mass of secondary cover plate (per unit area)
p	rms pressure
q	flow dynamic head, $\frac{1}{2}\rho U^2$
r	effective radius of cover plate
w	cover plate thickness
t	time
A	a constant
D	diameter of stud
E	Young's Modulus
$E(\omega)$	pressure power spectral density
F	a function
I	sectional Modulus of Stud
L	correlation length
U	flow velocity
α	a constant defined in eq.(3)
β	a constant defined in eq.(3)
ξ	secondary cover plate rms displacement
ρ	material density
ρ_0	fluid density
ω	circular frequency
ν	Poissons ratio
σ	stress

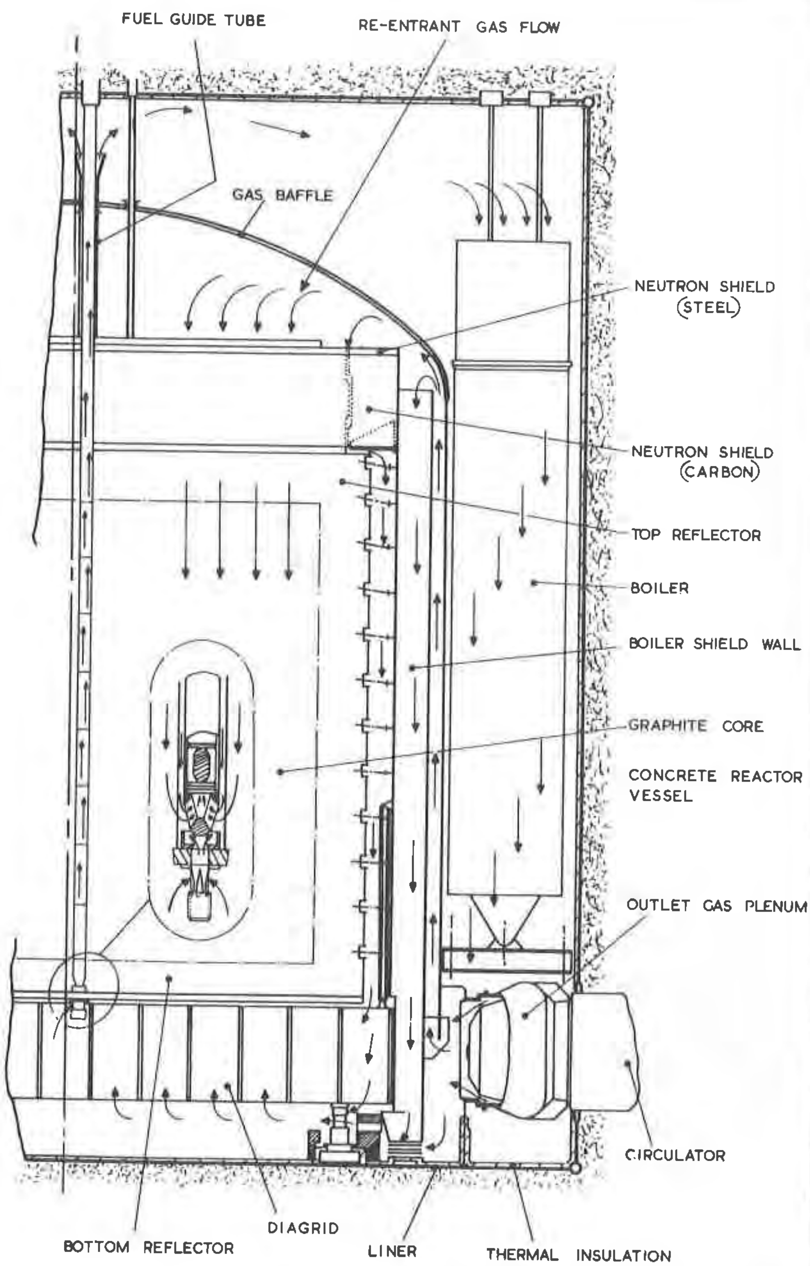

FIG. 1: ADVANCED GAS COOLED REACTOR - LAYOUT & GAS FLOWS

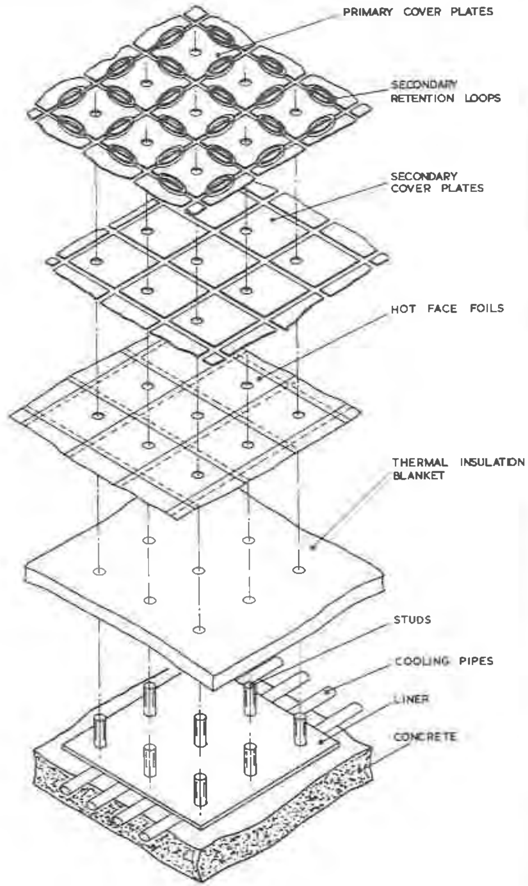

FIG. 2

ASSEMBLY OF A.G.R. PRESSURE VESSEL THERMAL INSULATION STRUCTURE

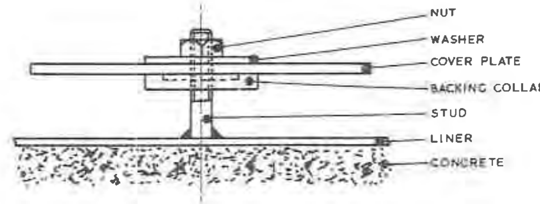

FIG. 3: TYPICAL PRIMARY COVER PLATE CLAMPING DETAIL

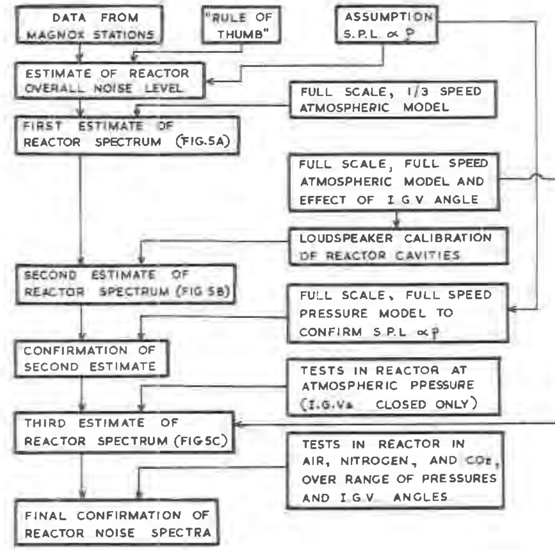

FIG.4: TESTS TO DETERMINE REACTOR NOISE SPECTRA

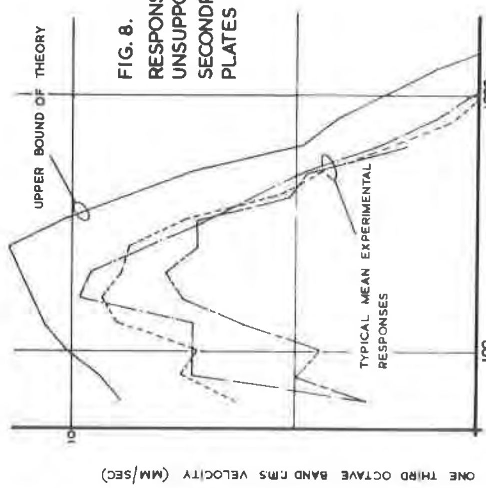

FIG. 8. RESPONSE OF UNSUPPORTED SECONDRY COVER PLATES TO NOISE

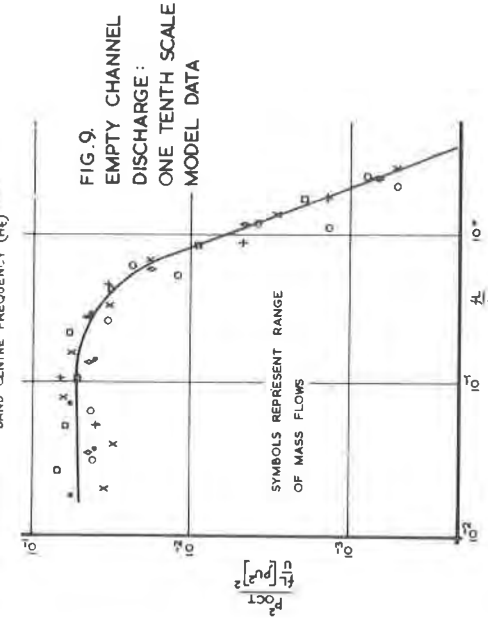

FIG. 9. EMPTY CHANNEL DISCHARGE : ONE TENTH SCALE MODEL DATA

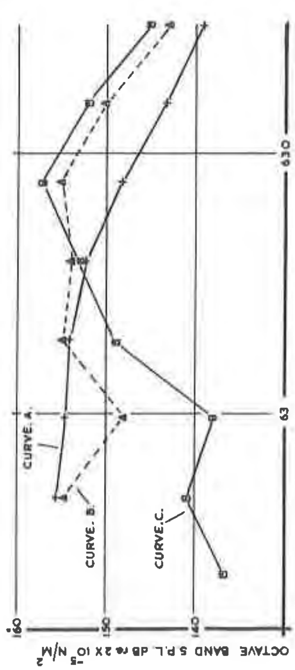

FIG.5: ESTIMATES OF MAXIMUM REACTOR NOISE SPECTRA

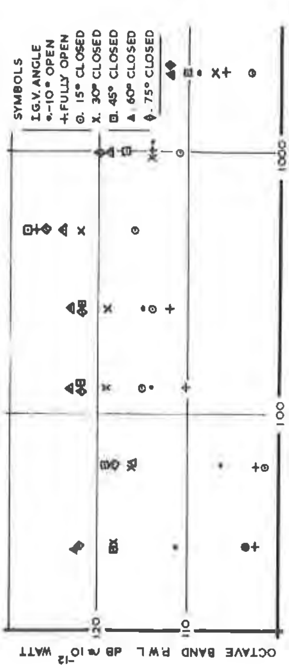

FIG. 6: EFFECT OF I.G.V. ANGLE ON CIRCULATOR NOISE SPECTRA

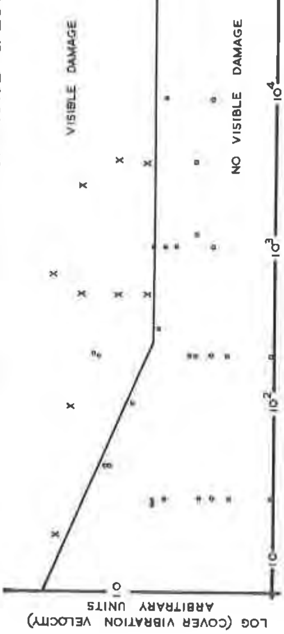

FIG.7: EFFECT OF COVER PLATE VIBRATION ON INSULATION BLANKET

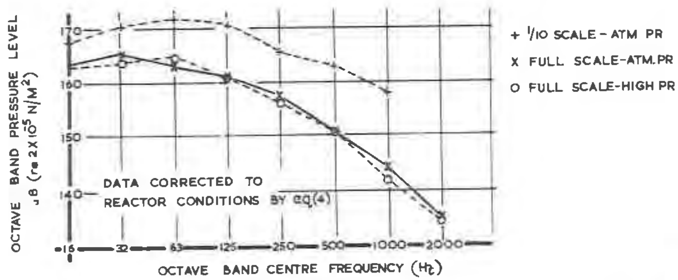

FIG.10: EMPTY CHANNEL DISCHARGE-COMPARISON OF RESULTS

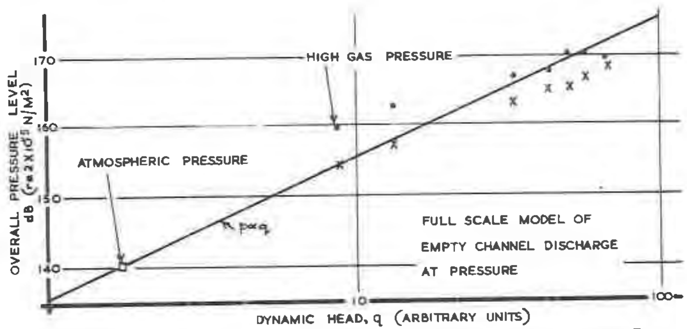

FIG.11: EFFECT OF DYNAMIC HEAD ON TURBULENCE LEVEL

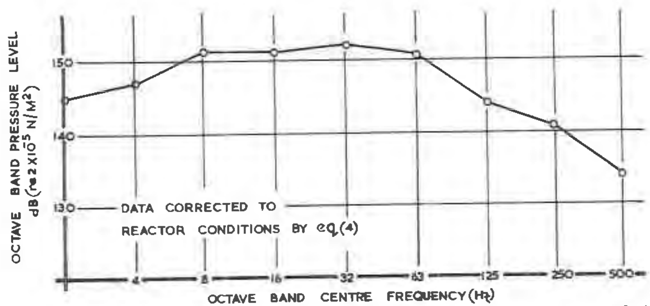

FIG.12: CIRCULATOR OUTLET DISCHARGE: 1/5 th SCALE MODEL RESULTS

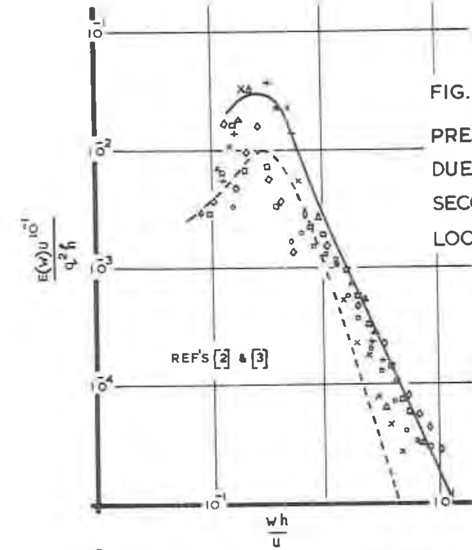

FIG. 13.

PRESSURE FLUCTUATIONS DUE TO GAS FLOW OVER SECONDRY RETENTION LOOPS

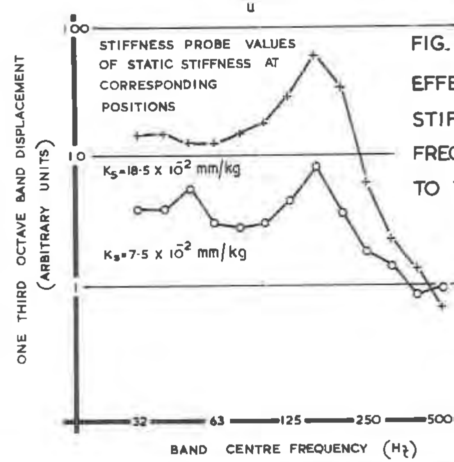

FIG.14.

EFFECT OF LOCAL STATIC STIFFNESS ON LOW FREQUENCY RESPONSE TO TURBULENCE