GAS CIRCULATOR NOISE GENERATION CHARACTERISTICS. A COMPARISON OF THE EFFECTS OF HELIUM, CARBON DIOXIDE AND NITROGEN

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SUMMARY

Failures have occurred in some of the U.K. power stations due to fatigue of reactor gas circuit components induced by the noise generated by the coolant gas circulators. It is important that the dynamic stresses in these structures are appreciated at an early stage in the design and construction of a reactor. The sound pressures and frequency spectra of the noise generated by the circulators are important parameters affecting these dynamic stresses. Very often the design engineer has to rely on measurements taken from model circulator, or commissioning tests carried out under conditions differing from the normal reactor operating conditions in order to estimate the sound pressure levels at appropriate operating conditions. To do this, he must have a firm understanding of the basic characteristics responsible for the noise generation relating to his particular operating conditions.

Data have been published on the noise characteristics in carbon dioxide and nitrogen, but not using helium as the acoustic medium. The significance of helium is that the velocity of sound in the medium is much higher than in either nitrogen or CO_2, and hence the operational Mach numbers of circulators in helium reactors may be much lower than those in present reactors. It is conceivable that the dominant mechanism responsible for noise generation may be different.

In this paper, the basic characteristics of noise generation are discussed. The effectiveness of these characteristics depends on the circulator rotor tip Mach number, and it is important to know how these characteristics vary over the Mach number ranges pertinent to gas cooled reactors. Data presented are selected from a large number of measurements taken of the sound pressures generated by a variable speed centrifugal circulator operating in helium, nitrogen and CO_2 over a wide range of densities, temperatures and speeds. A wide range of Mach numbers has thus been encompassed with these gases from which their characteristics of noise generation are compared.

Mention is also made of the influence of different gases on the propagation of modes through the outlet duct of a centrifugal circulator. Theories and measurements presented to date have only considered axial fan circulators, and relatively simple outlet ducts. The theory and measurements referred to in this paper consider the propagation of modes through a radially symmetric outlet annulus. This highlights one of the difficulties that can be encountered when commissioning in a gas different from that used during normal operating conditions.

NOTATION

W	Sound Power*
P	Sound Pressure*
A	Characteristic flow area of circulator†
U	Characteristic flow velocity of circulator
ρ	Density of acoustic medium**
c	Velocity of sound in acoustic medium**
f	Frequency
k	Wave number $= \frac{2\pi}{\lambda}$
λ	Wavelength
Ω	Rotor speed (radians/sec)
V	Rotor tip speed
N	Circulator r.p.m.
M	Mach number**
B	Number of rotor blades
S	Number of stator blades
r	Radius††
n	Order number of mode $n = 1$ is blade passing frequency etc.
m	Number of lobes of rotating pressure
ℓ	integer . . . $-1, 0, 1,$ . . .

* Subscripts D, M, Q refer to monopole, dipole and quadrupole respectively.

† Superscript ' refers to cross sectional area of outlet duct.

** Subscript s refers to sweep velocity of mode.

†† Subscript o refers to duct, T to rotor tip.

1. INTRODUCTION

It is important for the design engineer to know the sound pressure levels generated by the coolant gas circulators within the reactor gas circuit. Very often his estimates of these levels have to be based on measurements taken from model circulator or commissioning tests carried out under conditions different from the normal reactor operating conditions. The earliest and until recently the only available information resulted from attempts by Piestrup and Wesler [1] and Beranek, Kamperman and Allen [2], to relate the sound power output of the circulator to its nameplate horsepower and the pressure rise across the circulator. Only very small axial and centrifugal fans (< 40 HP) suitable for heating and ventilating systems were used in these measurements. More recently, investigators have used dimensional analyses to determine non-dimensional relationships by which to express the power radiated by a fan. Notable among many such investigations are those performed by Maling [3] and Chanaud [4]. All of these investigations were primarily concerned with the overall power radiated, and in general with broad-hand noise. Unfortunately these empirical formulae are not accurate enough for reliable estimates of the in-service sound power and sound pressure levels required.

In recent years, the need to reduce the noise generated by modern jet engines has produced a considerable amount of useful information on the mechanisms responsible for noise generation. It has also been established that each of these mechanisms gives rise to radiation characteristic of a particular source type namely either monopole, dipole or quadrupole. Furthermore the strengths or efficiencies of these sources vary with mach number (Lowson [5]), monopole sources being the most efficient source at very low mach numbers, dipole sources the most efficient at intermediate mach numbers, and quadrupole source the most efficient at very high mach numbers. Much of this work on noise generation has been concentrated at the relatively high rotor tip mach numbers achieved in modern jet compressors where dipole source radiation has been found to dominate. In helium cooled reactors, very much lower rotor tip mach numbers (~ 0.1) will be employed (Penry [6]), whereby the possibility arises that the dominant source of radiation will alter.

In this paper, the basic mechanisms responsible for monopole, dipole and quadrupole radiation are discussed. Results from a recent experimental programme in which the sound pressure levels were measured of the noise generated by a centrifugal circulator operating over a mach number range of 0.04 to 0.6 are presented. From these results the nature of the predominant mechanisms are ascertained.

The now classical paper by Tyler and Sofrin [7] focussed attention on the concept that acoustic modes are excited in a circulator duct as a result of rotor/stator interactions, and that under certain conditions, modes can propagate along the duct, and that under other conditions the modes will decay within the duct. Morfey [8] subsequently extended this work, but it was left to Lawson and Scott [9] to demonstrate this phenomenon of modal cut-off in an engineering application. They performed experiments using a siren, and subsequently using a model compressor. All three papers were concerned with axial compressors discharging into circular outlet ducts. In this paper a simple extension has been made to Tyler and Sofrin's theory for a thin annulus, in order to consider the case of a centrifugal circulator discharging into a radially symmetric outlet annulus.

2. NOISE GENERATION CHARACTERISTICS

2.1 Sources of Noise Generation

In general the frequency spectra of both axial and centrifugal circulators take the form of broad-band noise extending over a wide frequency range, superimposed on which are a number of discrete peaks. These discrete peaks are associated with the blade passing frequency and its harmonics. The various mechanisms responsible for this spectrum can be defined in terms of the three basic sources.

Monopole radiation occurs when mass or heat is introduced into a fluid at a non-steady rate. A typical example is the pulsating flow from an exhaust pipe. In a circulator such radiation arises from the volume displacement of fluid due to the finite thickness of the rotor blade. The sound pressure radiated by a monopole source can be expressed by the relationship (Beranek [10])

$$W_M \propto \frac{\rho A U^4}{c} \qquad \ldots(1)$$

Dipole radiation occurs when a flow of gas interacts with a body to produce unsteady forces. In a circulator such interactions occur as a result of the unsteady flow components in the wake fields behind each blade, and the turbulence induced in these wakes. Wake interaction effects are responsible for discrete frequency noise radiation, whilst the turbulent flow is responsible for the broad-band noise. The sound power radiated by a dipole source can be expressed by the relationship

$$W_D \propto \frac{\rho A U^6}{c^3} \qquad \ldots(2)$$

Quadrupole radiation results from viscous stresses within a turbulent gas flow in the absence of obstacles. The most familiar practical example is the roaring noise from the tail pipe of jet and rocket propulsion engines, where turbulent mixing of the jet exhaust with the surrounding medium occurs. Broad-band noise in a circulator can be generated by the forces arising from the turbulent fluid flow and the stationary walls of a circulator structure. The sound power radiated by quadrupole sources can be expressed by the relationship

$$W_Q \propto \frac{\rho A U^8}{c^5} \qquad \ldots(3)$$

n.b. Circulator speed N has been used instead of characteristic flow velocity U in the discussion and diagrams of this paper.

Sound power is related to sound pressure through the relationship

$$W \propto \frac{A' P^2}{\rho c}$$

hence

$$\begin{array}{llll} & \underline{\text{Monopole}} & \underline{\text{Dipole}} & \underline{\text{Quadrupole}} \\ \text{Pressure } P & \propto \rho U^2 & \propto \rho \frac{U^3}{c} & \propto \rho \frac{U^4}{c^3} \end{array}$$

the constants of proportionality are measures of the impedance matching of the sources to their inlet and outlet geometries. Their magnitudes are dependant on the geometry of the circulator and its inlet and outlet ducts, and the wavelength of the sound generated.

2.2 Experimental Programme

Sound pressure level measurements have been taken of the sound generated by a 100 HP centrifugal circulator which forms part of a helium heat transfer loop. Details of the inlet and outlet geometries are shown in Figure 1. The circulator has twelve backward curved rotor blades, the gas discharging radially through seventeen curved outlet vanes. Flow variation is by varying the rotor speed, the rotor being electrically driven. Above approximately 1500 rpm the circulator shaft is supported on gas bearings.

Measurements were taken at three positions in the outlet annulus of the circulator. At positions A and B accelerometers were placed behind the pressure transducers to detect any significant structural resonances that might adversely affect the results. By varying the temperature and pressure of the gases in the loop, a wide range of densities and velocities of sound have been achieved.

2.3 Results and Discussion

Figures 2 and 3 illustrate typical variations of sound pressure with density and velocity of sound. Clearly a linear dependence exists between sound pressure and density, as is expected. Although figure 3 shows that the sound pressure is inversely proportional to the velocity of sound in the acoustic medium, the exact dependences vary somewhat from the theoretical value, and a considerable scatter in the experimental data is obtained. It is not surprising that the values of sound pressure for a particular gas exhibited a rather random scatter, with such small variations in velocity of sound (∿ 4% in He for example). To measure sound pressure in a large rig with so many other variables with such accuracy is difficult. It is encouraging that variations of the order of 50% in sound pressure can be more reliably detected as seen from the variations in density.

The general trends shown in figures 4 and 5 for nitrogen and carbon dioxide indicates that sound pressure varies with circulator speed to the power 3.0 to 3.3. This implies that dipole mechanisms are responsible for the noise generation. It is interesting to note, however, that the same dependence in helium is slightly lower, approximately 2.6, and is of the same order at all three transducer positions. This on first inspection might lead one to conclude that the both monopole and dipole sources might be equally responsible for the noise generation in this lower mach number region. However, it is interesting to note that when sound pressure measurements were made at very low mach numbers, and very close to the noise source, Chanaud [4] noticed a similar deviation from the dipole relationship. This deviation was attributed to near field effects. On investigating this effect further, Chanaud found that for a given distance x from the source, for frequencies such that $k.x < 1.4$, the near field effects had a significant influence on the measured sound pressures. In the near field, a component of the particle velocity is 90° out of phase with the pressure, and the corresponding part of the acoustic field is reactive. This reactive part of the acoustic field may be higher than the normal resistive part, leading to higher sound pressures than anticipated. Accepting Chanaud's criteria the author rejected those frequencies likely to influence the measured sound pressures. This showed (c.f. open and closed squares in figure 4), as in fact Chanaud found, that near field effects influence the measured sound pressures particularly at low mach number. Near field effects were also present in the nitrogen and carbon dioxide results, but to a lesser extent (the near field pressures are only plotted for the helium results for the sake of clarity). This result is not surprising as the frequency below which the sound pressure is rejected is much higher in helium than in the other two gases. At some speeds it thus includes the blade passing frequency (where it propagates), whilst it is never high enough to do so in nitrogen and carbon dioxide. When near field effects have been excluded from the measured helium sound pressures, the variation of sound pressure with circulator speed increases to a power between 2.7 and 3.1, which is virtually the same as achieved with nitrogen and carbon dioxide. These exponents fall well within the range that other authors have considered to represent dipole mechanisms (Deeprose and Brooks [11]).

These results have more significance than explaining the departure of the experimental results from the dipole relationship. They show that care must be exercised in positioning instrumentation in helium cooled reactors, or care exercised when interpreting the results.

3. MODAL CUT-OFF

3.1 Rotor/Stator Interaction

Tyler and Sofrin [7] showed that for the propagation of modes down a thin annulus, the mach number of the propagating mode can be defined as

$$M_s = \frac{c_s}{c} \qquad \ldots(4)$$

where c_s is the velocity with which the pressure pattern sweeps the walls of the duct.

When $M_s > 1$ the mode will propagate along the duct
$M_s < 1$ the mode will decay within the duct
$M_s = 1$ this defines the cut-off mach number of the mode.

When outlet guide vanes are introduced into the pressure field of a rotor, its lobed pressure pattern is modified. Instead of the number of lobes being equal to the number of rotor blades, the number may be decreased or increased depending on the phase change caused by the interaction. The pattern thus has to rotate faster or slower in order to produce fluctuations of the same frequency. The number of lobes is given by [7] (see also Lawson and Scott [9]).

$$m = nB + \ell S \qquad \ell = \ldots -1, 0, 1, \ldots$$

The rotation speed of the pattern now becomes

$$c_s = \frac{nB}{m} \cdot \Omega\, r_o \qquad \ldots(5)$$

n.b. in order to determine the lowest frequency at which a mode is cut-off, ℓ is varied until the lowest value of m is achieved. A negative m implies that the pattern rotates in the opposite direction to the rotor.

The rotor tip speed $V = \Omega r_T$, and hence substituting this into equation (5) yields

$$c_s = \frac{nB}{m} \cdot \frac{r_o}{r_T} \cdot V \qquad \ldots(6)$$

Hence the rotor tip mach number for a particular mode to propagate is given, on dividing by c as

$$M_s = \frac{c_s}{c} = \frac{nB}{m} \frac{r_o}{r_T} \frac{V}{c} > 1$$

$$\text{i.e.} \qquad \frac{V}{c} > \frac{m}{nB} \frac{r_T}{r_o} \qquad \ldots(7)$$

$$\text{Now} \qquad V = \frac{2\pi r_T N}{60}$$

and so a mode propagates when the circulator speed is such that

$$N > \frac{60}{2\pi} \frac{mc}{nBr_o} \qquad \ldots(8)$$

The cut-off frequency can be found since

$$c_s = \lambda_s f = \frac{2\pi r_o}{m} \cdot f.$$

i.e. on dividing by c and re-arranging

$$f = \frac{mc}{2\pi r_o} \qquad \ldots(9)$$

Another useful parameter when selecting the number of rotor and stator blades in order for a mode to decay is the smallest number of lobes that can be accommodated. Re-arranging equation (9) this becomes

$$m > \frac{2\pi r_o}{c} \cdot f. \qquad \ldots(10)$$

where f will refer to the pertinent blade passing frequency or its harmonics.

Modes that decay, do so exponentially. The decay rate for a thin annulus is given by

$$\frac{\Delta dB}{\Delta x} = \frac{8.69m}{r_o} \sqrt{1 - M_s^2} \ \text{dB/radius} \qquad \ldots(11)$$

3.2 Results and Discussion

Values of the cut-off frequencies, circulator speeds and rotor tip mach numbers of the experimental outlet duct relating to the spectra of figures 6 and 7 are presented in Table 1. Inspection of these frequency spectra indicates reaosonably good agreement with theory. For example the spectra of figure 6(a) and 6(b) show that at low speeds the blade passing frequency is not clearly definable above the general broad-band noise. It does start to propagate at 7000 rpm, however, which is at a lower speed than predicted. The first harmonic which according to theory should be cut-off at 5100 rpm is present at 5250 and 7000 rpm, but not at 3000 rpm, whereas the second harmonic is present throughout the speed range as expected. In helium, the blade passing frequency and its first harmonic should not propagate and indeed are not present in any of the spectra in figure 7. The second harmonic which should propagate however is present throughout the speed range. Although modes should be cut-off at transducer position A, this was not observed. This is not surprising, as the modes do not decay instantaneously, a certain distance being necessary before a measurable difference is detectable with any accuracy (see equation 11). The agreement is encouraging as Tyler and Sofrin's [7] work referred to axial flow circulators. These results indicate that their basic theory can be extended to consider the case of a centrifugal circulator discharging into a radially symmetric outlet annulus. It is thus possible that by carefully selecting the numbers of rotor and outlet guide vanes to cut-off the blade passing frequency and some of its harmonics whilst still maintaining the requisite aerodynamic performance.

It is interesting to note when making sound pressure measurements during the commissioning of a helium reactor in air, that the cut-off speeds of the circulator and duct configuration in air are approximately a quarter of that in helium. It is thus conceivable that a mode which might be cut-off with helium as the acoustic medium, will propagate with air as the acoustic medium.

4. CONCLUSIONS

The experimental results indicate that in the mach number region investigated (0.04 - 0.6), dipole sources are the dominant sources responsible for the noise generation. The effect of circulator speed on sound pressure had a power relationship with a slightly lower exponent in helium, than in both nitrogen and carbon dioxide. This has been attributed to near-field effects that are known to influence noise measurements when they are taken close to the source (compared to the wavelength of sound generated).

An examination of the frequency spectra of the circulator operating over a wide range of speeds indicates reasonably good agreement between theoretical and experimental values of the modal cut-off speeds.

ACKNOWLEDGEMENTS

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TABLE I

Values of m, The Theoretical Modal Cut-Off Frequencies, Speeds, and Mach Numbers for the Experimental Outlet Duct

n	|m|	Cut-off Frequency Nitrogen	Cut-off Frequency Helium	Cut-off Speed Nitrogen	Cut-off Speed Helium	Cut-off Mach Number
1	5	1924	5974	9624	29872	0.53
2	7	2694	8364	6737	20901	0.37
3	2	769	2390	1283	3982	0.07
4	3	1154	3585	1443	4480	0.08

(Radius of Duct = 0.51 ft., Velocity of sound in Helium 3827 ft/sec.
Velocity of sound in Nitrogen 1233 ft/sec).

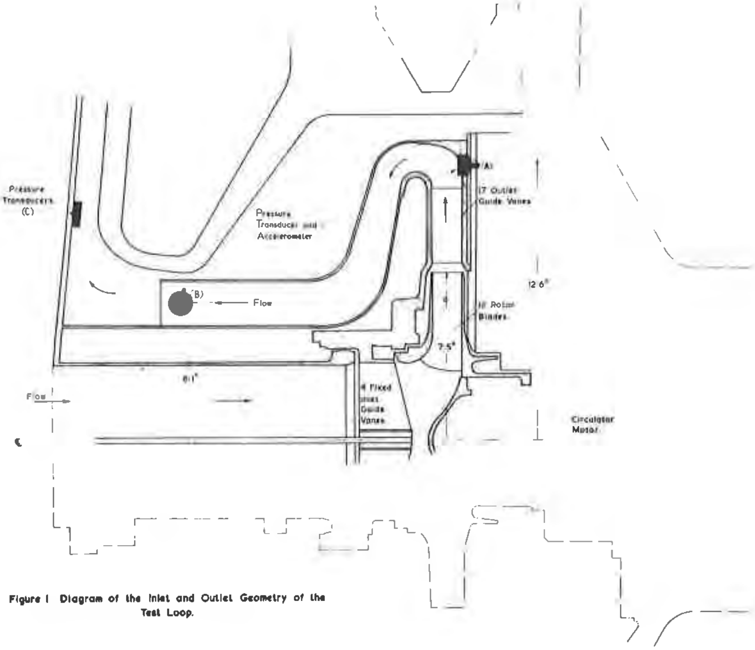


Figure 1 Diagram of the Inlet and Outlet Geometry of the Test Loop.

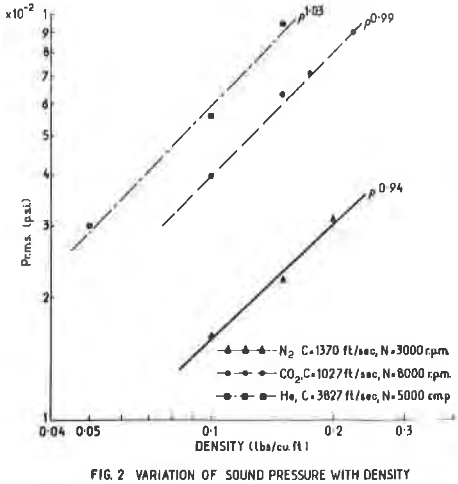


FIG. 2 VARIATION OF SOUND PRESSURE WITH DENSITY

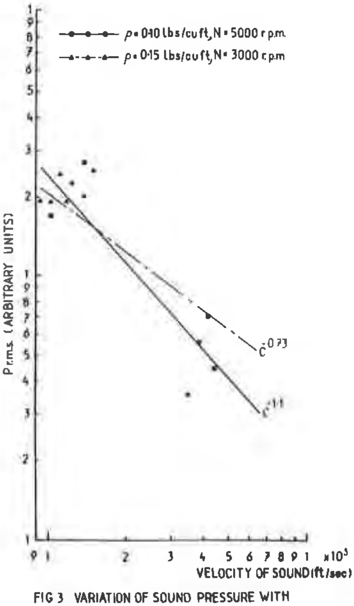


FIG 3 VARIATION OF SOUND PRESSURE WITH VELOCITY OF SOUND IN ACOUSTIC MEDIUM

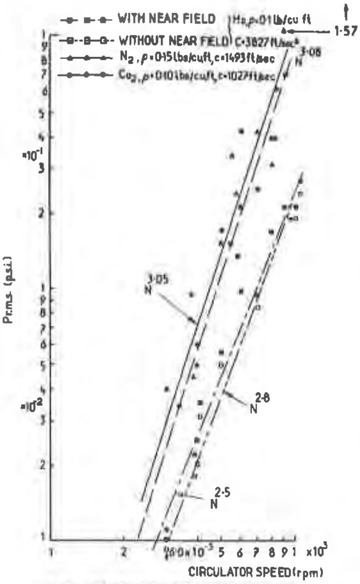


FIG 4 VARIATION OF SOUND PRESSURE WITH CIRCULATOR SPEED (TRANSDUCER POSITION A)

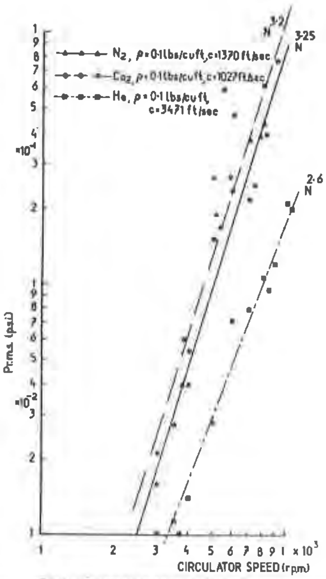
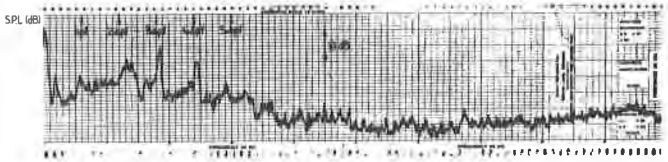
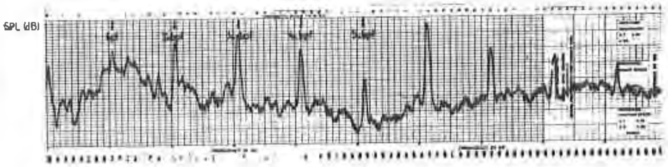


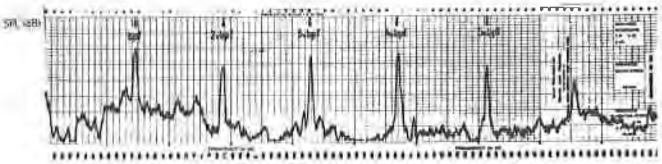
FIG 5 VARIATION OF SOUND PRESSURE WITH CIRCULATOR SPEED (TRANSDUCER POSITION B)



(a) CIRCULATOR SPEED = 3000 rpm

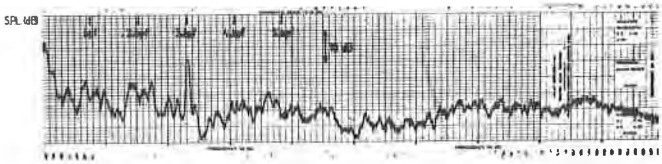


(b) CIRCULATOR SPEED = 5250 rpm

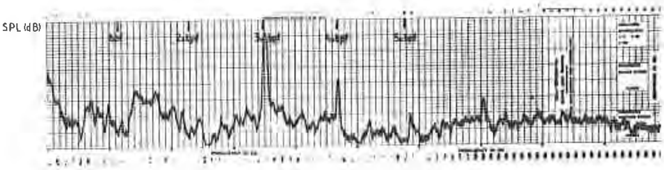


(c) CIRCULATOR SPEED = 7000 rpm

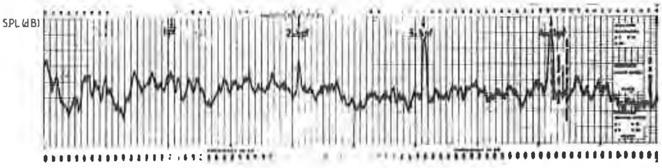
FIG 6 TYPICAL 50 hz BANDWIDTH FREQUENCY SPECTRA NITROGEN
(TRANSDUCER POSITION C)



(a) CIRCULATOR SPEED = 3837 rpm



(b) CIRCULATOR SPEED = 5800 rpm



(c) CIRCULATOR SPEED = 10,000 rpm

FIG 7 TYPICAL 50 hz BANDWIDTH FREQUENCY SPECTRA HELIUM
(TRANSDUCER POSITION C)